EASTERN SECTION
SEISMOLOGICAL
RESEARCH LETTERS

Shear-Wave Velocity Survey of Seismographic Sites in Eastern Canada: Calibration of Empirical Regression Method of Estimating Site Response

Igor A. Beresnev and Gail M. Atkinson
Carleton University, Ottawa, Canada

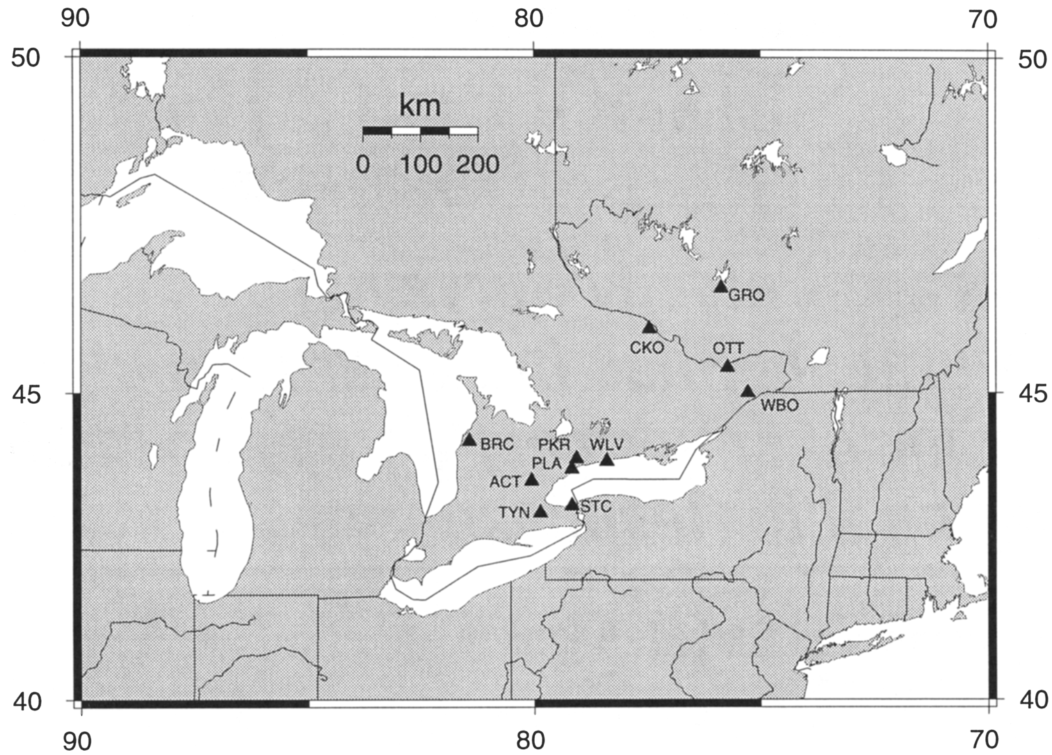
ABSTRACT

Reliable information concerning the predominant site effects on ground motions can be obtained from low-cost shear-wave refraction surveys using a sledgehammer as an energy source. For the south and southeast Ontario region, the velocity structure can be determined to a depth of approximately 70 m. Near-surface shear-wave velocities of hard-rock sites range from 1.7 to 3.1 km/sec, with an average value of approximately 2.6 km/sec. Typical soil sites have shear-wave velocities of 250–700 m/sec near the surface.

Empirical methods of determining the relative values of frequency-dependent amplification are commonly employed. These methods fit the observed earthquake spectra with a regression model that decomposes the recorded spectrum into source, path, and site terms. By regression analysis of large amounts of recorded data, the average site term for a particular station can be determined. We calibrated such an empirical technique against the theoretical responses based on the velocity structure obtained from a detailed field survey. The empirical-regression approach and the theoretical-response approach provide reasonably consistent estimates of amplification at hard-rock sites. We conclude that the amplification for an average hard-rock site is about a factor of 1.3. At soil sites, empirical-analysis and theoretical-response results agree as to the frequency of the fundamental resonance peaks. The maximum theoretical amplification values generally exceed those indicated from the empirical analyses; theoretical amplifications by as much as factors of 6 and 7 were calculated, while empirical amplifications were below a factor of 3. Thus use of theoretical site responses may be conservative.

