Ninth Canadian Conference on Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007
Paper No. 1162

SOIL AMPLIFICATION IN OTTAWA FROM URBAN STRONG GROUND MOTION RECORDS

J. Adams[1]

ABSTRACT

A strong motion network, established in Ottawa in the winter of 2002, was expanded with additional ETNA and IA (Internet Accelerometer) instruments in 2004-2005. It has now recorded weak motions from three earthquakes: M5.0 (Au Sable Forks, 20020429) at 180 km, M4.7 (Charlevoix, 20050306) at 525 km and M4.0 (Thurso, 20060225) at 32-56 km distance. The records have been analysed using site-to-reference spectral ratio and H/V spectral ratio methods and show significant amplification and sharp resonance peaks at the thick soil sites. Although strong ground motion records are of the greatest value, these weak motion records help to calibrate engineering models in the linear range of soil behaviour.

Introduction

An urban strong motion network was established in Ottawa in the winter of 2002. The network was designed to sample typical site conditions across the urban area, especially on thick soft soil sites, and forms one prototype for the Canadian Urban Seismology Project, intended to gather weak motion data in the short-term, and produce near-real time shake maps in the long-term. Initial earthquake records, from the Au Sable Forks earthquake, were reported by Al-Khoubbi and Adams (2004).

Siting, Instrumentation, Settings and Processing

Five ETNA strong motion instruments were deployed in early 2002 across Ottawa to sample representative ground conditions across the city (Fig. 1). The network was extended to 6 ETNA instruments, and beginning in mid-2004, was supplemented by six Internet Accelerometers (Table 1). The instrument sites vary from the OTT seismometer vault to the basement slabs of wood-frame houses and masonry structures (Fig. 2), on site conditions that vary from rock to circa 50 m of clay (Table 1). Soil conditions were obtained from nearby boreholes (GSC 2006a,b; Douma and Nixon 1993) and by depth-to-basement contours given by Hunter and Motezedian (2006) and Pugin et al. (2007), who also show that Vs_{30} at thick, soft clay sites may be as low as 130 - 170 m/s.

The ETNA instruments have low internal noise characteristics and excellent sensors, but are triggered systems with limited on-site memory. After careful attention to site noise characteristics, the trigger thresholds were set in the range 0.02 - 0.08 %g (Al-Khoubbi and Adams 2004). Frequent service visits (relatively simple in our home city but time consuming) are required to ensure that free memory will remain

[1]Seismologist, Geological Survey of Canada, Natural Resources Canada, 7 Observatory Cres., Ottawa, ON K1A 0Y3

for an important event. Even with these precautionary settings, four of the six ETNAs had full memory and did not record the latest (Thurso) earthquake discussed in this paper.

The Internet Accelerometer (IA) instruments record continuously and store 1.5 days worth of data (Rosenberger et al 2004). As they are connected via the internet, their day-to-day operation can be verified and it is relatively quick to recover any earthquake records. However, their MEMS sensors have quite high internal (electronic) noise, so that weak earthquakes are sometimes at or below the noise level; the IAs generally have not produced useful records for the mostly-weak earthquakes recorded to date (Molnar et al., 2006a, 2006b). This was also the case for the IA recordings of a magnitude 3.8 earthquake 148 km east of Ottawa on 20060109.

A broad-band seismometer records continuously in the Observatory vault; its 3-component velocity records remained on-scale for all the earthquakes discussed and was processed into an acceleration record. A test broad-band seismometer happened to be recording at Blackburn during the Thurso earthquake and was processed likewise.

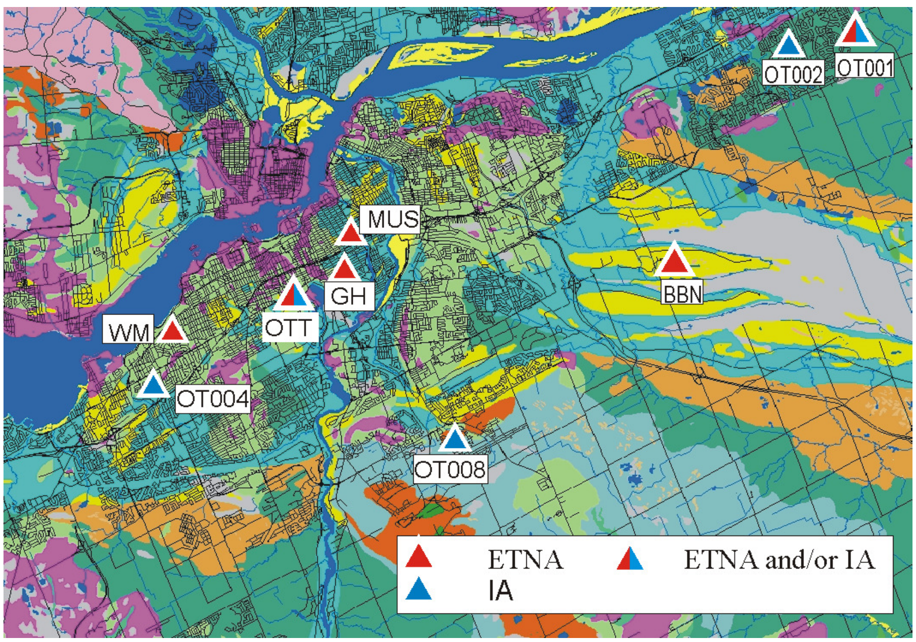


Figure 1. Locations of recording stations (triangles with code), superimposed on a surficial geology map (GSC 1977) of Ottawa. For geological legend see GSC (2006b). Red/blue triangles indicate sites that operated both instrument types, either sequentially or concurrently. The distance from OT001 to OT004 is 27 km.

