13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2504

LOCAL SITE EFFECTS IN OTTAWA, CANADA - FIRST RESULTS FROM A STRONG MOTION NETWORK

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SUMMARY

A five station strong motion network of ETNA instruments was established in Ottawa in the winter of 2002. The network was designed to sample typical site conditions across the urban area, and forms one prototype for the Canadian Urban Seismology Project, intended to gather weak motion data in the short-term, and produce near-realtime shake maps in the long-term. Sites were placed at the Ottawa Observatory and the Eco-Musee (rock), Glebe High School (<5 m soil), Westminster Avenue (10 m soil), and Fallingbrook (18 m soil). After careful attention to site noise characteristics, the trigger thresholds were set in the range 0.02 - 0.12 %g. Observatory recorded a magnitude 3 earthquake at 50 km distance in January 2002, and then all stations (less Eco-Musee which had flooded) recorded a Mw 5.0 event at 190 km in April 2002. Remarkably, two instruments recorded a Mw 3.7 aftershock. We have analyzed the 6 records for consistency and find significant amplification and sharp resonance peaks in the Fallingbrook site. 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 behavior. Some degree of extrapolation will probably be required to predict local effects for damaging strong motions.

INTRODUCTION

The Ottawa Strong Motion Network is one prototype test of the Canadian Urban Seismology Project [1], intended to gather weak motion data and in the long-term produce near-real time shake maps for Canada's cities. Local urban seismograph networks assess in a direct way how local geology and topography influence earthquake motion and thus help to predict the local distribution of future strong shaking.

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The City of Ottawa lies in the Ottawa valley which follows the Ottawa-Bonnechere Graben, an ancient zone weakness that dates back to the opening of Iapetus Ocean, 550 million years ago. The normal faults that formed the graben down-faulted Ordovician sedimentary rocks that overlie the Precambrian rock of the Canadian Shield and this has partially preserved them from erosion. The entire region underwent multiple glaciations, ending with the last deglaciation about 12,000 years ago. At that time the weight of the ice had depressed the land, and the sea flooded the Ottawa Valley and most of Ottawa. Rapid sedimentation near the ice margin deposited thick glaciomarine clays, locally called Leda clay, and wave and river reworking of the postglacial materials as the land rebounded and the sea retreated and the Ottawa River downcut formed loose sand deposits. Thus the urban geology of Ottawa varies from exposed Precambrian rock of the Canadian Shield and Paleozoic limestones and shales to tills, sand and clay deposits. The clay deposits present special geotechnical issues as they have very low shear strength [2]. Large regressive landslides have occurred historically in these deposits [3], and a cluster of such landslides that occurred about 4000 years ago appears to represent the effects of a large earthquake [4]. The loose sands are expected to have liquefaction potential, though no liquefaction has been observed in historical times. However, some areas of disturbed postglacial sediments 70 km east of Ottawa dated to 7000 years ago likely represents the effects of liquefaction of the underlying sands due to another large prehistoric earthquake [4]. An urban surficial geology map [5] is shown in Figure 1 with the sites of the strong motion instruments indicated.