INTRODUCTION

Most of our current database of ground motions from earthquakes in eastern North America (ENA) is comprised of recordings from the Eastern Canada Telemetered Network (ECTN), operated by the Geological Survey of Canada, and the Southern Ontario Seismographic Network (SOSN), operated by the University of Western Ontario (Atkinson and Mereu, 1992; Atkinson and Boore, 1995; Adams *et al.*, 1996; Asmis and Atkinson, 1996; Atkinson, 1996). The ECTN and SOSN stations have been sited on hard rock whenever possible. Over much of southern Ontario, however, there are no bedrock exposures, and most of the SOSN stations are located on sedimentary layers with variable depth. In deriving ground-motion attenuation relations and source parameters for ENA earthquakes, average site effects are generally removed from the observed records by using a regression model. In a typical example, logarithms of the observed spectral amplitudes are represented as a sum of the logs of source amplitude, path-effect terms, and a site effect term (*e.g.*, Atkinson and Mereu, 1992, equation 1). By fitting a large amount of empirical data with a regression model, the relative site terms can be determined as a function of frequency. Generally, the site terms are determined relative to an assumed average amplification of unity for hard-rock sites. Data recorded at a site can then be reduced to a reference "hard-rock" condition by simply dividing the observed



▲ **Figure 1**. Location of surveyed ECTN and SOSN seismographic sites. Three first letters have been retained in station names, compared to Table 1.

spectra by frequency-dependent amplification factors. The resulting attenuation curves can be directly used in engineering design.

Because regression models generally make the assumption that the average response over all hard-rock sites is unity, it is important to establish the reference rock conditions to which this constraint applies. If we know the shear-wave velocity profile for "average" hard-rock sites, and also know the regional attenuation, we can then calculate the source amplitudes of events recorded on these sites. Furthermore, we can determine the responses of other soil or soft-rock stations relative to a known reference condition. Finally, we can evaluate whether regression-determined site responses are in agreement with theoretical expectations, based on the velocity profiles of the recording sites.

In this study, we address these calibration objectives, by determining the shear-wave velocity profile for 11 seismographic sites in southeastern Canada. We compute the theoretical site responses of these profiles, and compare them to empirical site amplification terms previously determined from regression analyses.