Figure 2. Site OT002. (Left) View of basement under construction in 1986. The IA is now installed under the red arrow. Current house is similar to the ones in the background. (Right) The IA is oriented and then bolted to the floor slab.

Table 1. Details of strong motion installations and their foundation conditions.

Site Name	Code(s)	Basement of	Lat N	Long W	Foundation	Soil Thickness (m)
Observatory	OTT OTTE OT012 OT011	Vault Vault Vault 3rd floor table	45.3942	75.7167	Paleozoic limestone **(SSR reference site)**	0
Glebe High School	GH	4-storey masonry building	45.4014	75.6967	Stratified medium sand	<5
Westminster	WM	2-storey wood frame house	45.3824	75.7628	Thin sand over clay	~10
Blackburn1	BBNE	1-storey wood frame shed	45.4068	75.5548	50 m clay over till	58
Blackburn2	BBNS	Open field	45.4060	75.5535	50 m clay over till	58
Museum	MUS	4-storey masonry building	45.413	75.689	23 m clay over silty-gravel & till	40
Orleans1	OT001	2-storey wood frame house	45.4787	75.4745	Clay, silt, and silty-clay	~40
Orleans2	OT002	2-storey wood frame house	45.4742	75.5019	Clay	~30
Lincoln Fields	OT004	2-storey wood frame house	45.3644	75.7746	Clay or till	<5
Blossom Park	OT008	2-storey wood frame house	45.3496	75.6418	Sand	~35

Table 2. Details of Ottawa instruments with earthquake records.

Earthquake		Au Sable Forks	Charlevoix	Thurso
Magnitude (Mw)		5.0	4.7	4.0
Date YYMMDD (UT)		20020420	20050306	20060225
Location (lat, lon)		44.48, 73.71	47.75,69.73	45.66, 75.24
Distance range (km)		180	525	32-56
S-wave window length (s)		20	40	6
Code	**Instrument**			
OTT	Seismometer	xx	xx	xx
OTTE	ETNA	xx	o	xx
OT012	IA			xx
OT011	IA			xx
GH	ETNA	xx	o	o
WM	ETNA	xx	xx	o
BBNE	ETNA		xx	xx
BBNS	Seismometer			xx
MUS	ETNA		xx	o
OT001	ETNA	xx		
OT001	IA		o	xx
OT002	IA			xx
OT004	IA			xx
OT008	IA			xx

Note: blank = not operating, xx = record obtained, o = no record obtained

Kinemetrics Strong Motion Analyst software was used to retrieve and display the ETNA data, correct the acceleration data, and export it as an ASCII file for use by SAC (Seismic Analysis Code). The IA and seismometer data is directly readable by SAC. Original time history data will be available from www.earthquakescanada.ca. SAC was used to produce the time history plots and the Fourier spectra. The spectra were smoothed using $1/10^{th}$ log unit bins of frequency before the spectral ratios were calculated. Table 2 gives the window length used, beginning at the first S arrival. The root-mean-square (RMS) of the two horizontal components was used to represent the horizontal spectra. The site-to-reference spectral ratio (SSR) method had been used by Al-Khoubbi and Adams (2004) to analyze the Au Sable Forks data. However, most of the analysis in the present paper uses the horizontal / vertical spectral ratio (HVSR) method (e.g., Molnar et al. 2004; Molnar and Cassidy 2006; Molnar et al. 2007).

Results

M_W 5.0 Au Sable Forks (New York State) Earthquake

Al-Khoubbi and Adams (2004) used the SSR method, with the OTT site as the bedrock reference, to analyze RMS horizontal data from the three soil stations identified in Table 2. Their SSR results shown in Figure 3A demonstrate that there was very little amplification at the Glebe High School (GH) site, significant amplification with a dominant frequency of 5 Hz (period of 0.2 s) at the Westminster (WM) site, and significant amplification with a dominant period of 1 Hz at the Oreleans1 (OT001 site; same site named ORL in Al-Khoubbi and Adams 2004). Figure 3B shows the results of applying the HVSR method to the same spectral data. There is excellent agreement in the position of the resonance peaks and good agreement in their amplitudes. The HVSR method also reveals a clear resonance peak for GH at 10 Hz, which was not apparent in the SSR plots.

