DATA COLLECTION FOR EARTHQUAKE HAZARD MAPPING IN THE OTTAWA AREA

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RÉSUMÉ
Les provisions sismiques du Code de Construction National du Canada 2005 mentionnent la possibilité que d'importants tremblements de terre peuvent avoir lieu dans la région d'Ottawa. Une étude démonstrative de l'Université de Carleton et de la Commission Géologique du Canada est en cours pour mesurer les propriétés de l'onde cisaillante des unités géologiques dans la région d'Ottawa, Ontario. Le but de ce travail est d'améliorer notre connaissance des propriétés de l'onde cisaillante des sols meubles dans la vallée d'Ottawa pour une meilleure estimation et pour cartographier les amplifications sismiques et les effets de résonnances. Les résultats préliminaires indiquent qu'il existe d'importants contrastes de vitesse de l'onde cisaillante entre les unités glaciaires et postglaciaires ainsi que des variations locales majeures d'épaisseur des sédiments. En accordance avec les profondeurs variables, la prédiction et la cartographie de période fondamentale et des pics de résonance des sites démontrent également une grande variabilité. L'observation du bruit sismique ambiant local et d'événements télé-sismiques de tremblements de terre a confirme le faible mouvement estimé de la réponse du sol. Dans l'ensemble on peut prédire qu'un important tremblement de terre à Ottawa pourrait générer des intensités variables selon l'endroit en raison des épaisseurs variables et des propriétés géotechniques des sédiments glaciaires et postglaciaires qui reposent sur le fond rocheux de la région. La finalisation de la cartographie des paramètres de l'amplification sismique et de la période de réponse pour la région d'Ottawa est prévue pour 2009.

ABSTRACT
The seismic provisions of the National Building Code of Canada 2005 reflect the possibility that significant earthquake shaking can occur in the Ottawa area. A joint demonstration study by Carleton University and the Geological Survey of Canada is currently underway to measure the shear wave properties of geological units in the Ottawa area, Ontario. This work is designed to improve our knowledge of the properties of soft soils in the Ottawa Valley region in order to better estimate and map earthquake amplification and resonance effects. Results to date indicate that there are large shear wave velocity contrasts between glacial and postglacial surficial geological units as well as major local variation in unit thicknesses. Prediction and mapping of fundamental site periods and associated resonant peak amplitudes also reveal large variability, reflecting these same factors. Monitoring of ambient seismic noise of both local and teleseismic earthquake events has confirmed the estimated weak motion ground response. Overall, it is expected that a significant earthquake in the Ottawa area will generate variable shaking intensities spatially because of differing thicknesses and geotechnical properties of the glacial and post-glacial sediments that overlie the bedrock of the region. Mapping of earthquake amplification parameters and site period response for the Ottawa area is planned for completion in 2009.

1. INTRODUCTION

The shaking experienced at a given site during an earthquake can be amplified significantly depending on the local geological-geotechnical properties of the underlying soil. The 2005 National Building Code of Canada (NBCC 2005) introduced descriptions of site categories that take into account the thickness and stiffness of a soil and provide estimates of the relative amount of amplification from seismic shaking. These site categories can be mapped using three-dimensional geological and geophysical data to produce seismic hazard microzonation maps that depict the spatial distribution of earthquake amplification hazards. Such maps have application towards, for example, allowing municipalities to enhance their emergency response planning, improve earthquake mitigation strategies, and develop urban growth plans that avoid amplification susceptible terrain.

The Geological Survey of Canada (GSC) is currently mapping the NBCC site categories within the City of Ottawa, Ontario, to produce seismic hazard microzonation maps. This mapping represents a research activity of the 'Eastern Canada Geohazards Assessment Project' within the Natural Resources Canada 'Reducing Risk from Natural Hazards Program'. The intent of this project is to produce science-based hazard assessment products for eastern Canada that have a direct application for the reduction of risk from earthquakes and landslides. This current paper provides an overview of the type of work being conducted in this project, along with some preliminary results to date.

2.   STUDY AREA

Ottawa is the fourth largest city in Canada with an area of 2,760 square kilometers; it is also situated close to the Ottawa Valley and West Quebec seismic zones, as shown in Figure 1(a). Hence, Ottawa has been identified as the city with the third highest earthquake risk in Canada (Adams and Halchuk (2003).
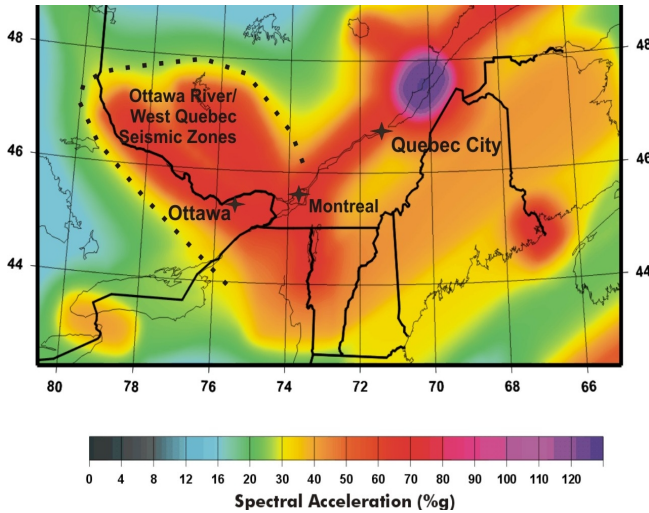