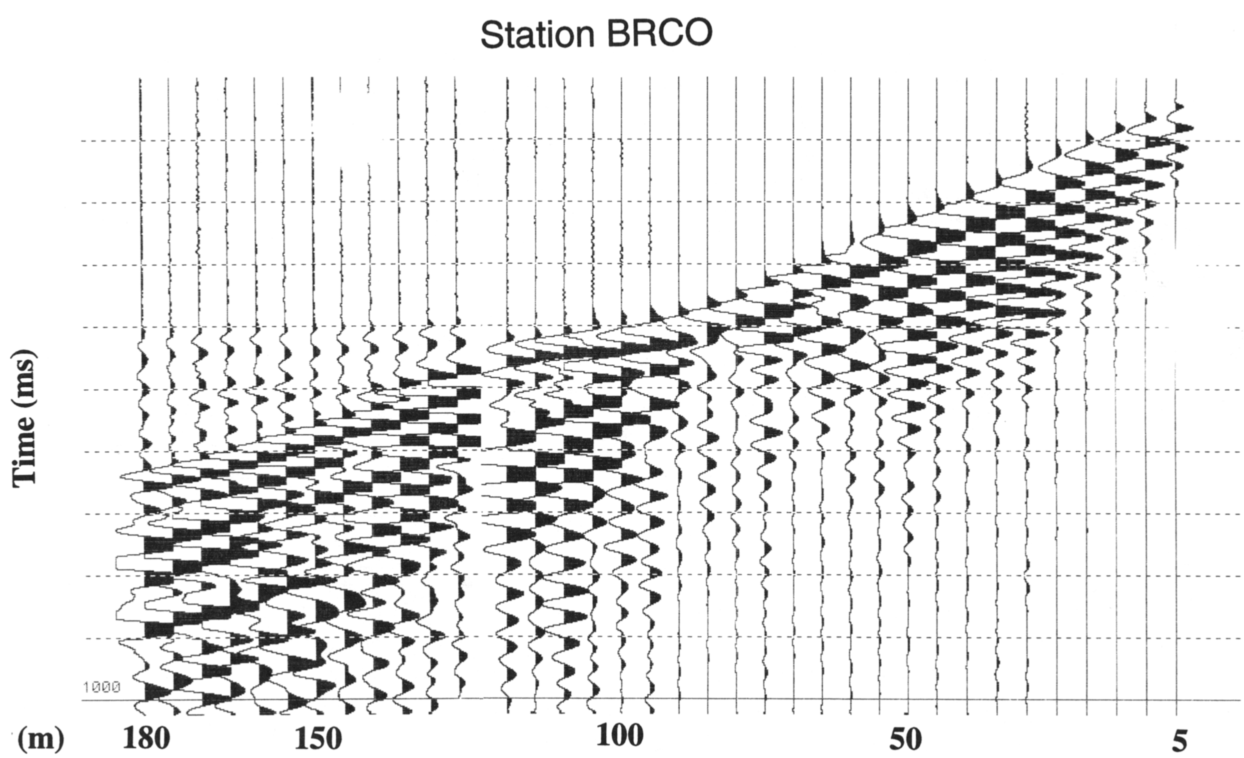
LOCATION OF THE SITES

The ECTN and SOSN regional networks have approximately 25 stations, stretching for about two thousand kilometers from Lake Huron to the Atlantic coast (Atkinson, 1996, Figure 1). Eleven sites have been chosen for our analysis. Four of them are the ECTN stations located within a radius of approximately 200 km of Ottawa, Ontario, and seven others are the SOSN stations situated between Lakes Huron and Ontario (see Figure 1 and Table 1). The selected ECTN sites are in an area characterized by very thin (a few m) or no sedimentary cover, while the SOSN stations are believed to be underlain by soil deposits with the exact depths to the basement poorly known. The chosen ECTN stations are all founded on hard rock or at the base of the thin soil cover.

GATHERING AND PROCESSING OF FIELD DATA

We used the conventional hammer-seismic refraction technique of shallow velocity surveys (*e.g.*, Street *et al.*, 1995). Since we are primarily interested in shear-wave velocities, only *SH*-wave data were collected. The *SH*-waves were excited by a steel I-beam struck horizontally by a sledgehammer in the direction perpendicular to a spread of geophones. A single spread of 24 4.5-Hz horizontal geophones (Mark Products L-28) with 5 m spacing was used. Sledgehammer impacts were produced at the center of the spread and at offsets of 5 and 65 m from each end, giving a maximum source-receiver distance of 180 m. Digital seismograms from the source impacts in the two opposite directions were stacked, with the reversal in acquisition polarity, to enhance *SH*-waves and cancel *P*-waves. Recordings with each impact polarity were stacked 4 to 16 times, depending on noise conditions. Seismic data were collected by the Geometrics ES-

TABLE 1 Locations of Surveyed Stations				
Station	**Location**	**Network**	**Latitude (deg)**	**Longitude (deg)**
OTT	Ottawa, Ontario	ECTN	45.39	–75.72
WBO	Williamsburg, Ontario	ECTN	45.00	–75.28
CKO	Chalk River, Ontario	ECTN	45.99	–77.45
GRQ	Grand Remous, Québec	ECTN	46.61	–75.86
BRCO	Bruce Nuclear Power Plant, Ontario	SOSN	44.24	–81.44
STCO	Saint Catharines, Ontario	SOSN	43.21	–79.17
TYNO	Tyneside, Ontario	SOSN	43.09	–79.87
ACTO	Acton, Ontario	SOSN	43.61	–80.06
PKRO	Pickering, Ontario	SOSN	43.96	–79.07
WLVO	Wesleyville, Ontario	SOSN	43.92	–78.40
PLANT	Pickering Nuclear Power Plant, Ontario	SOSN	43.48	–79.11