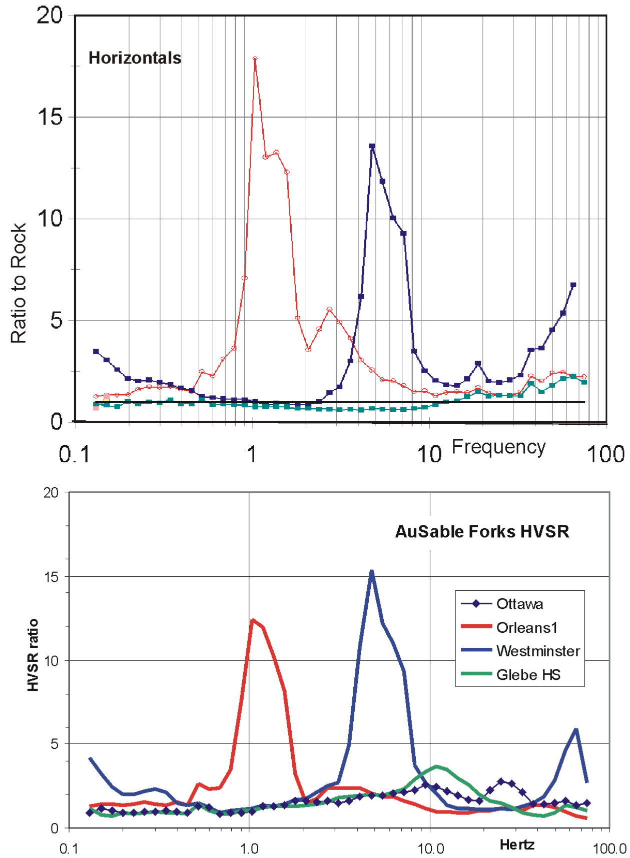


Figure 3A. SSR analysis of the Au Sable Forks spectra at stations OT001, WM, and GH, relative to OTT (black line at value =1), as taken from figure 10 of Al-Khoubbi and Adams (2004).

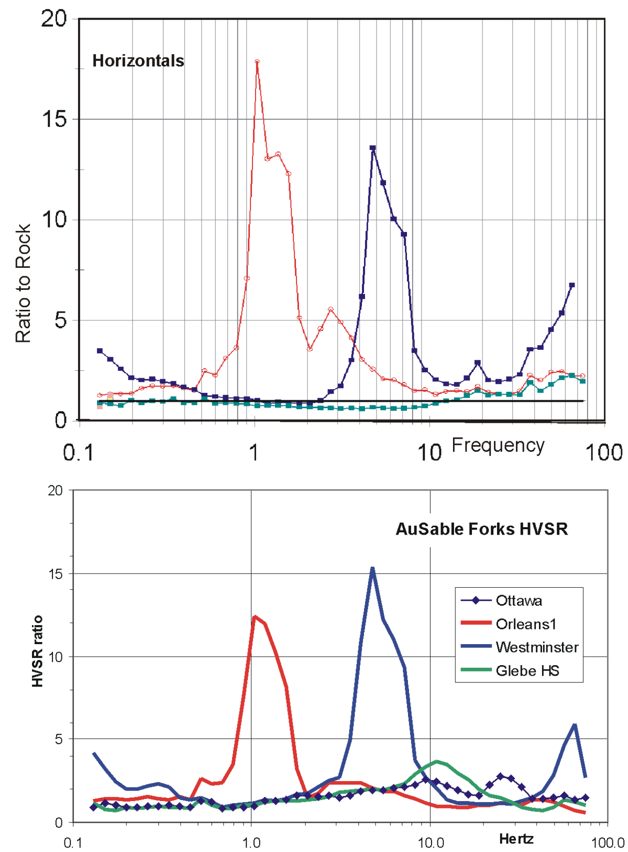


Figure 3B. HVSR analysis of the Au Sable Forks spectra at stations OT001, WM, GH, and OTT.

M_W 4.7 Charlevoix Earthquake

Three ETNA records (Table 2) together with the Ottawa seismograph are available for the Charlevoix earthquake (Fig. 4A). The spectra for WM are similar to those of the Au Sable Forks earthquake, but the spectra for the Museum (MUS) and Blackburn (BBNE) show a strong double peak with a sag at 3 Hz for MUS and at 1.5 Hz for BBN (Fig 4B). Such a double peak usually represents a two-layer soil structure (S. Molnar, pers. com. 2006) and will deserve further study.