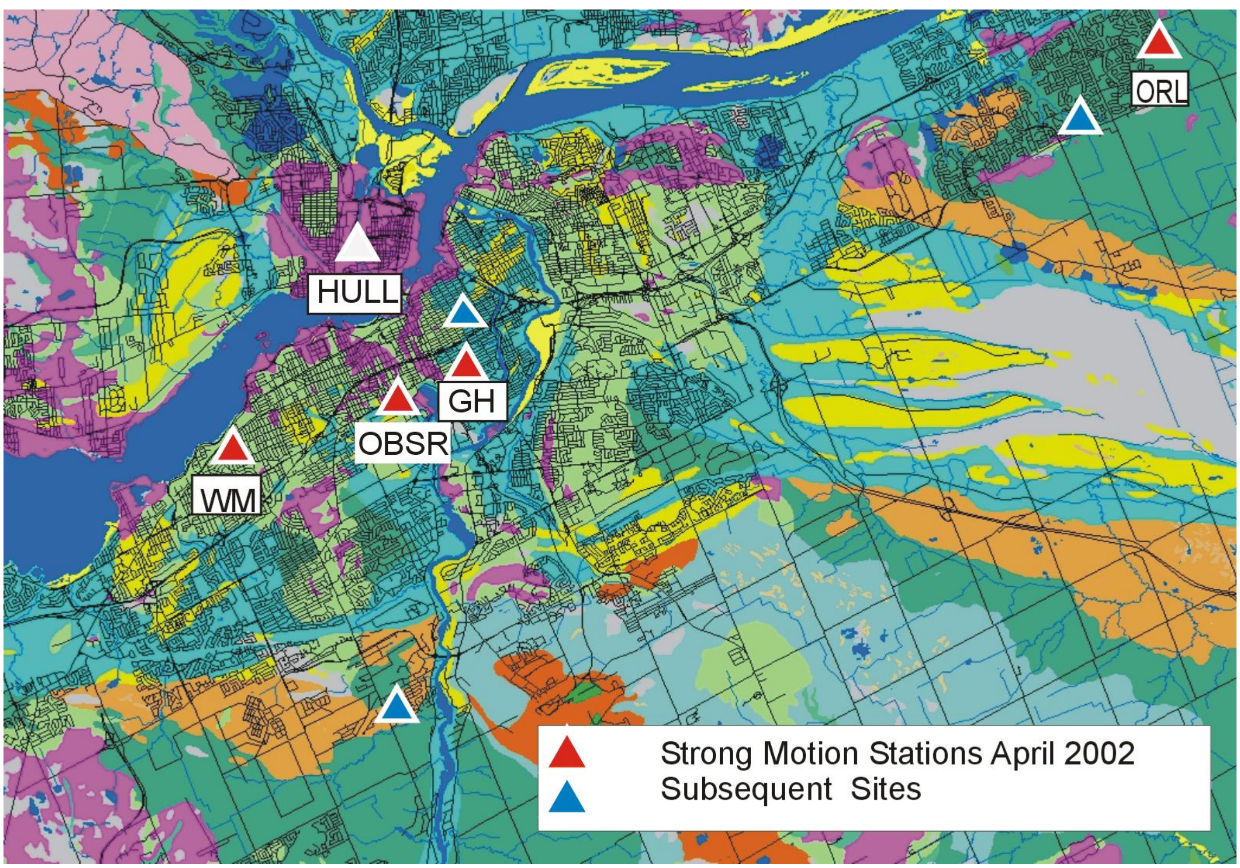

Figure 1. Locations of recording stations (red), failed station (white) and two subsequent stations (blue), superposed on a surficial materials map [5] of Ottawa. For geological legend see [12].

EXPECTATIONS FROM THE EARTHQUAKE HISTORY

Ottawa lies in a seismically active zone and has been shaken fairly strongly by a number of earthquakes (Table 1). Fortunately most have been distant from Ottawa, including a magnitude 5¾ earthquake near Montreal (200 km east of Ottawa) in 1732, that caused little damage to the then-small settlement of Montreal. The historical record of earthquakes for the Ottawa region extends back to about 1850. A magnitude 5.0 earthquake occurred in the vicinity of Ottawa in 1861, and caused some fallen chimneys. In 1935 a magnitude 6.2 earthquake happened in the upper Ottawa Valley, and in 1944 a magnitude 5.7 earthquake occurred close to the border towns of Cornwall, Ontario, and Massena, New York. The latter produced the strongest shaking in Ottawa (predicted to have been about 0.035 g) in the last 140 years, apparently without causing damage in Ottawa. The most recent strong shaking in Ottawa was from the 1988 Saguenay earthquake, with which did not cause damage in Ottawa because it was 460 km away. However, that earthquake caused damage to the Montreal-Est townhall (at 330 km), a heavy structure on soft soil somewhat similar to the Orleans site instrumented below.

Table 1. Earthquakes producing the strongest shaking in Ottawa, sorted by their predicted shaking.

Date	Lat N	Long W	Magnitude	Distance from Ottawa (km)	Predicted PGA (g)
18610712	45.40	75.40	5.0	22	0.038
19440905	44.97	74.90	5.6	71	0.035
19140210	46.00	75.00	5.5	91	0.025
17320916	45.50	73.60	5.8	162	0.021
18160909	45.50	73.60	5.7	162	0.019
19351101	46.78	79.07	6.2	310	0.019
18701020	47.40	70.50	6.5	467	0.018
19881125	48.11	71.18	6.5	464	0.018
18931127	45.50	73.30	5.7	185	0.016

The current National Building Code of Canada (NBCC) is the 1995 version [6], based on the 1985 seismic zoning maps prepared by the Geological Survey of Canada [7]. The 1985 maps described the seismic hazard in terms of the Peak Horizontal Ground Acceleration (PGA) and Peak Horizontal Ground Velocity (PGV), determined for an annual probability of exceedence of 0.0021, or 10% in 50 years. PGA is a measure of short-period ground motion, which affects short, rigid buildings; PGV is a measure of long-period ground motion,which will affect tall, flexible buildings. The 1985 values for Ottawa are 0.20 g for PGA and 0.098 m/s for PGV. Canada was divided into 7 zones based on PGA and PGV values; Ottawa is in zone 4 for acceleration (Za=4) and zone 2 for velocity (Zv=2), however the design spectrum adopted for Ottawa capped the short-period ground motions at the equivalent of Za=3.