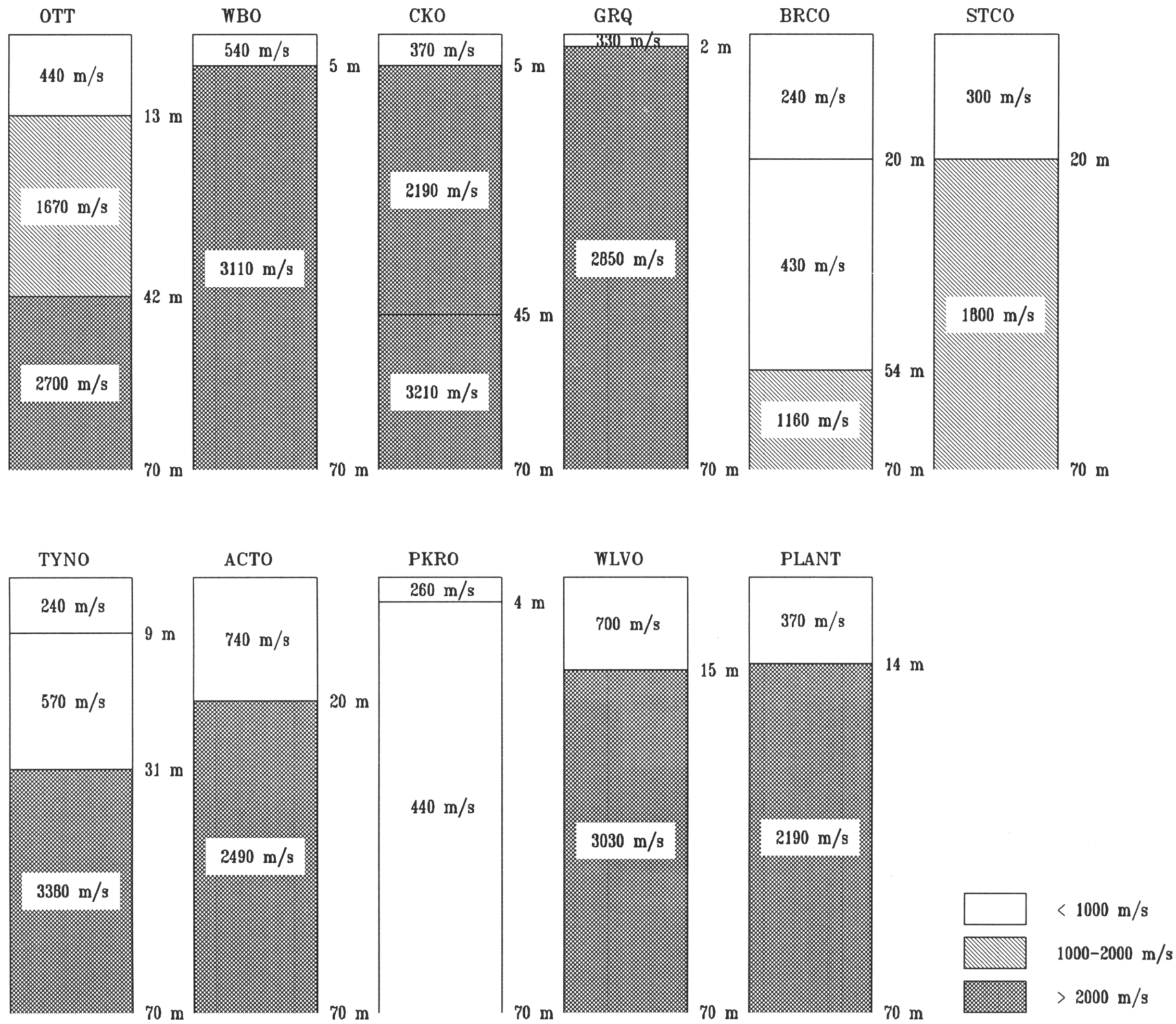


▲ **Figure 2**. *SH*-wave walkaway section collected at station BRCO. The interval between geophones is 5 m. No filtering was applied.

2401 instantaneous engineering seismograph and were processed on a PC using the seismic refraction software package SIP (Rimrock Geophysics Inc., 1995), which calculates layer depths by inversion of first arrivals. The program is based on ray tracing and model-adjusting iterations to minimize the discrepancies between measured and theoretical arrival times. The maximum depth of penetration in our field setup is about 70 m. Figure 2 shows an example of stacked raw seismic data collected at station BRCO.

NEAR-SURFACE SHEAR-WAVE VELOCITY STRUCTURE

The interpretation program produces a table of layer depths and shear-wave velocities (V_S) under each geophone and under three shotpoints. Inferred depth variations along the profile were insignificant, except for the station BRCO, where a two-dimensional structure was clearly indicated. We therefore represent all sites as one-dimensional cross sections,



▲ **Figure 3**. Soil columns based on *SH*-wave refraction data. The average depths and shear-wave velocities are indicated.

showing the average layer positions. For station BRCO, we show both the one-dimensional profile and the more accurate two-dimensional structure.

