AN APPLICATION OF SHEAR WAVE REFLECTION LANDSTREAMER TECHNOLOGY TO SOIL RESPONSE EVALUATION OF EARTHQUAKE SHAKING IN AN URBAN AREA, OTTAWA, ONTARIO

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Abstract

Previous shear wave seismic test locations and boreholes had indicated the presence of a buried bedrock valley in the Orleans suburb of Ottawa, Ontario. This region is in a significant high seismic hazard zone, and the surficial materials are primarily high water-content, poorly compacted Holocene-age Champlain Sea sediments. The valley was interpreted to be a NW-SE trending feature about 2.5 km in length and about 1.2 km in width, and with a maximum overburden thickness of approximately 95 m. Since the in-filled sediments exhibit an extremely low average shear wave velocity (~200 m/s) and the bedrock beneath contain shear wave velocities on the order of 2500 m/s, it is suspected that the buried valley may give rise to three-dimensional ground motion amplification phenomena in the event of significant earthquakes. In order to confirm the presence and configuration of the buried valley and to prepare for future three-dimensional shake modeling, two shear-wave, reflection landstreamer lines were shot: one in the center portion of the valley, to confirm the depth to bedrock, and the other across the eastern portion of the valley to detail its shape. Despite the large broad frequency band of ambient traffic noise, on both seismic lines it was possible to observe reflections from the bedrock as well as additional infra-overburden reflectors. The valley shape and its internal structure, as determined by these surveys, will form a vital contribution to the three dimensional interpretation for soil response to earthquake shaking in the Ottawa area. Shear wave reflection streamer applications in other high ambient noise level urban environments of eastern Canada may be possible.

Introduction

The Geological Survey of Canada and Carleton University are mapping the soft soil earthquake hazard variation within the City of Ottawa, as a demonstration project. As a result of recent changes to the building code of Canada, amplification of earthquake motion at a site is, in part, related to rock and soil site properties as given by NEHRP (National Earthquake Hazard Reduction Program) site classifications A through F (Finn and Wightman, 2003). The NEHRP classifications can be defined in terms of Vs_{30} (average shear wave velocity to 30 m depth), varying from site class A (hard rock, Vs_{30}>1500 m/s), to site class E (soft soil, Vs_{30}<180m/s). Our survey focuses on measurement of Vs_{30} using surface and borehole shear wave seismic techniques, including SH reflection, refraction and down-hole measurements as well as MASW.

Within the boundaries of the City of Ottawa, a wide variety of site conditions exist, ranging from rock outcrop (both PreCambrain and Paleozoic), Pleistocene glacial till overlying shallow bedrock, through to thick Holocene clays and silts overlying till and bedrock (see Figure 1). Hence all NEHRP zones can be found in the study area.