The Geological Survey of Canada's 4th Generation seismic hazard model will be the basis for the seismic design provisions of the 2005 National Building Code [8, 9, 10]. The key factors of the new model relevant to Ottawa are:

- seismicity rates near Ottawa have not changed very much
- design values for short-period shaking have been revised upwards
- ground motion is given as spectral accelerations for a range of periods, not peak values
- probability level is 2%/50 years (0.000404 per annum (p.a.)), not 10%/50 years

The new hazard values for the 2%/50 year probability are approximately twice the current 10%/50 year values. However, because these hazard values will be used with a different formulation for the base shear, it is expected that the resulting designs will be similar on average to past designs, though they may differ significantly for certain types of structures such as short-period buildings on soft-soil sites for moderate earthquake shaking.

Monitoring

A seismograph has been operated at the observatory as station OTT in Ottawa since 1906 [11]. With improving instrumentation at OTT, and supplemented by an increasing number of seismographs of the Canadian National Seismograph Network (www.EarthquakesCanada.ca) we have a good history of recent small earthquakes near Ottawa. Figure 2 gives the magnitude-recurrence curve for earthquakes within 250 km of Ottawa. We determined the maximum distance for which shaking from a given magnitude earthquake would exceed the trigger levels on our strong motion instruments and using similar magnitude-recurrence curves estimated the annual probability of those earthquakes. This gave us per annum (p.a.) probabilities for a trigger on the Ottawa instrument as: 1.5 p.a. from a M≥3 within 100 km, 0.6 p.a. from a M≥4 within 250 km, 0.1 p.a. from a M≥5 within 420 km, and 0.015 p.a. from a M≥6 within 620 km. From these rates we concluded that we can expect about 2 triggers per year on OBSR, the instrument with the lowest trigger threshold.

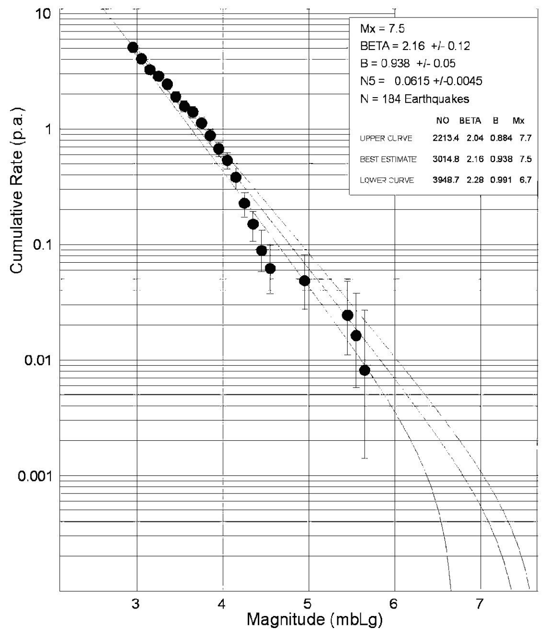

Figure 2. Magnitude-recurrence curve for earthquakes within 250 km of Ottawa.

SITING, INSTRUMENTATION AND SETTINGS

Five Etna strong motion instruments were deployed in early-mid 2002 across Ottawa to sample representative ground conditions across the city (Figure 1). The instrument sites vary from the OTT seismometer vault to the basements of wood-frame houses and masonry structures (Figure 3), on site conditions that vary from rock to 18 m of clay (Table 2). Soil conditions were obtained from nearby boreholes [12].

Table 2. Details of strong motion installations and their foundation conditions.

Site	Basement of	Lat N	Long W	elevation (m asl)	Trigger (g)	Foundation	Soil depth (m)
ECO-Musee **HULL**	2-3 story masonry building	45.4298	75.7250	~70	0.0002	Paleozoic limestone	0
Observatory **OBSR**	3 story masonry building.	45.3942	75.7167	81	0.0002	Paleozoic limestone	0
Glebe High School **GH**	4 story masonry building	45.4014	75.6967	70	0.0012	Stratified medium sand	<5
Westminster **WM**	2 story wood frame house	45.3824	75.7628	75	0.0008	Thin sand over clay	10
Orleans ORL	2 story wood frame house	45.4787	75.4745	89	0.0008	Clay, silt, and silty-clay	18