Figure 1(a). Probability of exceedance of 2% in 50 years for 5% damped pseudo-acceleration at a period of 0.2 seconds for NEHRP class C for the Ottawa-St. Lawrence valley area (after Adams and Halchuk, 2003).

The city limits are shown in Figure 1(b) superimposed on a generalized geology map. Although detailed bedrock and surficial geology maps are available for the Ottawa area (Belanger, 1998), we have simplified the geological units to reflect geotechnical properties of interest to the earthquake response study. Bedrock outcrops (20% of the area) consist of Precambrian gneisses or more commonly lower Paleozoic limestone, dolostone, sandstone or shale. Glacial sediments (till and glacio-fluvial material) overlie bedrock and are relatively thin (~1-4 m), but can thicken locally in narrow bedrock topographic lows associated with paleo-channels. These sediments represent firm ground and are exposed on 10% of the study area. Post-glacial sediments outcrop over 65% of the study area and consist of sand, silt and clay which were deposited during or immediately after the occupation of the area by an extensive body of sea-water called the Champlain Sea (11,500 to 9800 years before present in the Ottawa area). Since depositional rates of sea bottom sediments were high, pore water content is unusually high. The combination of salt-water leaching, fine-grained sediments and high water-contents commonly result in so-called "sensitive clay" conditions.

3.   METHODOLOGY

To estimate ground shaking at any location in Canada, the 2005 NBCC recommends using ground acceleration estimates for four spectral frequency components within the earthquake spectral range. These spectral acceleration estimates are given for a 1-in-2500 year return period earthquake, discussed in detail by Finn and Whitman (2003).
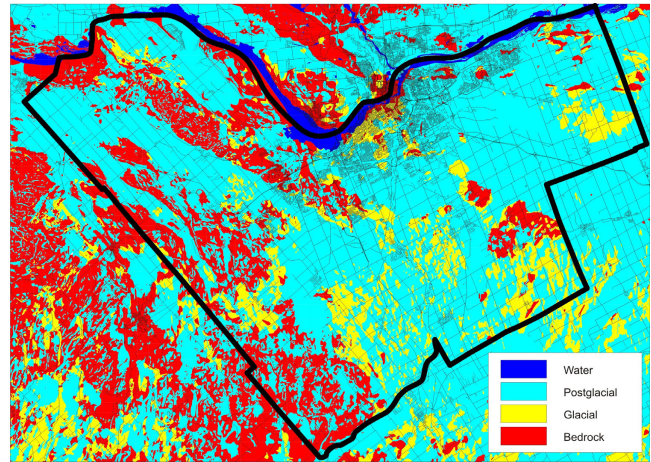

Figure 1(b). Generalized geology map for the Ottawa region. The black lines indicate the boundary of the city of Ottawa.

The 2005 NBCC also contains soil and rock site classifications adopted from the U.S. National Earthquake Hazard Reduction Program recommendations and are listed in Table 1 as Class A through F (NEHRP, 1994). Spectral values given for Canadian sites by the 2005 NBCC are for firm ground conditions (NEHRP class C). Using the look-up tables provided in the NBCC amplification effects can be scaled up for soft ground (NEHRP E) or scaled down for hard bedrock outcrop conditions (NEHRP A) to reflect differing ground response.   Site classifications can be defined using "standard blow count", shear strength measurements, or shear wave velocity measurements all averaged over the upper 30 m of the ground. Only the shear wave velocity method is applicable for assessing most of the NEHRP classes. Hence geophysical techniques, in association with geological borehole information, are being used as the primary mapping methods in the Ottawa region.

3.1 Vs_{30}

Vs_{30} is defined as the travel-time weighted average shear wave velocity from surface to 30 m depth. It is used to define the NEHRP site classification for a given location, as shown in Table 1.