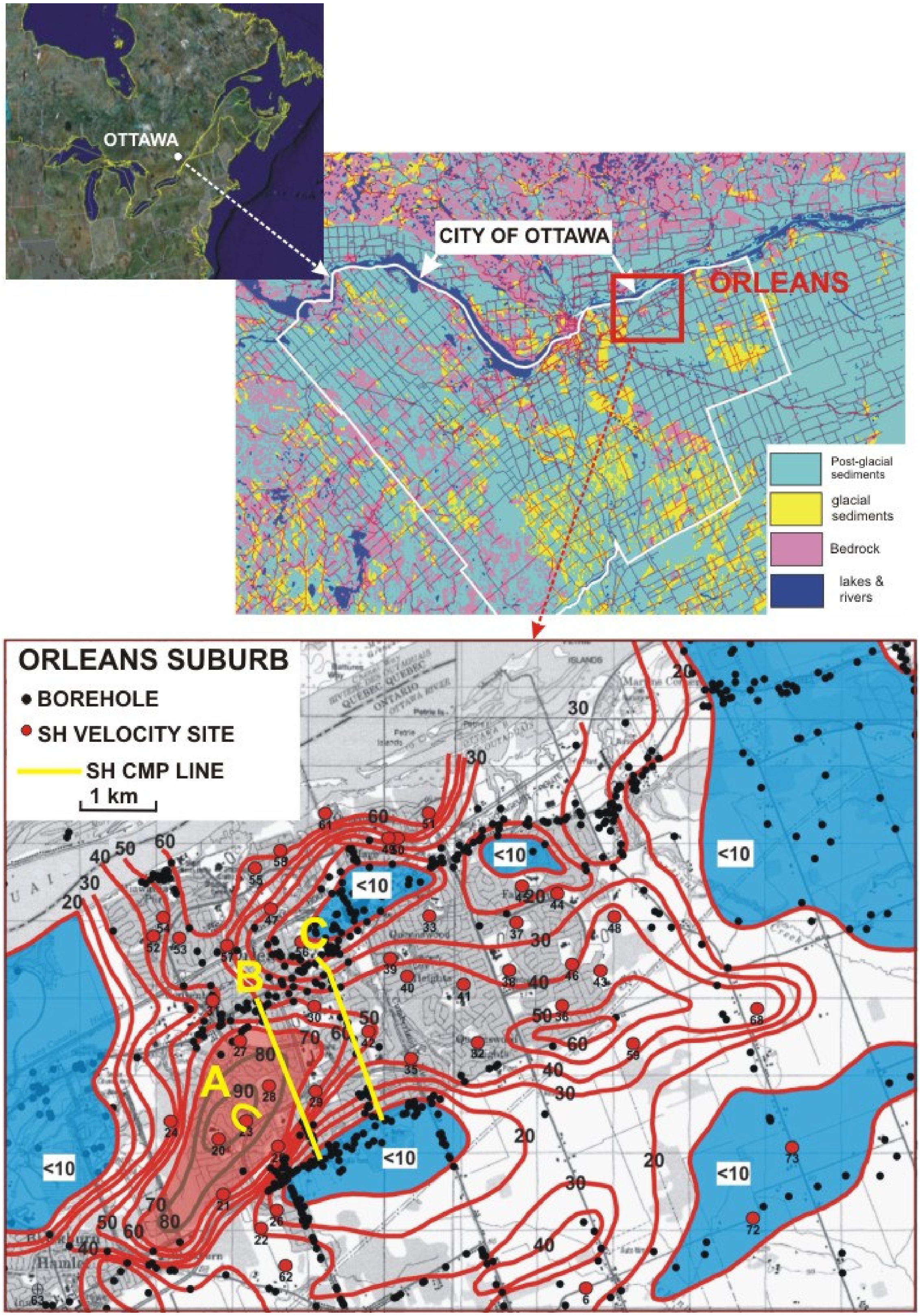

Figure 1: Maps showing the location of the study area in the suburb of Orleans in Ottawa, Ontario, Canada. The contour lines in the lower map represent thickness of unconsolidated sediment. The three SH-wave seismic lines discussed in this paper are indicated in yellow.

In the early phases of field work, we chose to examine the eastern portion of the study area where thick (>20m) Holocene Champlain Sea deposits of silt and clay overly thin (~2-6 m) glacial tills and bedrock. In particular, the Ottawa suburb of Orleans was studied in detail (see location in Figure 1). The, preliminary mapping results reported by Hunter and Motazedian (2006) showed that Holocene Champlain Sea deposits were associated with extremely low near-surface Vs velocities in the range of 80-150 m/s. In contrast, glacial deposits yielded Vs velocities of 500-1000 m/s and bedrock Vs velocities were 2200+ m/s. These studies also showed extreme lateral variation in Vs_{30} with changes in NEHRP zones A through to E within 500 m. Also, because of the large seismic impedance contrast between the Holocene sediments and the firm Pleistocene and Paleozoic/PreCambrian rock, resonance effects should contribute to the shaking.

Hunter and Motazedian (2006) also indicated that a buried bedrock valley existed beneath the Orleans suburb (Fig. 1) which was filled with soft Holocene sediments (~95 m depth). They outlined the shape based on existing drill hole information as well as specific shear wave reflection sites.

In preparation for future 2- and 3-D earthquake shake modeling, this paper reports on some refinements of the buried valley shape through the use of shear wave reflection landstreamer technology in a noisy urban environment. Based on this information, additional teleseismic earthquake and ambient noise observations were made at a strategically-placed monitoring site; the results confirmed the occurrence of the resonance phenomenon.

Figure 1 shows a map of overburden thickness in the Orleans area (after Hunter and Motazedian, 2006) along with the locations of seismic sections and the seismograph monitoring station discussed in this paper.

Shear Wave Reflection Seismic Techniques

Land-streamer shear wave reflection techniques have been used in several urban and rural settings in recent years (Inazaki, 2004, Pugin et al. 2004). One of the variants that we have applied in this survey area was developed by Pugin et al., 2006 which consists of 24 sleds of SH-oriented 8 Hz geophone pairs, at 0.75 m spacing and a horizontally-struck hydraulic ram-loaded roller (Fig. 2a) offset 1.5 m from the first geophone sled. Source spacings of 1.5 or 2.25 m result in CMP bin spacings of 0.75 or 1.125m intervals along the survey line. The sample rate was 1 millisecond and the record length was 1.5 seconds. The system is shown in Figure 2(a) being transported by a light truck with the seismograph arranged on the tail-gate in front of the hammer swinger-operator for quality control.