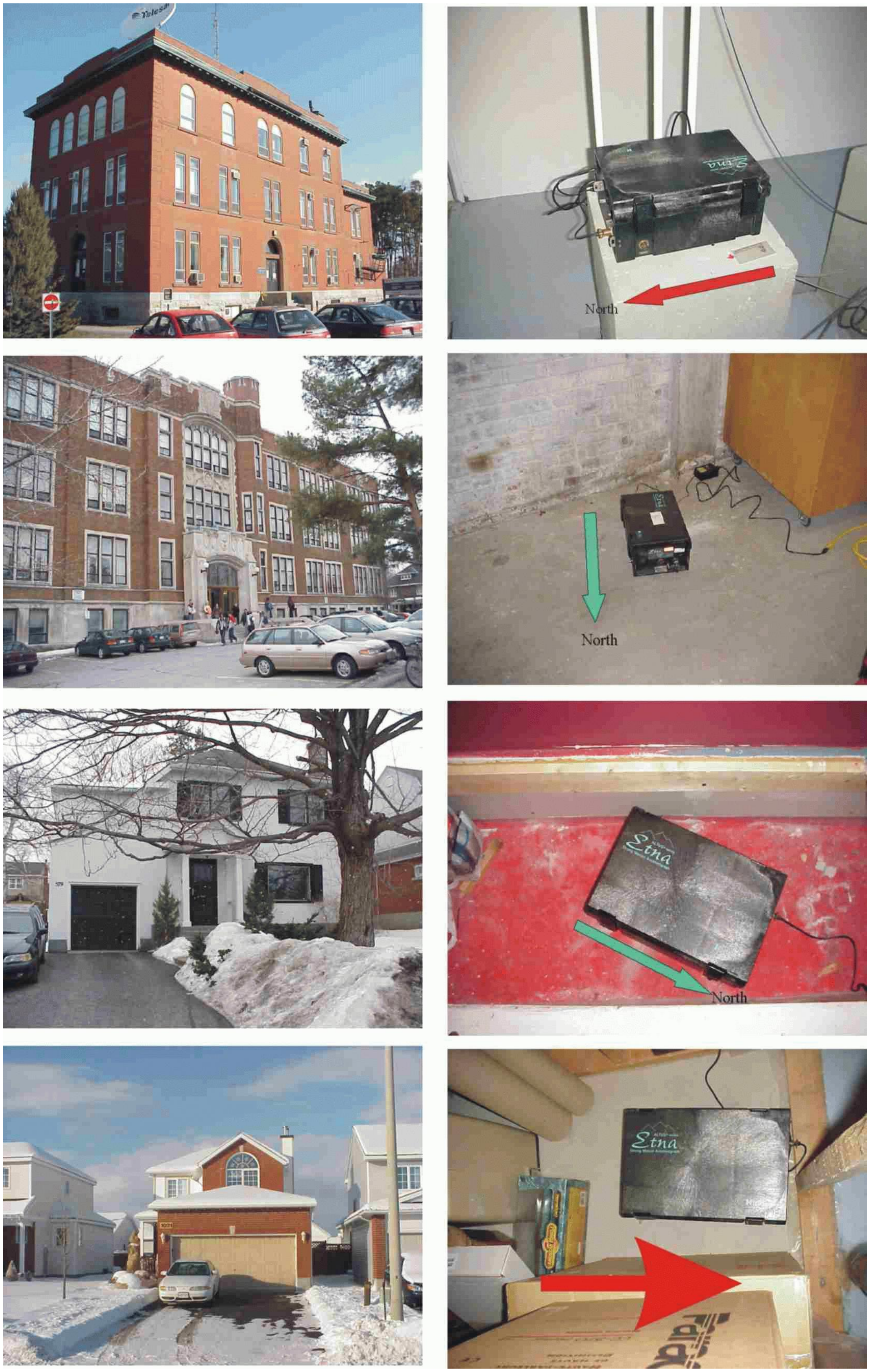

Figure 3. Building foundations monitored and ETNA installation: top pair OBSR; next GH; next WM; bottom pair ORL.

The ETNA strong motion accelerograph acquires data with 18 bits of resolution. Recorded events can be off-loaded automatically via a modem, manually retrieved by PC, or by collecting the PCMCIA memory card. To achieve the recording of earthquakes on triggered instruments like the ETNAs it is necessary to apply great care in setting the trigger thresholds. A threshold set too high will reduce the chance of any record being obtained, while a threshold set too low runs the risk of the instrument repeatedly triggering on urban noise and so being too full to record an earthquake, should it occur. We installed the ETNAs in as quiet a location as we could find, given these urban environments, and then examined the nature and amplitude of the noise to devise the lowest reasonable trigger settings. Levels of 0.02-0.12%g were obtained (Table 2) and used. As these instruments are in our home town we were prepared to visit the instruments every few months to delete noise triggers. Should a significant earthquake occur we are prepared to recover the data promptly.

INITIAL RESULT AND RECORDS FROM THE 2002 EARTHQUAKE

The first strong motion record was a Mw ~2.6 earthquake at 50 km on 2002 02 04 (Figure 4). This event demonstrated that the trigger levels were appropriate for the capture of interesting ground motions (Figure 5).

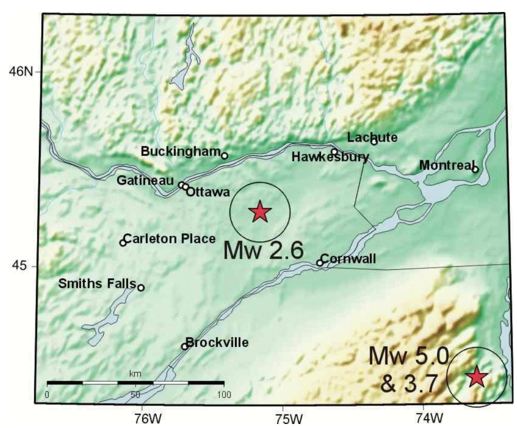

Figure 4. Location of M2.6 and M5.0 Au Sable Forks earthquakes.