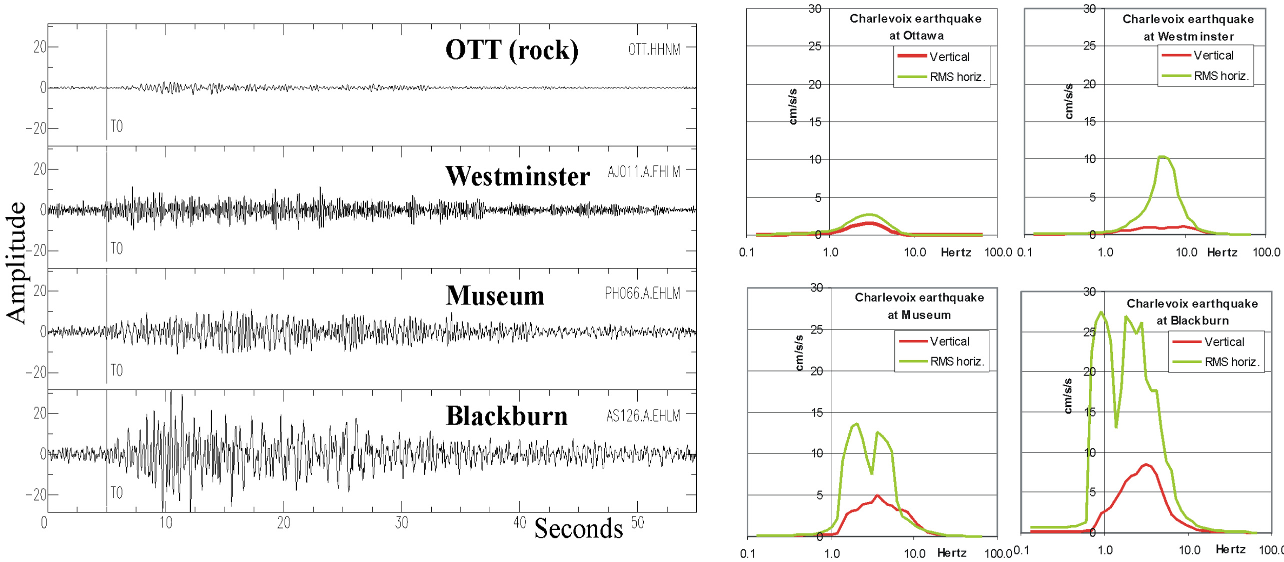


Figure 4. Acceleration time histories of the Charlevoix earthquake (left) and their source spectra (right).

Fig. 5A shows the HVSR results. The strong peak at WM seen for the Au Sable Forks data is reproduced. The OTT values are nearly flat at a value of about 2. MUS has a clear peak at 1.3 Hz, but with less amplification than WM. BBNE has a peak 0.7 Hz with an extreme HVSR amplification factor of 86. The reproduction of the peak at WM diminishes concern that ringing in the Au Sable Forks record was due to an unrecognized instrument malfunction (Al-Khoubbi and Adams 2004). Figure 5B shows the ratio of the HVSR for WM, BBNE, MUS to the HVSR for OTT. This should be more or less equivalent to the SSR method, but avoids reconciling the different frequency responses and magnifications of the various instruments. The peaks for the three stations are confirmed, but the amplitude values are of course halved. Although the BBNE SSR value of 41 is high, note that Pugin et al. (2007) obtained a factor of 49 on a site with ~80 m of similar clay. Note also that there seems to be some deamplification of 10-Hz energy at the MUS site. Some preliminary 1-D modelling of the soil column at the Museum has suggested a resonance peak at about 2 Hz with amplification of a factor of four (work by Raymond Casey, pers. com., Gail Atkinson, 2002).

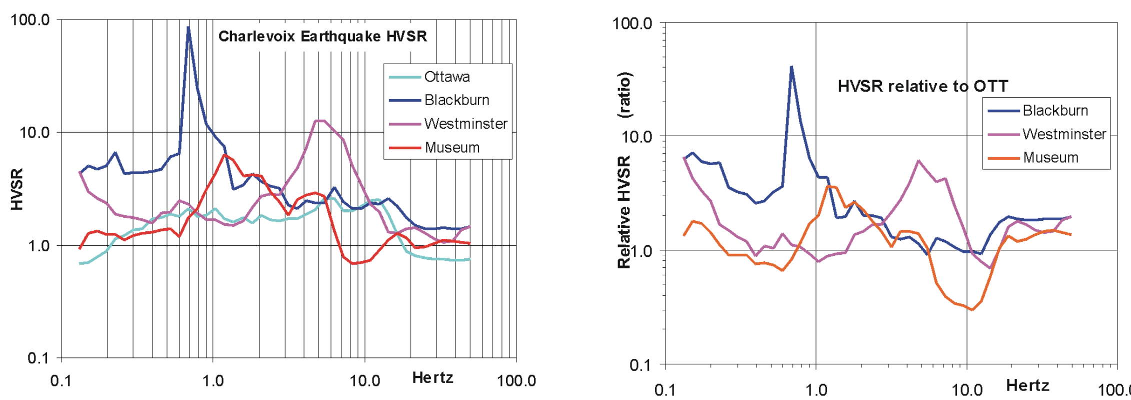


Figure 5A. (left) HVSR analysis of the Charlevoix spectra at stations WM, BBNE, MUS and OTT (note log-log plot to accommodate BBNE). 5B (right) Relative HVSR analysis of the Charlevoix spectra: stations WM, BBNE, MUS relative to OTT.