A new approach, wherein we improved the signal-to-noise, utilized the Minivib swept-frequency source (see Fig. 2b). The vibrator mass was oriented in SH mode and was swept from 10 Hz to 100 Hz over 6 seconds using a sample rate of 1 millisecond and a total recording time of 8 seconds. Pilot trace correlation was completed post-acquisition. In this arrangement, the seismograph was mounted in the cab of the Minivib and the operator controlled both the sweep trigger and recording. The source station spacing was 2.25 m.

Both systems required only 2 operators at any one time; however, since we were operating in busy urban streets, three or four people were required for traffic control. With either system, we were able to maintain an acquisition rate of 1.2 km per day.

The processing (Table 1) was carried out using Kansas Geological Survey software for pre-correlation processing and Winseis Turbo for the post-correlation processing. As the very-near surface is homogenous, no particular refraction static had to be applied. The binning at 0.75 m or 1.125 m for CMP record distribution allows a nominal stack fold of 12. Due to the short length of the landstreamer array (18 m) the topographic datum correction can be done as post-stack processing step.

Figure 2: Photos of the SH-wave landstreamer in operation in Orleans with a) hammer/roller source, and b) minivib source.

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Edit geometry
Frequency filter
Scaling (trace normalization)
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Table 1: Processing flow chart for SH-wave seismic reflection data

Seismic Lines

Three seismic reflection lines were obtained using the above systems. A first test was done along a service road in Heritage park (line A, see Fig.1 for location) using the roller system in order to confirm the structure of the valley at that location prior to installing a seismograph monitoring station. Part of the service road was compacted soil and gravel, and part was paved. Figure 3(a) shows the CMP section along the road. The portion of the section acquired over the gravel road was wet and soft and displays a lower signal/noise ratio. The softness of the gravel road may be responsible for poor coupling of the roller, as the coupling of the source on the paved road was much better at producing a larger amount of shear energy. The semicircular survey line A also indicated that the seismic impedance boundary, at that location in the valley, was relatively flat lying, and that no sloping structure existed immediately below the proposed monitoring site.