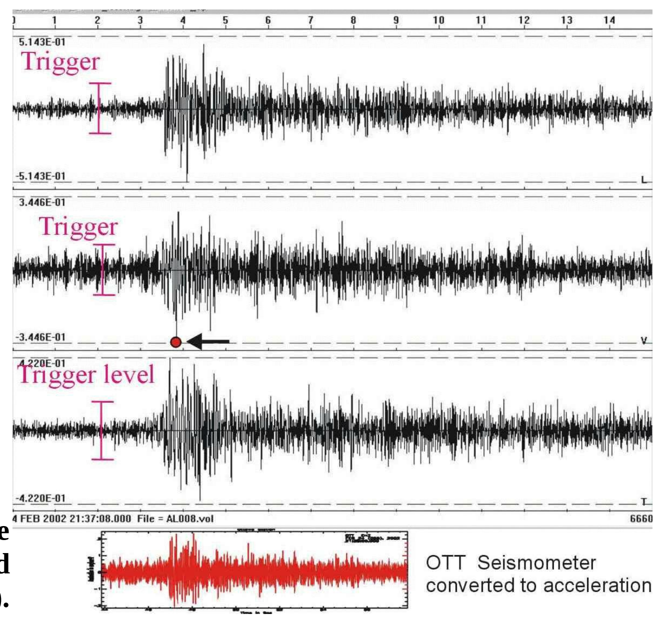

Figure 5. Accelerograph record from the 20020204 earthquake with converted seismometer record for comparison (red).

The Mw 5.0 Au Sable Forks earthquake [13] occurred 180 km from Ottawa on the 20th of April 2002, just a few weeks after the last of the strong motion instruments was installed. In Ottawa it was felt as Modified Mercalli intensity III. One of the five installed instrument had been flooded, and did not produce a record. The other four instruments triggered on the mainshock (three of them on the P-wave and one on the S wave), and remarkably, two triggered on the S-wave of the Mw ~3.4 aftershock 14 minutes later (Figure 6). Peak motions are given in Table 3. As seen from the monochromatic ringing on the time series (see inset at the lower right of Figure 6) and the unusually-large amplitude of the peak values, there seemed a chance that both horizontal sensors at WM might have malfunctioned. However, the instrument appeared to be functioning correctly when inspected. Hence we cautiously interpret the WM horizontal records in terms of site effects.

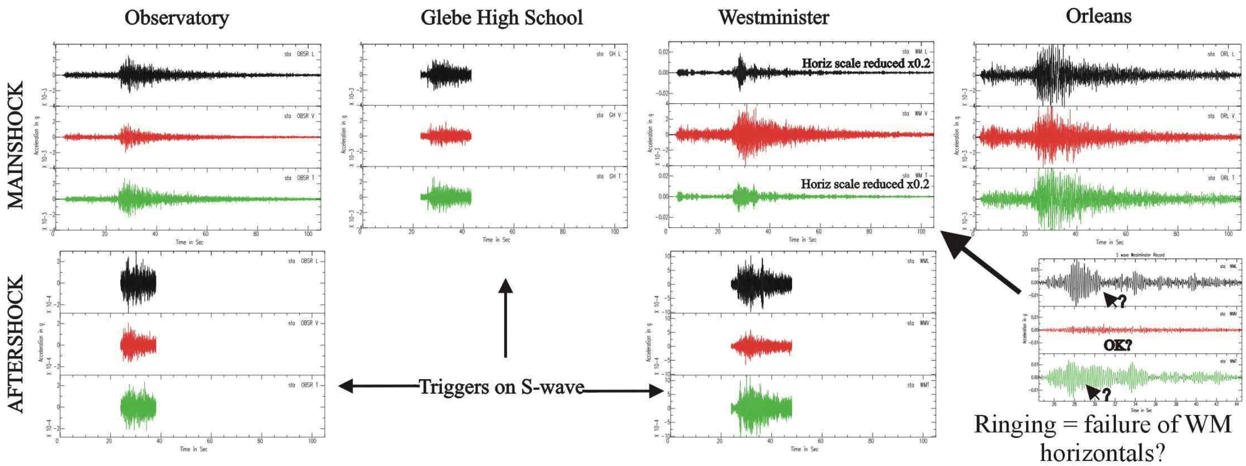

Figure 6. Records from the Au Sable Forks earthquake mainshock (top) and aftershock (bottom). From top to bottom the components are L, V, T.

Table 3. Peak values from the records (units = %g).