M_W 4.0 Thurso Earthquake

Although the Thurso earthquake has the lowest magnitude of the three earthquakes reported in this paper, it was just east of Ottawa and therefore produced strong shaking in the city's east end (Fig. 6). I was standing in my kitchen, on the ground floor of the 2-storey wood-frame house in which the OT002 IA is attached to the floor slab. The P wave was felt quite strongly and was followed a handful of seconds later by strong shaking in the S-wave. Overall, this earthquake felt as strong as the larger-but-more-distant M5.9 1988 Saguenay earthquake, which I felt in the same kitchen.

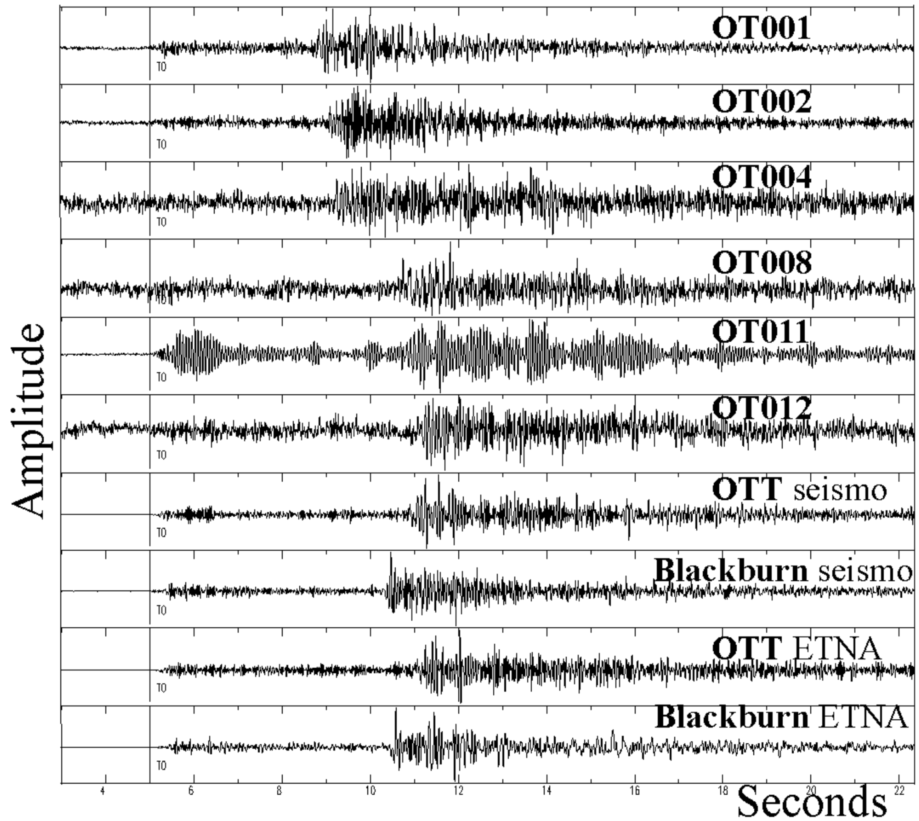


Figure 6. Acceleration time histories of the Thurso earthquake. These time histories are approximately aligned on the onset of the P-wave (i.e. before the bar “T0”) and each is scaled to fit the window height in order to show the different characteristics of the waves.

There is general agreement between the time histories, for example between the Blackburn seismometer and ETNA, and among the OTT seismometer, ETNA and the OT012 IA. The exception at OTT is the record from OT011, which came from a test instrument sitting unattached on a tabletop, on the third floor of the building.

Instrumental noise issues for the IA records

The level of pre-event noise can be seen in a qualitative way by examining the first 3 seconds of noise (that is, before the bar “T0” marking the arrival of the P-wave signal) on the time histories of Fig 6. Relative to the signal, the pre-event noise is very low for the seismometers and ETNA instruments. In comparison IA instruments at OT001, OT002 and OT011 exhibit moderate-amplitude pre-event noise while IA instruments at OT004, OT008 and OT012 have high noise levels. Although the source of noise on accelerograms may be real (ambient) vibrations, in the case of the IA records it appears to be due to internal instrument noise. The levels of signal and noise can be better quantified by spectral analysis. For this purpose a 6-second window of noise preceding the P-onset was taken for each component of each instrument, and analyzed the same way as the 6-second window of the S-wave. In general, the signal to noise was poorest on the vertical (Z) component (see examples on Fig. 7). This means that HVSR cannot be trusted for frequencies lower than where the Z-component for the S-window drops below the noise (~2 Hz for OT001), even though some of the signal spectra fall below the noise spectra (suggesting, perhaps, that the noise sample before the earthquake was higher than during it). Accordingly, the S-window HVSRs that follow (Fig. 8) are indicated by a thin line below that frequency. Note that the noise-limited frequency for OT001 is ~4 Hz if the Z-component of the P-window is considered. The lack of reliable data for lower frequencies is an expected limitation of the IA instrument for these weak motions. While this is a pity for the Thurso earthquake, because the lower frequencies are just where interesting soil-resonance peaks would be expected on thicker soil sites, my detailed analysis of the signals and noise indicates that a far more complete dataset will be acquired for any future earthquake with shaking only twice as strong.