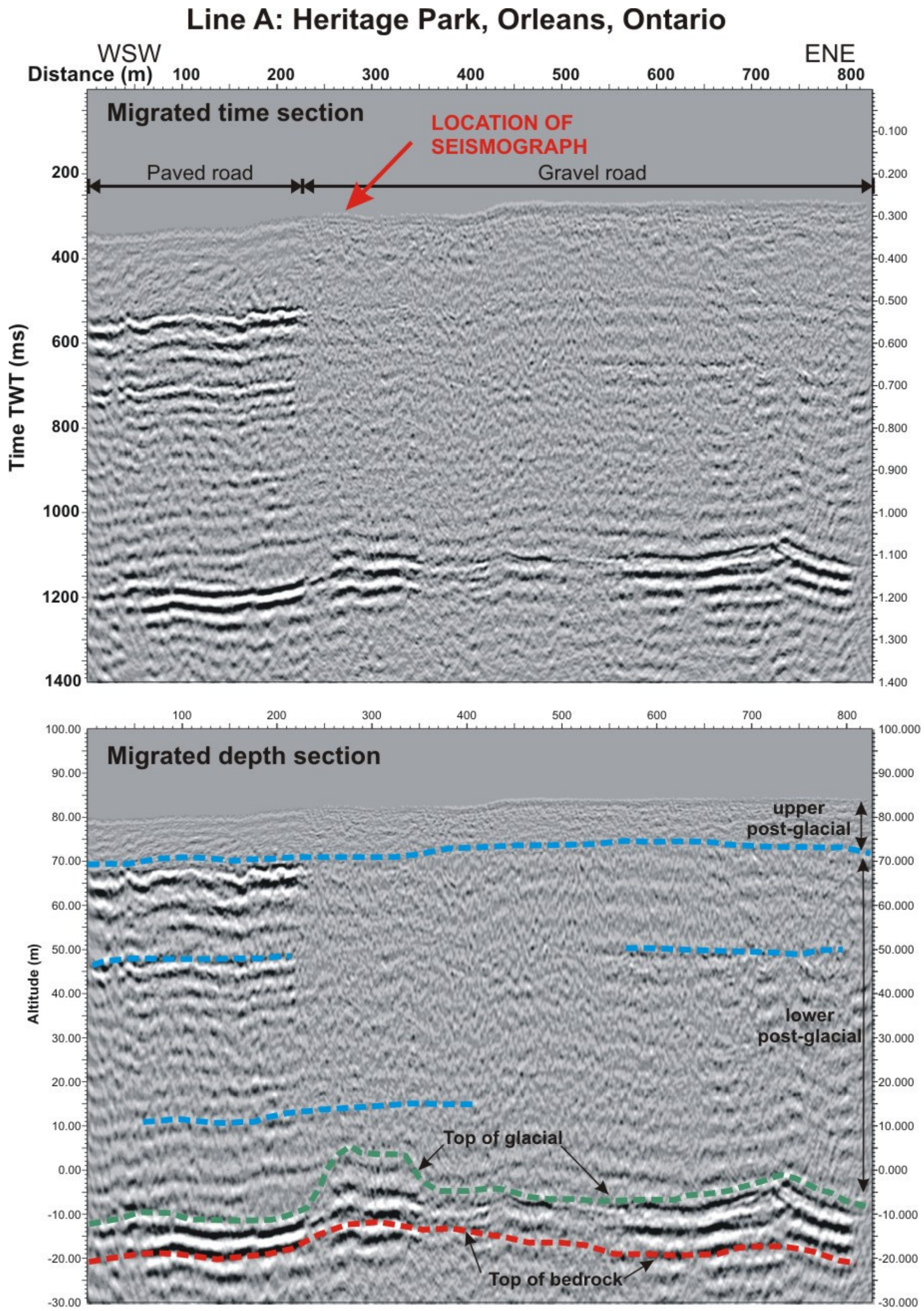

Figure 3a: Processed SH-wave seismic reflection section for Line A (see Fig. 1 for location). The source used was the hammer-roller system (Fig. 2). The upper panel shows the migrated section in two-way travel time; the lower panel shows the depth section (plotted in elevation above sea level) with interpretation.

Seismic line B (for location see Figure 1) was shot in the curb lane of Boyer Rd using the roller system described above. The ambient noise level was variable since this particular street was, in part, a residential one, and, in part, a "feeder" or "collector" street. We operated without stopping traffic, but occasionally had to clear memory and re-shoot a station if a heavy vehicle passed at a critical moment. As well, at intervals we encountered sewer pumping noise (usually at intersections) which we could not counter other than upping the shot stack and shooting through hoping that the CMP stack would rescue us (usually it did). Figure 3(b) shows the processed section.