Earthquake	Mainshock			Aftershock		
Component	L	V	T	L	V	T
Observatory (OBSR)	0.25	0.20	0.27	0.029	0.020	0.023
Glebe High School (GH)	0.20	0.20	0.27	-	-	-
Westminster (WM)	1.8*	0.45	1.5*	0.1*	0.064	0.1*
Orleans (ORL)	0.40	0.44	0.49	-	-	-

*= ringing signal.

PROCESSED RESULTS

Kinemetrics SWS software was used to retrieve and display the data, correct the acceleration data, and export it as an ASCII file for use by SAC (Seismic Analysis Code). SAC was used to process the data and smooth the spectra from which spectral ratios were calculated. Figure 7 shows the vertical component spectra of the mainshock and aftershock spectra recorded at OBSR and at WM. For each station the aftershock spectrum lies considerably below the mainshock spectrum by a factor of 7 to 40 times. The spectra for both the mainshock and the aftershock are similar on WM and OBSR to about 5 Hz, but at higher frequencies the WM spectra lie above OBSR, indicating amplification of these high frequency ground motions. Figure 8 shows the L, V and T spectra for the mainshock on the 4

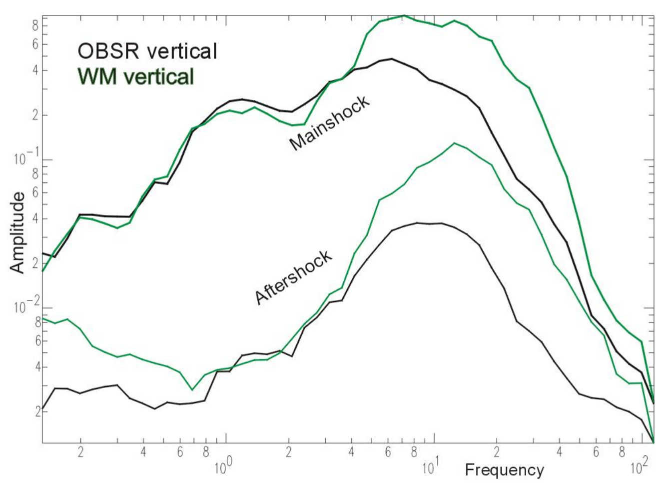

Figure 7. Spectra for the mainshock (top pair of curves) and aftershock (bottom pair) vertical records at OBSR (black) and WM (green).

instruments. The ringing on WM horizontals at 6 Hz is indicated by an asterisk. Immediately obvious on these plots is the relative spectral amplification at about 1.5 Hz on ORL relative to the other three records.

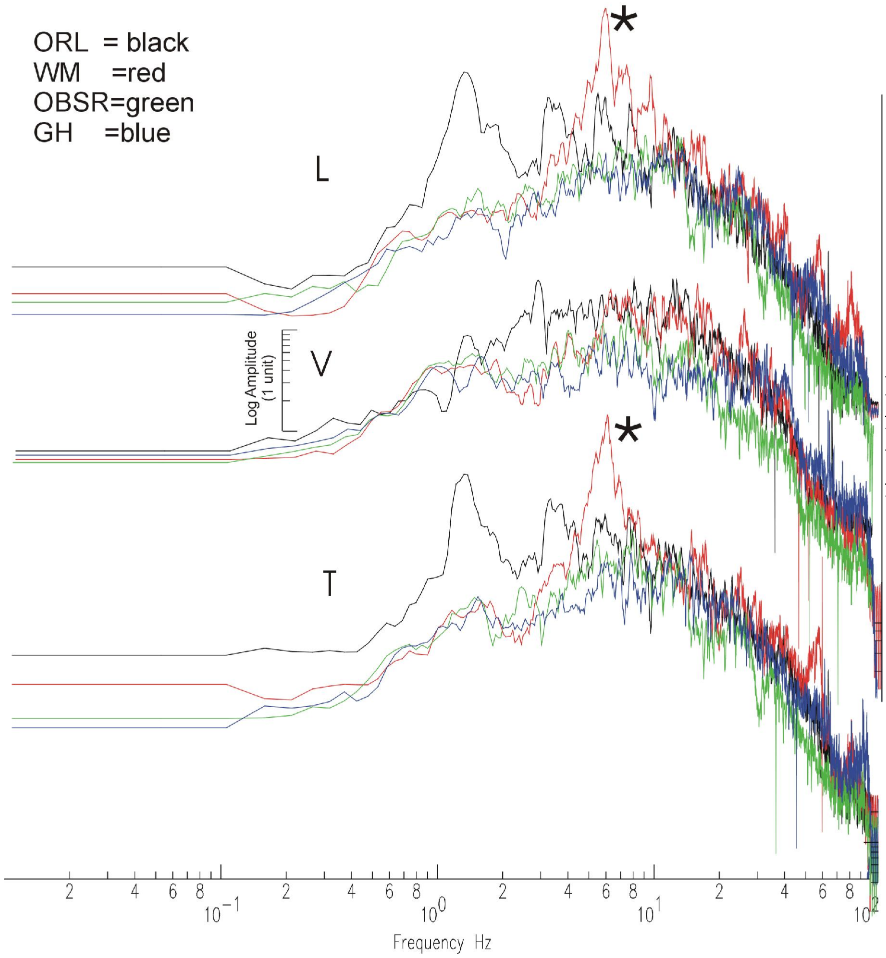

Figure 8. Mainshock spectra for longitudinal, vertical and transverse components of the four stations, OBSR (green), GH (blue), WM (red), and ORL (black).