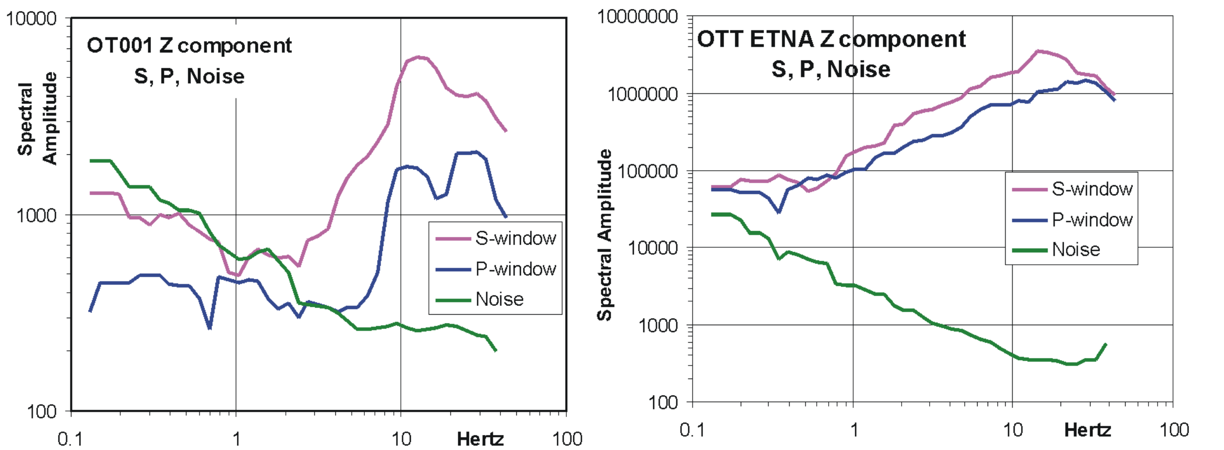


Figure 7. Vertical component spectra for S-, P-, and Noise-windows for examples from OT001 and OTTE, showing the relatively-high spectral noise in the IA (units differ between the two plots).

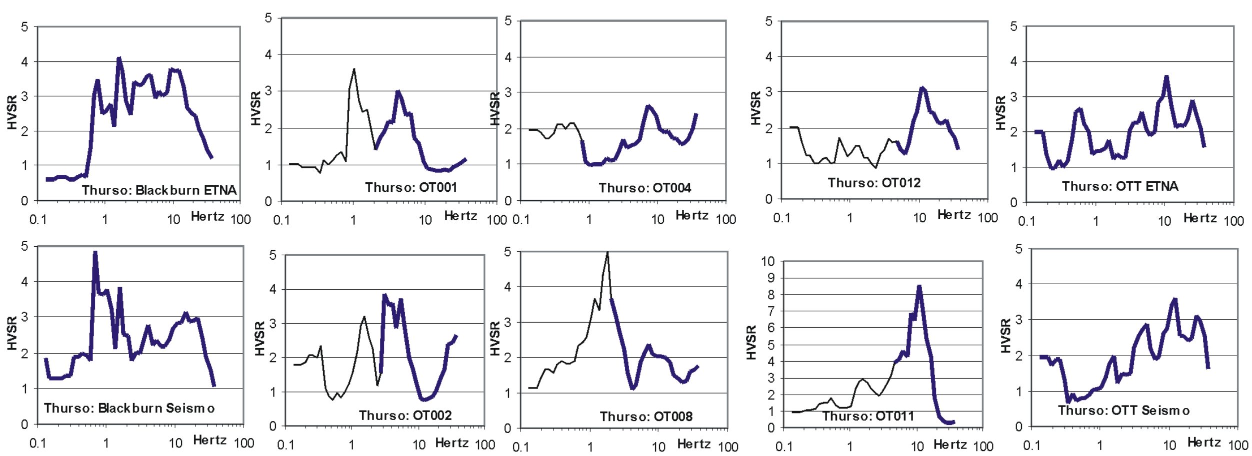


Figure 8. HVSR spectra for records of the Thurso earthquake; thin lines indicate dubious signal.

Discussion of the HVSR spectra in Figure 8

Firstly, there is general agreement, but not exact, in the position and amplitude of the peaks among the nearby recorders at Blackburn (first column), Orleans (second column) and OTT (OT012 and last column). Secondly, the IA data from OT001 and OT002 have a strong peak at ~4 Hz that was only a weak peak on the Au Sable Forks record at OT001, and they weakly (because of the issue of internal noise) confirm the ~1 Hz peak that was present. OT004 has a resonance peak at 7 Hz and OT008 may have a main resonance peak at 2 Hz and a second peak at 7 Hz. The OTT records are a bedrock site, and should not include any amplification with the exception of OT011, which indicates a combination of building amplification and perhaps rocking of the instrument on the tabletop. It has no engineering significance and is included for amusement only.