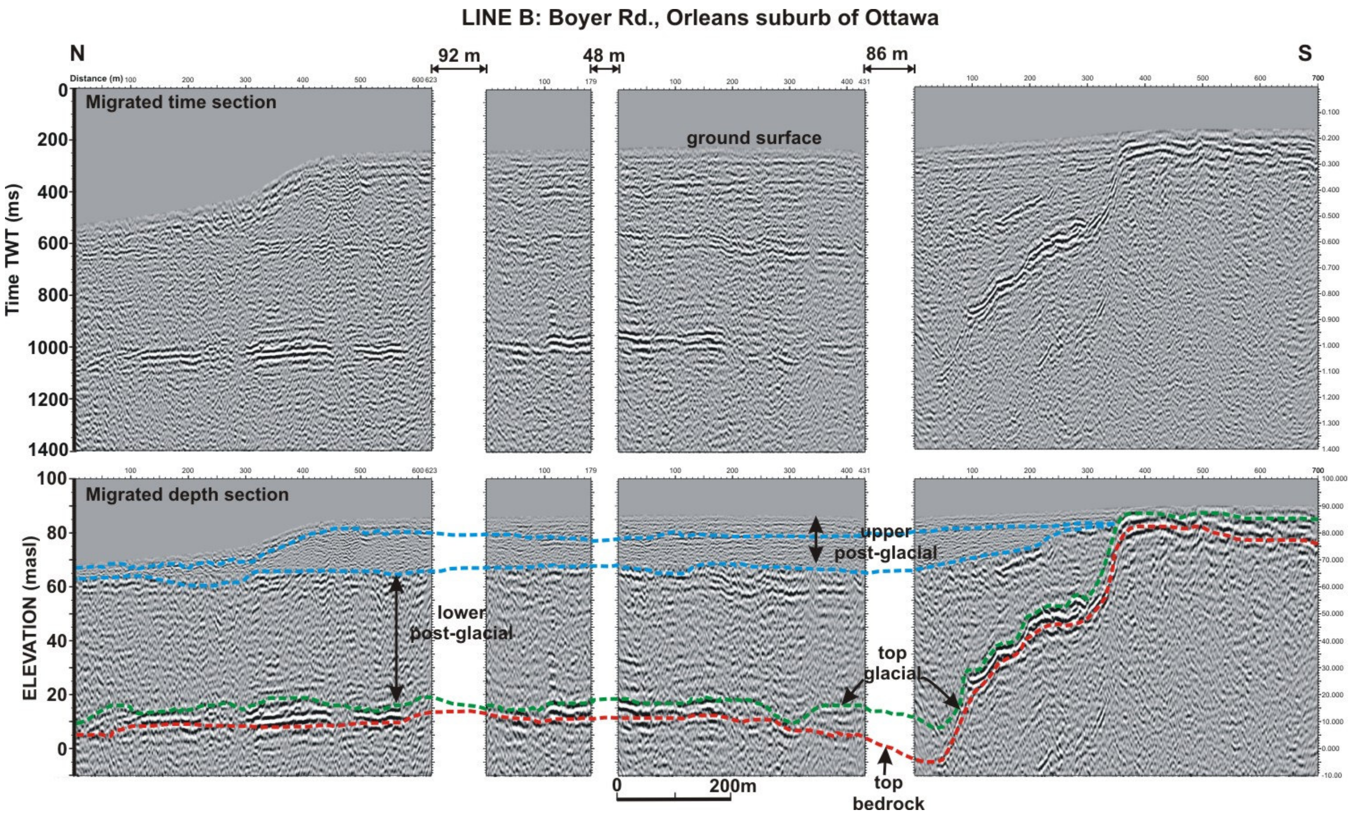

Figure 3b: Processed SH-wave seismic reflection section for Line B (see Fig. 1 for location). The source used was the hammer-roller system (Fig. 2). The upper panel shows the migrated section in two-way travel time; the lower panel shows the depth section (plotted in elevation above sea level) with interpretation.

Seismic line C shot along the curb lane of Belcourt Blvd, a busy "feeder" road in the urban system (see Figure 1). This was our first attempt to improve the signal-to-noise level with a larger source. We found that using the Minivib at 60% of its maximum force, we could increase our shot spacing and yet minimize the effect of Love wave interference. As well, we found that we could work through significant traffic noise including relatively heavy trucks and buses. In general, minimum traffic noise occurred between 9 AM and 11:30 AM and between 1 PM and 3 PM. With this technique (and a busier road) more effort was required for traffic control. Gaps in the line occurred where this road intersected four lane major thoroughfares and where we could not stop opposing traffic for any length of time. Figure 3(c) shows the processed section.