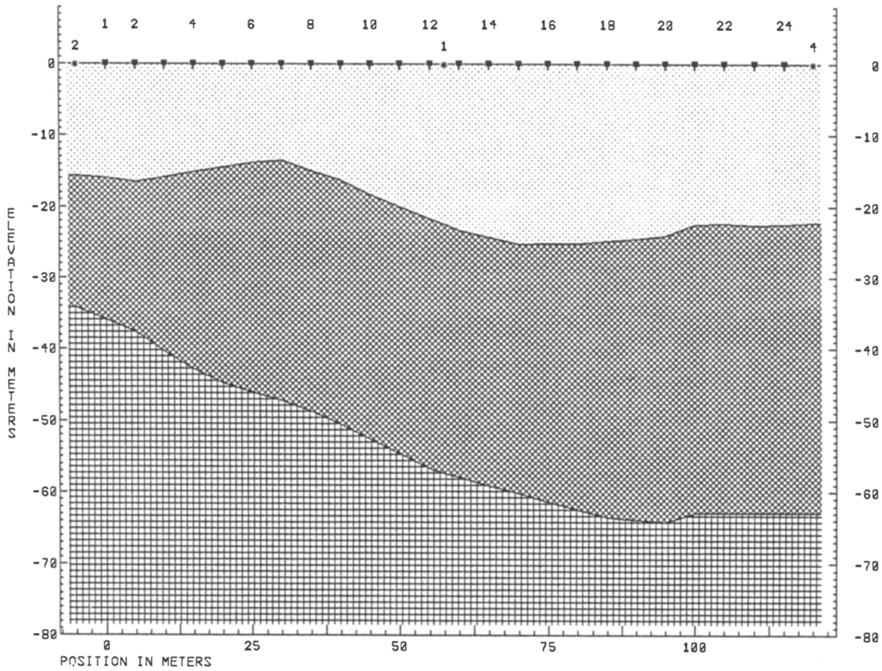
It should be noted that a one-dimensional representation of real structure is an idealization that can lead to unrealistically sharp resonances in the calculated responses. The real structure deviates from the profiles shown, due to a combination of uncertainty in picking arrival times and unresolved small-scale heterogeneity. The inversion results include an estimate of the standard error of all inferred depths and velocities. When computing theoretical responses, we randomize the average cross sections according to the estimated uncertainty in layer boundaries and velocities, to obtain more realistic responses (see below).

Figure 3 presents average shear-wave velocity profiles for all stations, and Figure 4 presents the two-dimensional BRCO model. All soil columns are plotted to a depth of 70 m. The four surveyed ECTN sites (OTT, WBO, CKO, and GRQ) are characterized by very shallow bedrock surfaces (first few meters). The seismographs at these sites are founded on these rock surfaces. The seven other sites, all located in southern Ontario, have much deeper soil-bedrock interfaces (> 15m); at station PKRO, our refraction experiments did not encounter the bedrock interface. We see from Figure 3 that, generally, very firm rock underlies surface deposits, with shear-wave velocities as large as 2 to 3 km/sec within the first 70 m from the surface. A maximum near-surface bedrock velocity of 3.4 km/s is observed at station TYNO. The shear-wave velocity profiles are rather simple, and none of the models have more than three layers.

COMPARISON OF THEORETICAL AND EMPIRICAL SITE AMPLIFICATIONS

Calculation of theoretical amplification functions

The site terms determined from regression of empirical data (*e.g.*, Atkinson and Mereu, 1992; see below) have been obtained as relative amplifications, for an average rock