Table 1 (after 2005 NBCC and Finn and Whitman, 2003)

NEHRP CLASS	Vs$_{30}$ RANGE	MATERIAL DESCRIPTION
A	>1500 m/s	solid rock
B	720 to <1500m/s	rock
C	360 to <720 m/s	firm soil or soft rock
D	180 to <360 m/x	soft soil
E	<180 m/s	very soft soil
F	(<180 m/s)	special case NBCC

3.2   Fundamental Site Period

In those parts of Ottawa where thick post-glacial sediments occur, there is a possibility of site resonance phenomenon, of concern in the construction of tall structures in high earthquake hazard areas. The seismic impedance contrast between post-glacial sediments and bedrock can be quite high (~30:1). In such situations, vertically travelling shear waves become "trapped" in a soft soil unit resulting in very large amplitudes at a single resonant period (or frequency) given by:

$$T = 4*h/Vs_{av} \qquad [1]$$

where:

T = resonant period (1/f)
h = thickness of soil overlying bedrock
Vs$_{av}$ = travel-time weighted average shear wave velocity from ground surface to the resonant surface (bedrock)

Both the average shear wave velocity and depth to bedrock can be measured to compute the estimated fundamental site period; alternatively, site resonance can be measured using passive monitoring of the ratio of horizontal-to-vertical teleseismic noise and/or small earthquakes (Bard, 1999: Nakamura, 1989).

3.3   Digital Database

A digital geological data base of water-well information and geotechnical borings has been developed based on the early work of Belanger (1998). An algorithm has been developed to interpret the geological descriptions and to reinterpret these in terms of the three basic geological units as given in Figure 1(b). The interpretation algorithm was applied to approximately 28000 boreholes and successfully interpreted all but 4000 of these. The remainder were manually inspected and interpreted.

When shear wave velocity-depth information becomes available from our surface and borehole measurements across the project area, geological units in the boreholes will be assigned average shear wave velocities (for rock or glacial materials) or shear wave velocity-depth functions (for post-glacial materials) interpolated from the nearest data collection locations. As a result, the shear wave velocity-depth functions will vary throughout the area incorporating the local thicknesses and varying shear wave velocity properties of surficial units. This technique will result in improved estimation of lateral variations in average shear wave velocities in the soil column and therefore improved estimates of Vs$_{30}$.

4.   METHODOLOGY

A number of near surface geophysical techniques (mainly passive and active seismic) are utilized in this study.

To measure site-specific shear wave velocities, a combined refraction-reflection technique has been used (Motazedian and Hunter, 2006) that can be applied to small open spaces (e.g. city parks, suburban roadsides) using small active sources. To date 522 sites have been occupied. In addition, a Multichannel Analysis of Surface Waves (MASW) technique is being applied using both active and passive seismic sources at approximately 50 sites.

To obtain detailed subsurface structure within the surficial deposits as well as mapping the structure of the buried bedrock surface, we have developed a shear wave reflection profiling "Minivib-Landstreamer" system which has been adapted for urban use along streets and sidewalks (Pugin *et al.*, 2007).

In order to obtain direct measurements of shear wave velocities with depth, we have used borehole well-locking geophones along with horizontally-polarized shear sources on surface to obtain detailed interval shear wave velocities in 13 boreholes throughout the city. Hunter and Woeller (1990) have shown that seismic cone penetrometer testing techniques (SCPT) yield slightly better statistical error on in-situ measurements as compared to the borehole technique mentioned above; however, such data are extremely limited in our project area to date. Those few available SCPT sites obtained from previous geotechnical work have also been included in our compilation.

Passive monitoring of ambient teleseismic noise is a technique which excels in areas such as the Ottawa project where high acoustic impedance contrasts exist. The technique has been in use in Japan and elsewhere for several years (Nakamura, 1989; Bard, 1999) and utilizes low frequency ground noise in the same range as earthquakes, to estimate the fundamental resonance peak from measurements of horizontal to vertical spectra ratios of ground motion. Ambient noise measurements can be made at multiple locations per day using light portable seismographs.

Additional resonance and ground amplification data can be obtained using weak-motion portable seismographs at soils sites where weak local, or teleseismic earthquakes are recorded, and also where the amplitude of the recorded motion can be compared to a near-by rock outcrop site.

4.1   Shear Wave Refraction-Reflection Site Examples

Detailed descriptions of shallow shear wave refraction and reflection field survey designs used in the Ottawa area have been given by Motazedian and Hunter (2006). Twenty-four

in-line horizontal component 8-Hz geophones, set at 3 m spacings, are aligned transversely in order to detect polarized shear (SH) waves generated by the surface seismic source (hammer and horizontal plate). Several source locations are offset from each end of the array, as well as midway along the array. This multiple source geometry is required to obtain sufficient shear wave refraction measurements of potential high velocity materials to at least 30 m depth (e.g. in order to be able to compute accurate Vs_{30} if bedrock should be present at depths less than 30m). The multiple source locations are also an aid in the interpretation of shear wave reflections from layering within the soil column as well as the soil-bedrock interface.