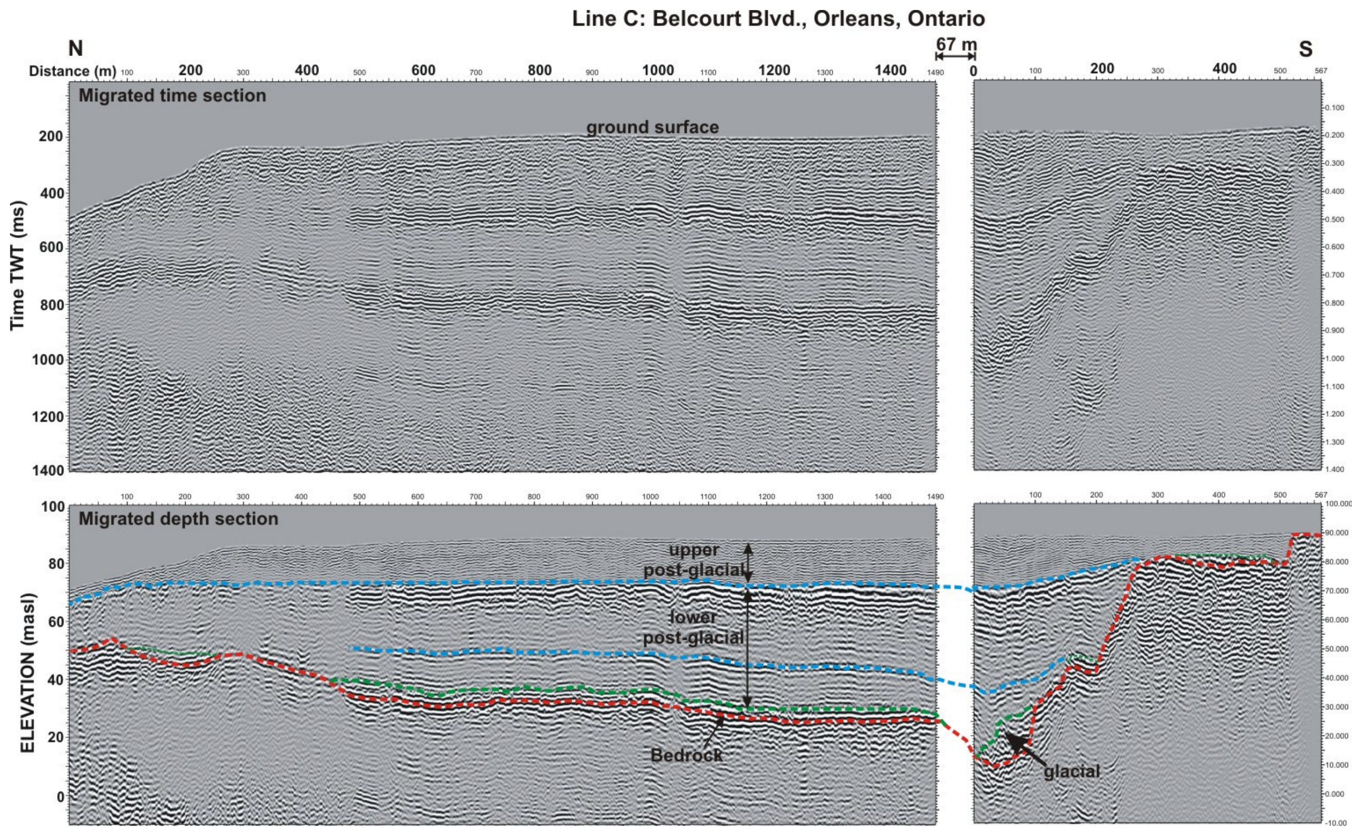

Figure 3c: Processed SH-wave seismic reflection section for Line C (see Fig. 1 for location). The source used was the minivib system (Fig. 2). The upper panel shows the migrated section in two-way travel time; the lower panel shows the depth section (plotted in elevation above sea level) with interpretation.

The raw record gather of the roller source (Figure 4a) shows various phases with different frequency bands (Figure 4b). The low frequency bands can be related with random ambient noise present in the city and surface waves, this noise amplitude is as high as the reflection signal that is situated within the 30-70 Hz frequency band but can be easily filtered using a band pass filter. Another noise that can be seen preferentially in the near offset traces is a high frequency band associated with a road bed noise, likely a Lamb wave propagating in the pavement itself. The frequency range of this wave is usually well above 100 Hz. A power line harmonic can be seen at 180 Hz. A 60 Hz phase can be seen near transformers but is greatly reduced by the stack operation. The presence of the low-frequency ambient noise and the high-frequency road-bed noise determined the choice of a sweep from 10 Hz to 100 Hz in order to vibrate within the range of the maximum energy of the reflection. As a result the Minivib record (Figure 4a) displays very little noise with the exception of a surface Love-wave noise (Figure 4b) that can be easily filtered using a high pass filter of 40 Hz.

Seismic Line Interpretations

Line A (Figure 3(a)) in Heritage park shows prominent reflectors at the elevation of 10 m, 33 m and 90 m depth. The velocity depth functions were derived from a "walk-away" long-offset geophone spread at the site (see also, Hunter and Motazedian, 2006). Low shear wave velocity Champlain Sea (Holocene) fine sands, silts and clays are interpreted to form the majority of the section down to 80-90 m depth. Within the Champlain Sea section, a continuous reflector at approximately 10 m depth can be found on most other seismic sections in the east Ottawa area, and is thought to be associated with a series of sand beds, and possibly indicating an unconformity. This event marks a distinct velocity boundary, with higher average shear wave velocities below it; the effect of this is plainly visible on the depth section. The prominent reflector package below the Holocene section represents the glacial materials (tills and gravels). Bedrock is interpreted to be the deepest continuous reflector.