Stability of the results

Stability of the results is indicated by various methods, such as looking at the spectra of the weaker P wave and the stronger S-wave separately. We find that they give similar amplifications to those we report here (which were all derived from the entire wave train). We also took the ratio of the mainshock to the aftershock spectra at OBSR and at WM. This process removes soil response, but will only work properly if the soil response is elastic for both records. The two curves (superposed on Figure 9) are very similar, indicating that the soil response at WM was linear over at least 0.7 - 10 Hz, for the 7 to 40-fold range of ground motions recorded.

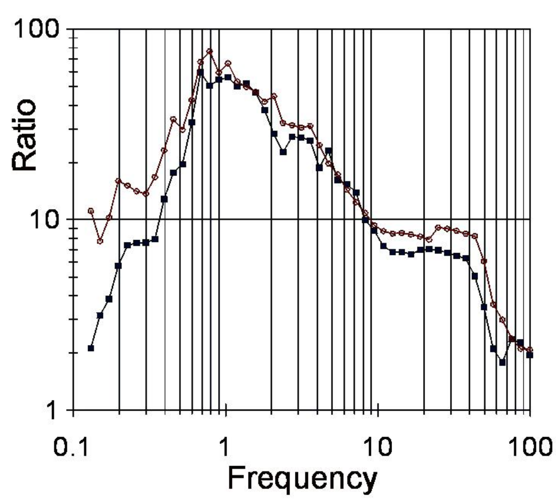

Figure 9. Vertical component main/aftershock spectral ratios for OBSR (red) and WM (black).

Spectral ratios

Although the spectra reveal the most obvious features, the spectral ratios relative to the bedrock site at OBSR are more informative (Figure 10). We computed a root-

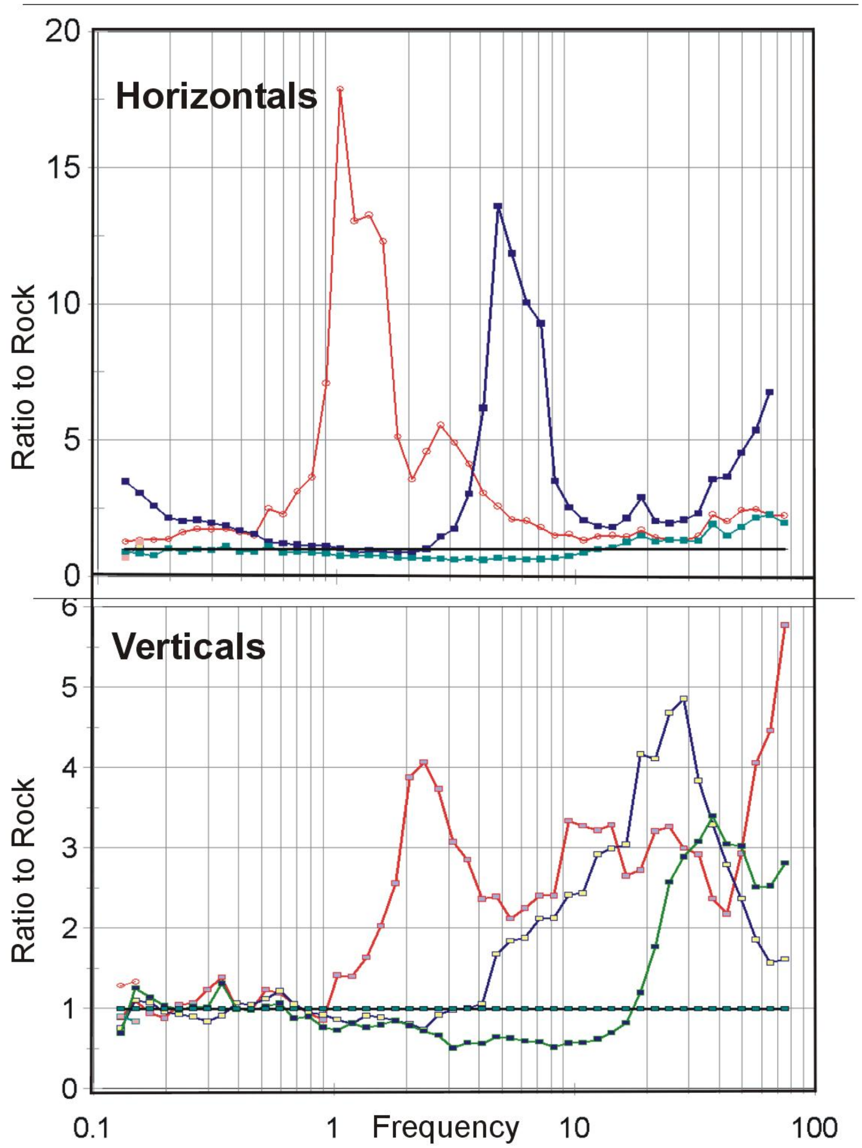

Figure 10. Horizontal and vertical spectral ratios relative to OBSR for stations ORL (red), WM (blue) and GH (green).