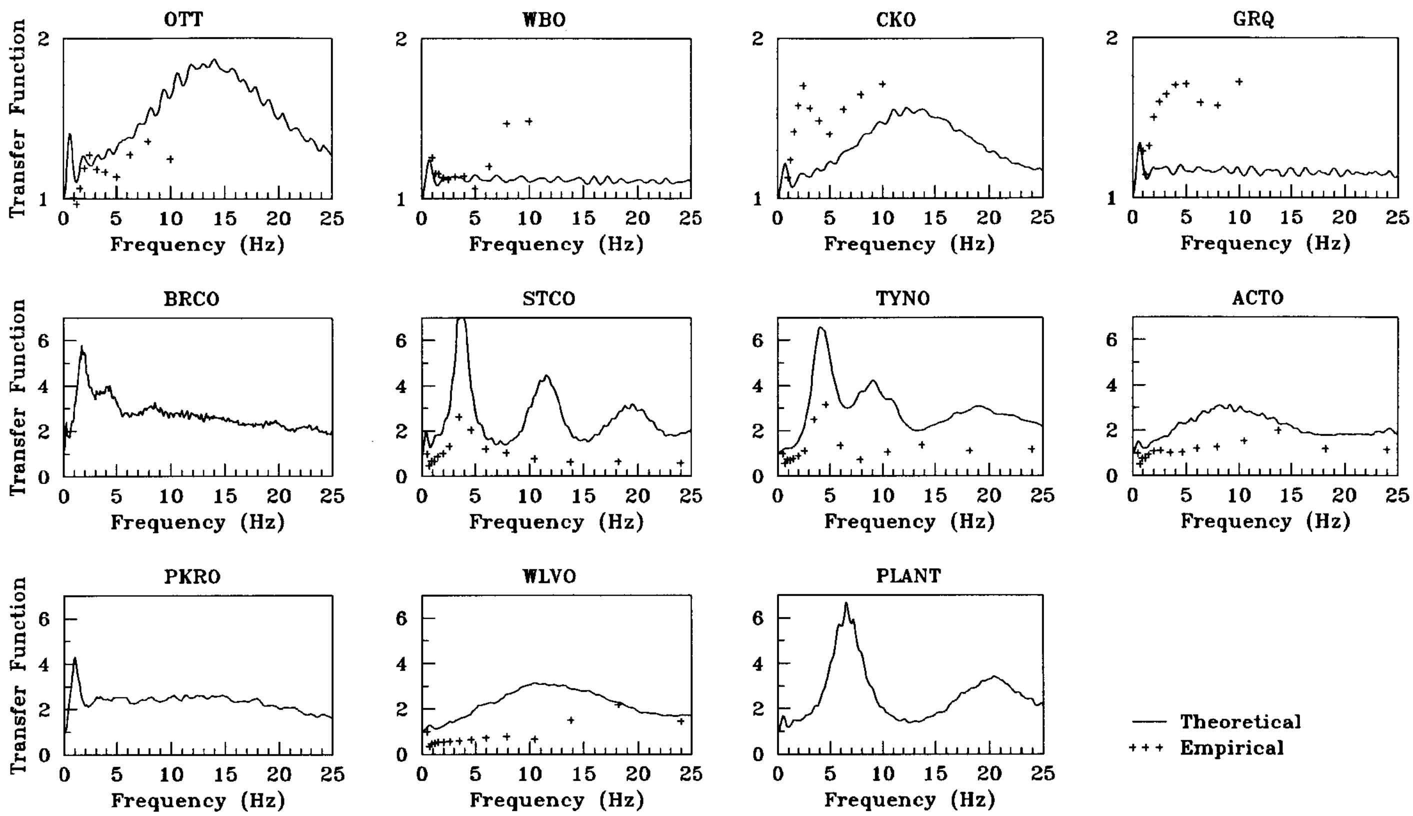
▲ **Figure 4**. Soil profile under the station BRCO, where the two-dimensional structure is significant. The lowermost high-velocity layer is dipping toward east. The positions of the twenty-four geophones and the three shotpoints nearest to the spread (1, 2, and 4) are shown on the top.

response of unity. In interpretation of the results of these regressions, Atkinson (1996) assumed a mid-crustal velocity of 3.8 km/sec and density (ρ) of 2.8 g/cm^3. To mimic this condition in the theoretical responses of columns shown in Figure 3, their bottom layers were allowed to extend to a depth of 1 km, below which a half-space with shear-wave velocity of 3.8 km/sec and the density of 2.8 g/cm^3 was assumed, corresponding to the average crustal structure of western Québec (Atkinson and Somerville, 1994, Figure 5). This assumption was made for consistency only; the values of amplification are entirely controlled by the velocity contrasts occurring at the upper 70 m. At station PKRO, the depth to bedrock was not established by our experiments. From a discussion with the property owner at PKRO, the local depth to the bedrock is believed to be about 100 m. Therefore the second soil layer (V_S = 440 m/sec) was extended to a depth of 100 m, under which the rock layer of the closest station PLANT (V_S = 2.19 km/sec) was assumed.

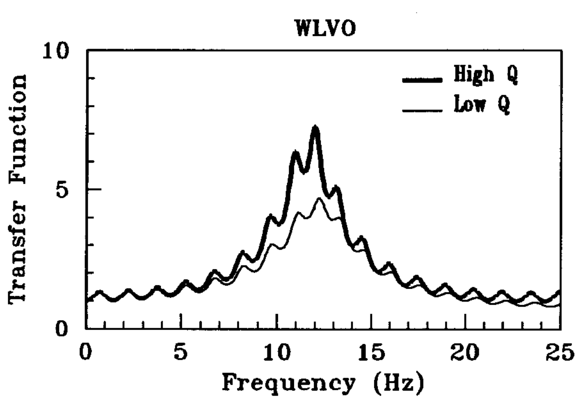
The average structures shown in Figure 3 were randomized for the calculation of the theoretical responses by using a Monte Carlo simulation approach. For each station, we generated 100 soil profiles, where layer depths and velocities were drawn from normal distributions having the mean values and standard deviations as determined from the interpretation of first-arrival data. The theoretical response was then taken as the mean of these 100 response functions. Typically, the standard errors of layer depths and velocities were less than 10 and 5% of the estimated values, respectively. The standard deviation of the response function was generally less than 20% of its mean values.