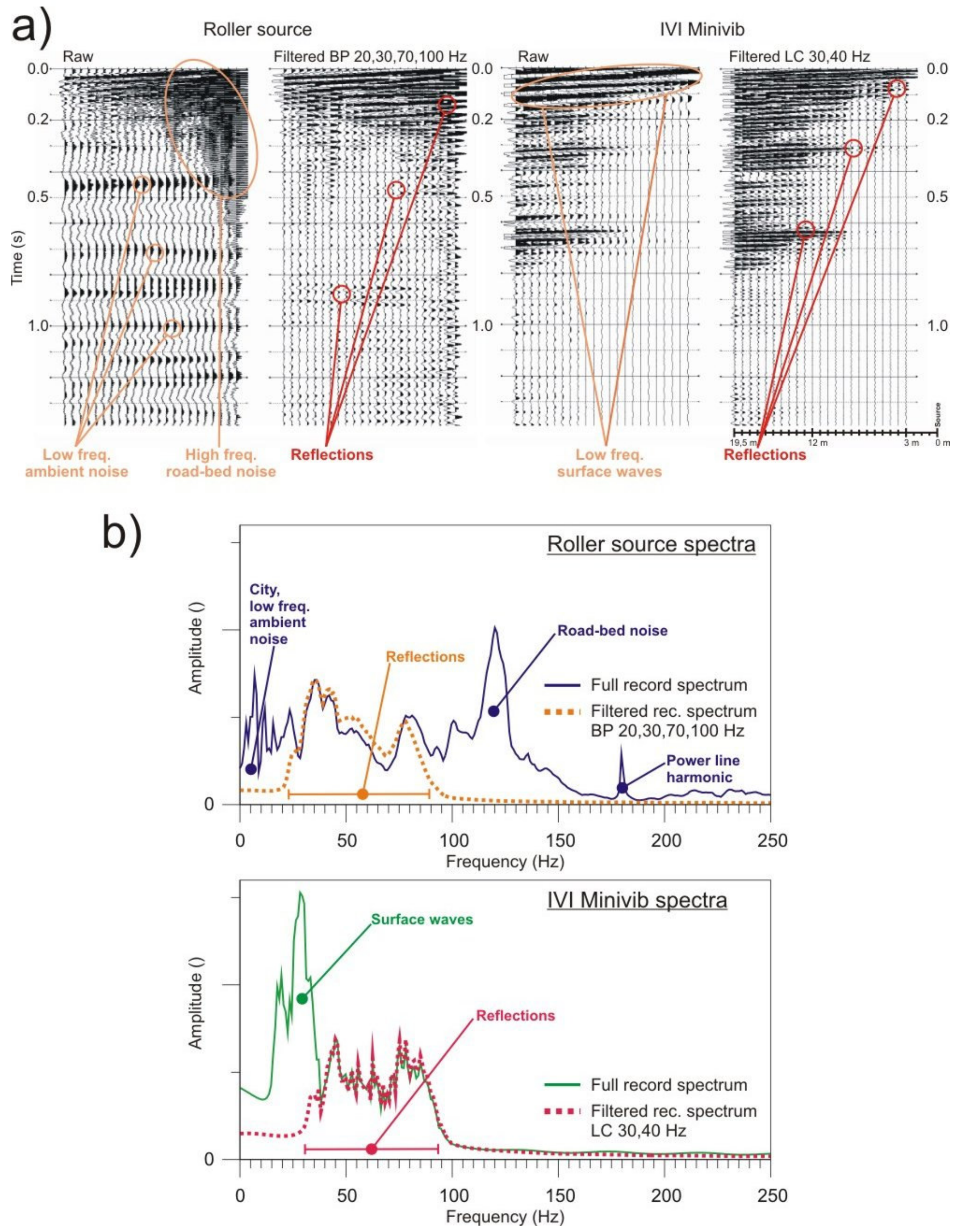

Figure 4: a) Raw and filtered field gathers using the roller and minivib sources. b) Frequency spectra for the records shown in a).

Seismic Line B (Figure 3(b)) along Boyer Rd shows similar reflectors as those of Line A. Here the bedrock interface is near surface at the south end (2-4 m depth) and drops precipitously to a depth of 90 m at the base of the buried escarpment. This surface is overlain with a few meters of glacial sediments and a very thick Holocene (Champlain Sea) marine deposit. The bedrock surface does not rise at the north end of the section, as might be expected from the angle at which the section cross-cuts the buried valley (see Figure 1).

Line C (Figure 3(c)) along Belcourt Blvd shows a section similar in may respects to Line B. Here, the bedrock interface is effectively on surface and drops to a depth of 80 meters across two (faulted?) buried "steps". The bedrock surface rises to the north, and outcrops 150 m to the north of the section. On this section, glacial sediments are interpreted to be thicker (~10 m) than on line B. As well, a prominent (possibly unconformable) continuous reflector within the Holocene marine section is visible.

Lines B and C indicate that the southern edge of the buried valley consists of a prominent buried escarpment(s). These could possibly be associated with pre-existing faults within the lower Paleozoic bedrock. Over-deepening of the bedrock surface at the base of the escarpment could have occurred during glaciation. At the locations of maximum depth to bedrock on Lines B and C, sags in the intermediate reflectors within the Champlain Sea sediments may indicate differential compaction due to some de-watering phenomenon (water flow associated with infilling gravels above bedrock?).

Lines A, B, and C, have shown detailed structure of the bedrock and overburden which serves to improve our image of the southern flank of the subsurface buried valley.

Evidence of Resonance within the Buried Valley

A seismic monitoring station was set up in the fall of 2006 in Heritage Park, at the approximate location shown in Figure 3(a). A M4.2 earthquake was recorded at the site on Dec. 7, 2006. The epicentre of this teleseismic event was approximately 624 km NW of Ottawa, near Cochrane Ontario, and was also recorded on bedrock at an almost identical epicentral distance on the Ottawa station of the Canadian National Seismograph Network. Figure 5(a) shows the earthquake time series recorded at Heritage Park. In order to investigate possible amplification at this site, the spectral horizontal-to-vertical ratios were computed and compared with identical computations done with the Ottawa rock records. The comparison, shown in Figure 5(b), indicates a 49-to-1 amplification at 0.7325 Hz at Heritage Park and no significant amplification at the Ottawa rock site.