Comparison of Different Earthquakes at the Same Soil Site

Westminster (WM)

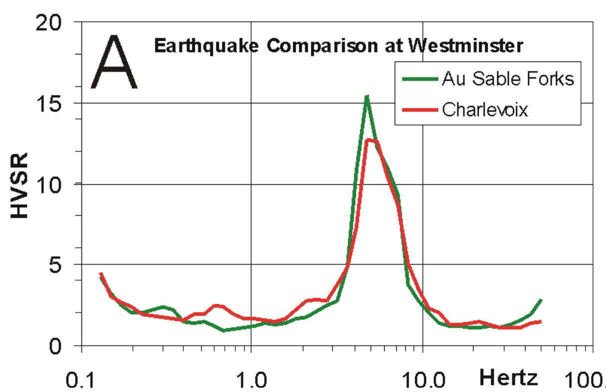
Both the Au Sable Forks and Charlevoix earthquakes were recorded by ETNAs. The HVSR values shown in Figure 9A show great similarity in both shape, peak period and amplitude. These results indicate a relatively simple structure and confirm that the instrument that operated in 2002 did not malfunction.

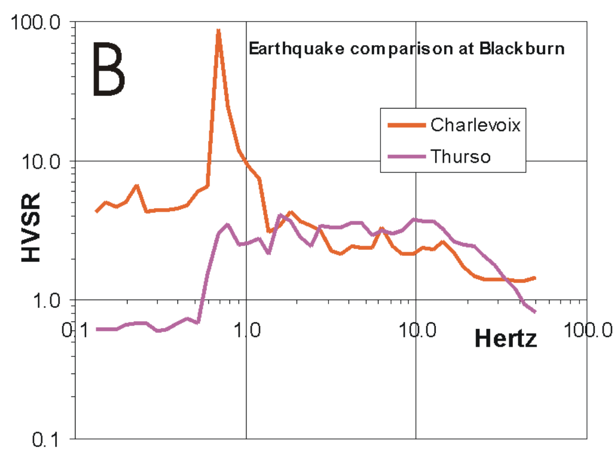
Blackburn (BBNE)

The Charlevoix and Thurso earthquakes were recorded by ETNAs. The HVSR values shown in Figure 9B show great similarity in both shape and amplitude above 1.5 Hz, but a major discrepancy in amplitude below 1 Hz. The discrepancy appears to arise entirely from the horizontal spectral amplitudes on the ETNA recording of the Charlevoix earthquake, and is due to an extremely rapid, 16-fold increase between 0.6 and 0.7 Hz. A less-dramatic (4-fold), but similar, increase occurs in the same frequency range for the Thurso earthquake, leading me to believe that it is a site effect (rather than an instrument malfunction), but this conclusion remains uncertain.

Orleans1 (OT001)

The Au Sable Forks and Thurso earthquakes were recorded at Orleans1, the first by an ETNA and the second by an IA. The HVSR values shown in Figure 8C show similarity in both shape and level frequency above 2 Hz; below 2 Hz (thin line on Fig. 9C), the signal was below the noise level (Fig. 7A). The reported HVSR is therefore too low by an unknown amount; on the figure the Thurso HVSR is only one third that of the Au Sable Forks HVSR. Thus the Thurso data fails to confirm or invalidate the resonant amplification found for the Au Sable Forks earthquake (though it may weakly confirm the resonant frequency).





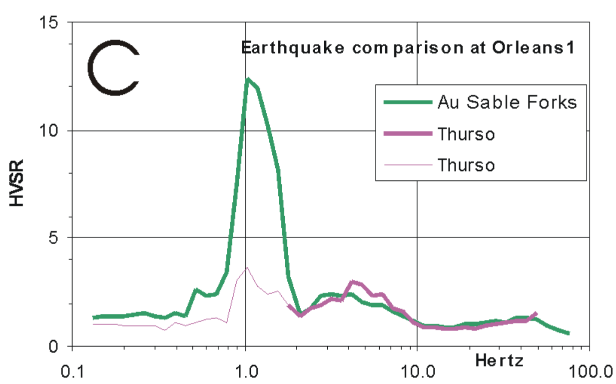


Figure 9. Comparison of HVSR of pairs of earthquakes A) at Westminster site, B) at Blackburn site, and C) at Orleans1 site. Thin line on Orleans1 curve for Thurso earthquake denotes unreliable ratios.

Ambient Noise Comparison

The HVSR method can also be used for the ambient noise analysis of purpose-made seismograph records. Some recent Ottawa work is reported by Hunter and Motezedian (2006). Although the continuous IA data includes a pre-earthquake noise sample, it cannot be used because of the internal-noise as discussed above. The ETNA sensors are too insensitive. However the seismograph at Blackburn2 (BBNS, Fig. 10) does give a reasonable result, confirming an amplification peak at just less than 1 Hz. The relative amplitude of this peak is quite small (for reasons unknown), but it appears to confirm the position of the peak shown by the Charlevoix earthquake (Fig. 5) on Blackburn1, even though that peak is not evident on the Thurso record. Note that the separation of the two Blackburn sites is about 140 m, so their soil responses could be different.