mean-square spectra from the two horizontal spectra at GH, WM and ORL, and then divided them by the equivalent at OBSR, which is taken as the reference (rock) site. Vertical spectral ratios were obtained by direct division. We ignore the small differences in path length. The chief features are:

Horizontal motions. GH shows amplification by a factor of 2 for f>15 Hz, WM shows amplification by a factor of 10 at 6 Hz, and ORL shows amplification greater by a factor exceeding 15 at 1.3 Hz, with a broad spectral peak with amplifications exceeding a factor of 3 from 0.9 - 4 Hz.

Vertical motions. GH shows amplification by a factor of 2-3 for f>15 Hz, WM shows vertical amplification by a factor of 3 for 13-40 Hz, and ORL shows vertical amplification by a factor of 2-3 for f>2 Hz, peaking at 2.5 Hz. GH shows deamplification by a factor of two for the 4-15 Hz band.

DISCUSSION

These results represent the first measurements of soil amplification in the Ottawa area. They demonstrate dramatic amplification on the 18-m-thick clay of Orleans, suggest similar but slightly smaller amplification on the 10-m-thick soil at Westminster (presuming the horizontal signal is real), and indicate almost no amplification of the thin soil at Glebe High School. The amplification of the horizontal motions is larger than the vertical ones.

The period of peak amplification relates to the soil thickness in the expected manner. This includes the amplification peak at 6 Hz for WM, which is consistent with a soil amplification effect. Similar ringing was observed in a strong motion record of the 1988 Saguenay earthquake, and was attributed to the effect of a thin layer of sediments [P.S. Munro, pers. comm.].

The main and aftershock records at WM show that the response was linear for the two input ground motions. Of all these records, only GH shows some evidence of deamplification by a factor of two, but only in the 4-15 Hz band. Deamplification due to non-linear effects is usually seen for strong ground motion on thick soils, so that its absence from these weak ground motions does not mean it will not occur during stronger shaking.

Continued operation.
The ETNAs, with the exception of ORL which failed, have continued operating through the winter of 2004, without generating any additional records. In the Spring of 2004 it is intended to supplement the ETNAs with prototype Internet Accelerometers similar to those deployed in the southwestern British Columbia [14]. While these are easier to recover data from (being linked over the internet), they use solid-state accelerometer chips with higher internal noise that of the ETNA sensors. The rms noise is 0.0005 g, so the effective threshold is likely 2-3 times higher than a triggered ETNA on a quiet site, and consequently the chances of recovering weak motion records are diminished.

Hazard and risk implications. Although some of Ottawa has bedrock at or near the surface, a substantial region involves thick clay deposits. If ground motion amplification exceeding a factor of ten exists in the 1-10 Hz range, this could become a significant parameter for hazard assessment. The Ottawa suburb of Orleans near ORL comprises chiefly 2-storey wood-frame houses with some 2-3 storey concrete block schools and some 1-storey steel frame "big-box" stores, mostly constructed in the past 20 years. Most of these structures are expected to respond to frequencies higher than those for which ORL demonstrated dramatic amplification. However, a detailed study of a 150-m-deep Quaternary basin east of Ottawa (the same place that has evidence for paleoliquefaction [4]) containing similar clays and sands to ORL revealed fundamental resonance periods of 0.4 to 2.6 seconds [15] with the shorter periods near the basin's edge. Thus, where the clay is thinner in Orleans the resonant period may coincide with that of the many nearby structures, likely accentuating any future earthquake damage.

CONCLUSIONS

Careful setting of trigger levels can lead to useful records, even on triggered strong motion instruments. Peak acceleration for the mainshock were 0.2%g on rock to >0.4%g on thick clay. Spectral ratios show considerable soft-soil amplification (relative to rock) by factors exceeding ten, with periods relating to the soil thickness. The soil amplification was similar for both main and aftershock recorded on one of the soil sites. These weak motion results should calibrate engineering models in the linear range of soil behavior, though extrapolation will probably be required to predict local effects for strong motions.

ACKNOWLEDGMENTS

We thank the administration of Glebe High School, Mr. F. M. Anglin and Mr. L. Saumure for hosting the instruments and Mr. G. Girouard for helping with the installations and the servicing. Dr. Allison Bent provided the spectral smoothing routine and advised on the SAC processing.

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