As a further check of resonance effects, we selected three periods of ambient noise at the Heritage Park site on December 12, 2006, and repeated the H/V analyses. The average of these noise sites is also shown in Figure 5(b) with an almost identical peak location, size and shape. As a further check, we selected the reflection time interpreted to be at the top of the glacial sediments (first significant seismic impedance boundary) at the location of the monitoring station shown in Line A (Fig. 3(a)) and computed the fundamental site frequency assuming a one-dimensional model ($F = Vsav/(4*thickness)$). The value obtained was 0.667 Hz. This value correlates well with that obtained from spectral ratios. The slight difference may result from errors in the applied velocity depth function, a possibly over-simplified impedance boundary model, or possibly from unaccounted two- or three-dimensional effects. Overall, the correlation is quite close, and we are confident that H/V ratios computed from ambient noise or small earthquakes are equivalent to estimates made from surface seismic reflection/refraction methods (Hunter and Motazedian, 2006).

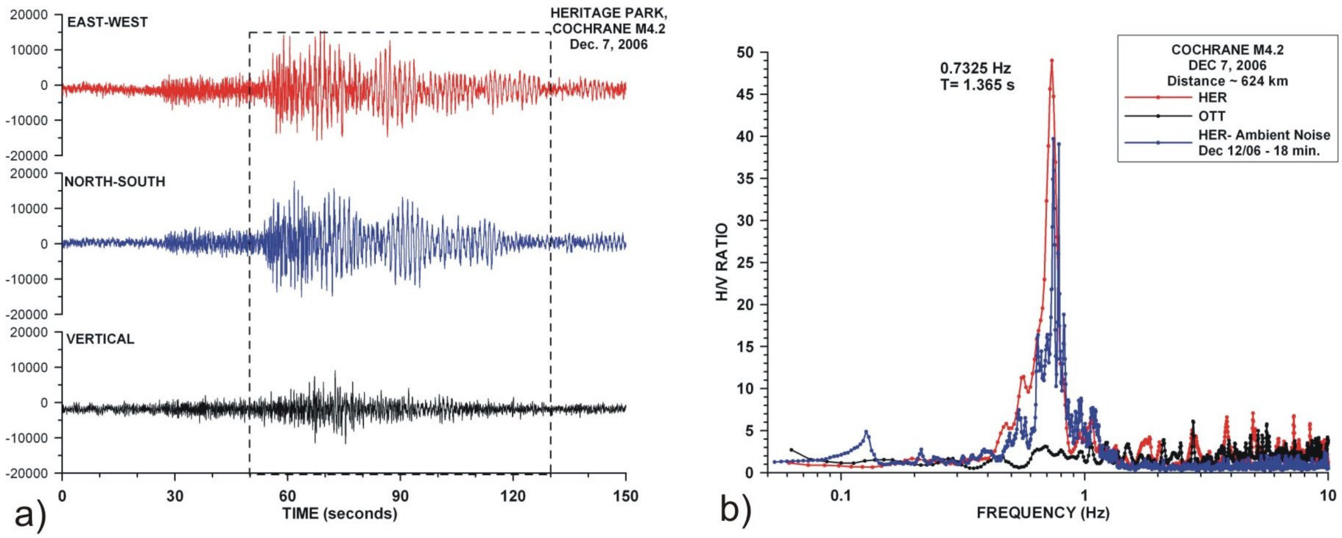

Figure 5: a) Cochrane earthquake time series recorded at Heritage Park. b) Spectral horizontal-to-vertical ratios for the Cochrane earthquake data recorded at Heritage Park (red line), at the Ottawa station (on rock, black line), and for ambient noise measurements from Heritage Park (blue line).

Summary

Shear wave reflection techniques using a landstreamer have accurately delineated the southern portion of a significant buried bedrock valley first indicated by Hunter and Motazedian (2006) in the Ottawa suburb of Orleans. The landstreamer reflection technique coupled with the Minivib seismic source is an optimal configuration for urban seismic studies associated with earthquake hazard surveys in eastern Canada.

Where high seismic impedance contrasts occur at the base of the unconsolidated overburden, resonance effects can be most prominent. Surface seismic techniques can be utilized to estimate fundamental frequencies. Further work on modeling of 2- and 3-dimensional resonance effects of narrow buried valleys will be conducted by Carleton University in the near future.

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