Figure 5 presents the theoretical site amplification functions in the frequency range from 0 to 25 Hz at each station (solid lines). The amplifications are calculated as amplitude spectra of the impulse response of a stack of plane layers subject to a vertically-incident plane *S*-wave, using the reflection/transmission matrix method of Kennett and Kerry (1979). All curves have been divided by the free-surface amplification factor of 2. For all "soil" layers (indicated as blank in Figure 3), the density of 1.8 g/cm^3 and the quality factor (Q) of 30 were assumed. For the remaining "rock" layers, the density and Q were assumed to be 2.5 g/cm^3 and 10^3, respectively. The adopted low Q for soil is characteristic of near-surface deposits (Gibbs *et al.*, 1994; Street *et al.*, 1995). The Q-value of 10^3 for rock has been derived as an average of the empirical ENA crustal attenuation model $Q = 670f^{0.33}$ in the frequency range of interest (Atkinson and Boore, 1995). However, theoretical site amplifications show little sensitivity to the exact choice of the Q model. This is illustrated in Figure 6, which compares the non-randomized transfer functions at site WLVO with two extreme attenuation assumptions. In the "low Q" calculation (thin line), the Q-values for "soil" and "rock" are reduced to 15 and 10^2, while in the "high Q" model (thick line), they are increased to 10^2 and 10^4, respectively. Despite these large differences in the assumed attenuation, the maximum difference in amplification is approximately a factor of 1.5, occurring only in the vicinity of the resonant frequency.

The ECTN instruments at stations OTT, WBO, CKO, and GRQ are placed either directly on the bedrock outcrop or on top of the bedrock in shallow pits. The apparently



▲ **Figure 5**. Theoretical site amplification functions calculated for randomized depth models below the stations. The vertical scale is 1 to 2 for ECTN "hard-rock" sites (upper row) and 0 to 7 for SOSN "soil" sites (second and third rows). For stations OTT, WBO, CKO, and GRQ, amplifications correspond to models with the upper soil layer removed. The "plus" symbols correspond to the amplification values derived for eight stations from the empirical regressions (Atkinson and Mereu, 1992; Atkinson, 1996).



▲ **Figure 6**. Theoretical amplification functions at station WLVO calculated with the assumption of low and high Q (thin and thick lines, respectively). An exact, non-randomized model from Figure 3 was used. The low-Q model assumes $Q = 15$ for soil and 100 for rock, while the high-Q model assumes $Q = 100$ and 10,000 for soil and rock, respectively.

larger soil thickness at station OTT, seen in Figure 3, is caused by the fact that our field survey was conducted at the foot of the hill, while the seismometer is installed in a basement vault on top of the hill, about 100 m away, where the soil thickness is likely reduced. To conform to the actual foundation of the seismometers on rock, the theoretical soil responses for the profiles at stations OTT, WBO, CKO, and GRQ were calculated without including the top soil layers. For the other sites, the calculated responses correspond exactly to the soil columns shown in Figure 3, randomized as described above.

Comparison of amplifications

The four ECTN stations have minimal site effects. The remaining seven stations show a pronounced local resonance structure (Figure 5). The most significant cause of amplification is the resonance of the top soil layer with fundamental frequency of $f_0 = V_S/4H$, where H is the layer thickness. The small-scale "undulations" about the average seen on nearly all amplification curves are an artifact caused by the 1 km-thick upper layer in the model.

The empirical amplification values at several logarithmically-spaced frequencies are available for stations OTT, WBO, CKO, and GRQ (Atkinson and Mereu, 1992, Table 1) and STCO, TYNO, ACTO, and WLVO (Atkinson, 1996, Figure 3), based on regression analyses of a large regional ground-motion database. They are shown as crosses in Figure 5. There is fair agreement in the absolute values of amplification between the theoretical and empirical responses for the four "hard-rock" stations (OTT, WBO, CKO, and GRQ). At soil sites, the theoretical and empirical data are in good agreement with respect to the frequency of fundamental resonance peaks, in cases where the peaks are significant (stations STCO and TYNO); this suggests that the refraction survey has correctly determined the average depth and shear-wave velocity. However, the theoretical amplifications generally exceed those estimated from the regional ground motion database by factors of 2 to 3. Thus large theoretical amplifications predicted at a site, based on a simple model of its shear-wave velocity profile, may not be fully realized on average, probably due to factors such as departures from 1D structure and scattering by random heterogeneities.