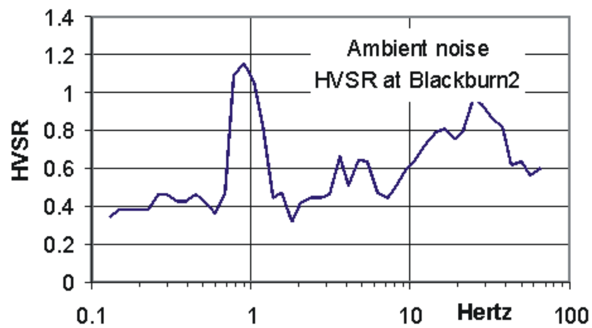


Figure 10. HVSR from ambient noise at site Blackburn2 (BBNS).

Conclusions

A strong motion network in Ottawa has now recorded weak motions from three earthquakes. The failure to obtain Thurso records from a majority of the ETNAs (due to full memory) and the uncertainty about low frequency results from the IAs (due to internal noise) indicates some of the difficulties of operating the network and interpreting the results. Nevertheless, while we wait for stronger ground motion, the weak motion records to date are useful, indicating resonance peaks at some soil sites, the best-documented being Westminster for which earthquake motions are increased 12-fold at 5 Hz (0.2 s). These and future weak motion records should provide a valuable check on the results from future ambient noise measurements and ground motions modeled from the geotechnical and geophysical knowledge of the soil column at selected sites. Although strong ground motion records are of the greatest value, these weak motion records help to calibrate engineering models in the linear range of soil behaviour. Some degree of extrapolation will probably be required to predict local effects for damaging strong motions.

Acknowledgments

The author would like to thank the GSC's staff, Issam Al-Khoubbi, Gilles Girouard, Scott Desjardins, Andreas Rosenberger and Phillip Munro, for their efforts in establishing and maintaining the Ottawa strong motion network. The author would also like to thank Allison Bent and Sheri Molnar for advice with SAC and the event processing and Sheri Molnar for a thorough review. GSC Contribution 20060523.

References

Al-Khoubbi, I., and J. Adams, 2004. Local site effects in Ottawa, Canada – First results from a strong motion network. *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada. Paper 2504 on CD-ROM.

Douma, M., and F. M. Nixon, 1993, "Geophysical characterization of glacial and post-glacial sediments in a continuously cored borehole near Ottawa, GSC Current Research, Part E, Paper 93-1E, p.275-279.

GSC, 1977. "Surficial materials and terrain features Ottawa-Hull Ontario-Quebec, scale 1:125,000". Geological Survey of Canada 1977: Map 1425A.

GSC, 2006a. Sub-surface database of the National Capital Area". Geological Survey of Canada web site: http://gsc.nrcan.gc.ca/urbgeo/natcap/sub_introduction_e.php

GSC, 2006b. Urban Geology of the National Capital Area - Drift thickness. http://gsc.nrcan.gc.ca/urbgeo/natcap/surf_drift_e.php

Hunter, J.A., and D. Motezedian, 2006. Shear Wave Velocity Measurements for Soft Soil Earthquake Response Evaluation in the Eastern Ottawa Region, Ontario, Canada. in *Proceedings of a Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP),* Environmental and Engineering Geophysics Society Annual Meeting, Seattle Washington, U.S.A., 2006 April 1-3.

Molnar, S., and J.F. Cassidy, 2006. A comparison of site response techniques using weak-motion earthquake and microtremors, *Earthquake Spectra*, 22, 169-188.

Molnar, S., J. F. Cassidy, and S. E. Dosso, 2004. Site response in Victoria, British Columbia, from spectral ratios and 1D modeling, *BSSA*, 94, 1109-1124.

Molnar, S., A. Rosenberger, J. F. Cassidy, G. C. Rogers, and J. Ristau, 2006a. Digital accelerograph recordings of the July 15 and 19, 2004 earthquakes, west of Vancouver Island, Geological Survey of Canada, Open File 5010, 76 p.

Molnar, S., A. Rosenberger, J. F. Cassidy, and G. C. Rogers, 2006b. Internet Accelerograph Recordings of Low-Level Earthquakes in southwestern British Columbia from 2002 to 2003, Geological Survey of Canada, Open File 5266, 21 p.

Molnar, S., J.F. Cassidy, P.A. Monahan, T. Onur, A. Rosenberger, and C. Ventura 2007. Earthquake Site Response Studies Using Microtremor Measurements In Southwestern British Columbia. *Proceedings of the 9th Canadian Conference on Earthquake Engineering*, June 24-27th 2007, Ottawa, Paper 1182.

Pugin, A.J.M, A. J. Hunter, D. Motazedian, G.R. Brooks, and K-B Kasgin 2007. An application of shear wave reflection landstreamer technology to soil response evaluation of earthquake shaking in an urban area, Ottawa, Ontario. in *Proceedings of a Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP),* Environmental and Engineering Geophysics Society Annual Meeting, Denver Colorado, U.S.A., 2007 April 1-5, 10 pp.

Rosenberger A, Beverley, K, Rogers, R. 2004. "The new strong motion seismic network in southwest British Columbia, Canada". *Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada.* Paper 3373 on CD-ROM.