Use of the theoretical response function would in all cases be conservative, from the viewpoint of predicting ground-motion amplitudes. Therefore, a practical approach to site-response estimation is to begin with the theoretical response curve as obtained from the shear-wave velocity profile. In cases where the predicted amplifications are large, and may have significant engineering implications, the theoretical response should be validated empirically through a regional seismic monitoring and analysis program. This is the principal "calibration" result obtained in this study.

Based on the results of this study, we estimate the average near-surface shear-wave velocity of hard-rock sites in southeastern Canada to be approximately 2.6 km/sec. This value has been calculated from shear-wave travel times from the depth of 70 m to the base of the soil layer, averaged over stations OTT, WBO, CKO, and GRQ. The corresponding average empirical site amplification factor, for these four stations, increases from 1.2 at 1 Hz to 1.5 at 10 Hz, based on the results of Atkinson and Mereu (1992).

For energy conservation, the amplitude of a wave traveling through a rock mass toward the surface must increase inversely with $(\rho V_S)^{1/2}$ (Shearer and Orcutt, 1987, p. 1172), assuming a velocity gradient without major internal reflections. By this criterion, the amplification for average rock sites in southeast Canada should be a factor of

$$\sqrt{\frac{2.8 \times 3.8}{2.5 \times 2.6}} \approx 1.3,$$

which is close to above empirical average for these four stations. Thus the empirical amplification is consistent with the amplification implied by the vertical impedance change.

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REFERENCES

Adams, J., D.H. Weichert, S. Halchuk, and P.W. Basham (1996). Trial seismic hazard maps of Canada—1995: Final values for selected Canadian cities, *Open-File 3283*, Geological Survey of Canada, 97 pp.

Asmis, H.W., and G.M. Atkinson (1996). Cost-effective seismic monitoring: a nuclear utility perspective, *Seism. Res. Lett.*, **67**, 1, 25–7.

Atkinson, G.M. (1996). The high-frequency shape of the source spectrum for earthquakes in eastern and western Canada, *Bull. Seism. Soc. Am.*, **86**, 106–112.

Atkinson, G.M., and R.F. Mereu (1992). The shape of ground motion attenuation curves in southeastern Canada, *Bull. Seism. Soc. Am.*, **82**, 2014–2031.

Atkinson, G.M., and P.G. Somerville (1994). Calibration of time history simulation methods, *Bull. Seism. Soc. Am.*, **84**, 400–414.

Atkinson, G.M., and D.M. Boore (1995). Ground-motion relations for eastern North America, *Bull. Seism. Soc. Am.*, **85**, 17–30.

Gibbs, J.F., D.M. Boore, W.B. Joyner, and T.E. Fumal (1994). The attenuation of seismic shear waves in Quaternary alluvium in Santa Clara Valley, California, *Bull. Seism. Soc. Am.*, **84**, 76–90.

Kennett, B.L.N., and N.J. Kerry (1979). Seismic waves in a stratified half space, *Geophys. J. R. astr. Soc.*, **57**, 557–583.

Rimrock Geophysics Inc. (1995). Seismic Refraction Interpretation Programs (SIP), Lakewood, Colorado.

Shearer, P.M., and J.A. Orcutt (1987). Surface and near-surface effects on seismic waves—theory and borehole seismometer results, *Bull. Seism. Soc. Am.*, **77**, 1168–1196.

Street, R., E. Woolery, Z. Wang, and J. Harris (1995). A short note on shear-wave velocities and other site conditions at selected strong-motion stations in the New Madrid seismic zone, *Seism. Res. Lett.*, **66**, 1, 56–63.

Wessel, P., and W.H.F. Smith (1995). New version of the Generic Mapping Tools released, *EOS Trans. Am. Geophys. U.*, **76**, 329.

Department of Earth Sciences
Carleton University
1125 Colonel By Drive
Ottawa, Ontario
K1S 5B6, Canada
(beresnev@ccs.carleton.ca; gma@ccs.carleton.ca)