Figure 2(a) is an example seismic record at a site where the bedrock interface is shallow and where the interest is focused on the first arrivals associated with refractions through the overburden and along the bedrock interface. Where the bedrock is encountered at shallow depths, it is possible to calculate the shear wave velocity-depth function using only the first arrival travel times and standard refraction relationships. The interpreted average velocity-depth curve is a compilation from all forward and reverse seismic records from all source offsets at the site, and is extrapolated to 30 m depth for the calculation of Vs_{30}.
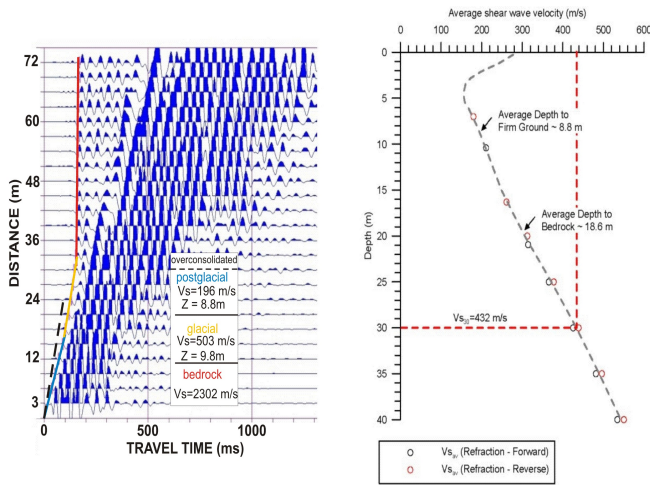

Figure 2(a). Shear wave refraction site example. Refraction first arrival velocities are used exclusively to estimate the velocity-depth function to 30 m depth.

Figure 2(b) is an example seismic record at a site where the bedrock surface is much deeper, and where the first arrival refraction analysis is combined with wide-angle reflection analyses to estimate the average shear wave velocity-depth function as well as Vs_{30}. Here intermediate wide-angle reflections are observed from within the soil column as well as a package of reflectors associated with the top of the glacial materials and the top of bedrock. Average velocities and depths obtained from reflection measurements are computed by interactively matching hyperbolic curves using

Interpex Ltd IXSEG2SEGY software for all seismic records using all source offsets. For all sites, best fitting curves are drawn through the data in order to estimate Vs_{30}. For any particular site, if a prominent reflection has been interpreted for the top of the bedrock (or firm ground associated with glacial materials), the fundamental site resonance period is also estimated using the two-way reflection travel time T_{2way} at vertical incidence as:

$$T_{fund} = 2 * T_{2way} \quad \text{(seconds)} \qquad [2]$$

This value can be compared to that obtained by passive monitoring (ambient noise or earthquake) techniques.

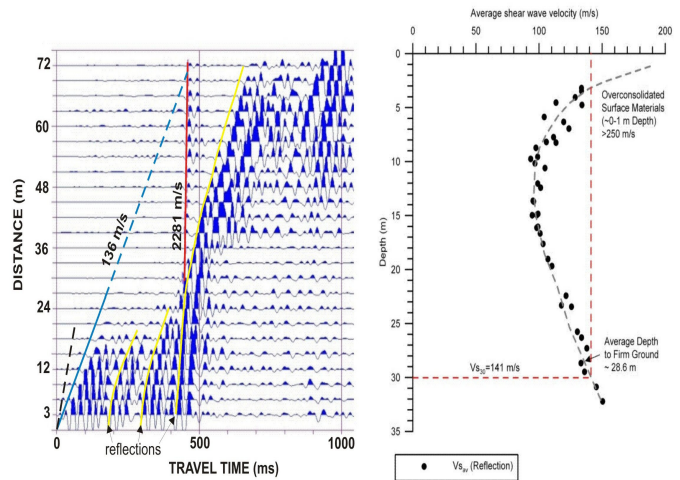

Figure 2(b). Shear wave reflection site example   Although refraction first arrivals are visible for the upper post-glacial and the bedrock, the average velocity analysis is primarily derived from hyperbolic wide-angle reflection curve fitting.

4.2   Reflection Profiling with "Minivib-Landstreamer"

Within the project area, extreme lateral variation in soil thickness and structure can occur locally where bedrock topographic lows are in-filled with soft post-glacial sediments. If the in-filled bedrock valleys are narrow enough, such areas can generate additional shaking effects which are governed by the structural shape of the seismic impedance boundary (Bard and Bouchon, 1985). A recent technology advance in high resolution reflection profiling has been made using a towed geophone array and vibratory (swept-frequency) sources (Pugin et al, 2007). This method gives adequate results even in a seismically noisy urban environment and has been applied to some critical areas of the Ottawa project. Figure 3 is a shear wave reflection profile, obtained with this system, which shows the overburden structure adjacent to a temporary seismic recording station (STN HOBBS). There is approximately 60 m of relief to the bedrock (hard ground) interface. Interpreted soil stratigraphy from such sections can yield vertical resolutions of < 1m.
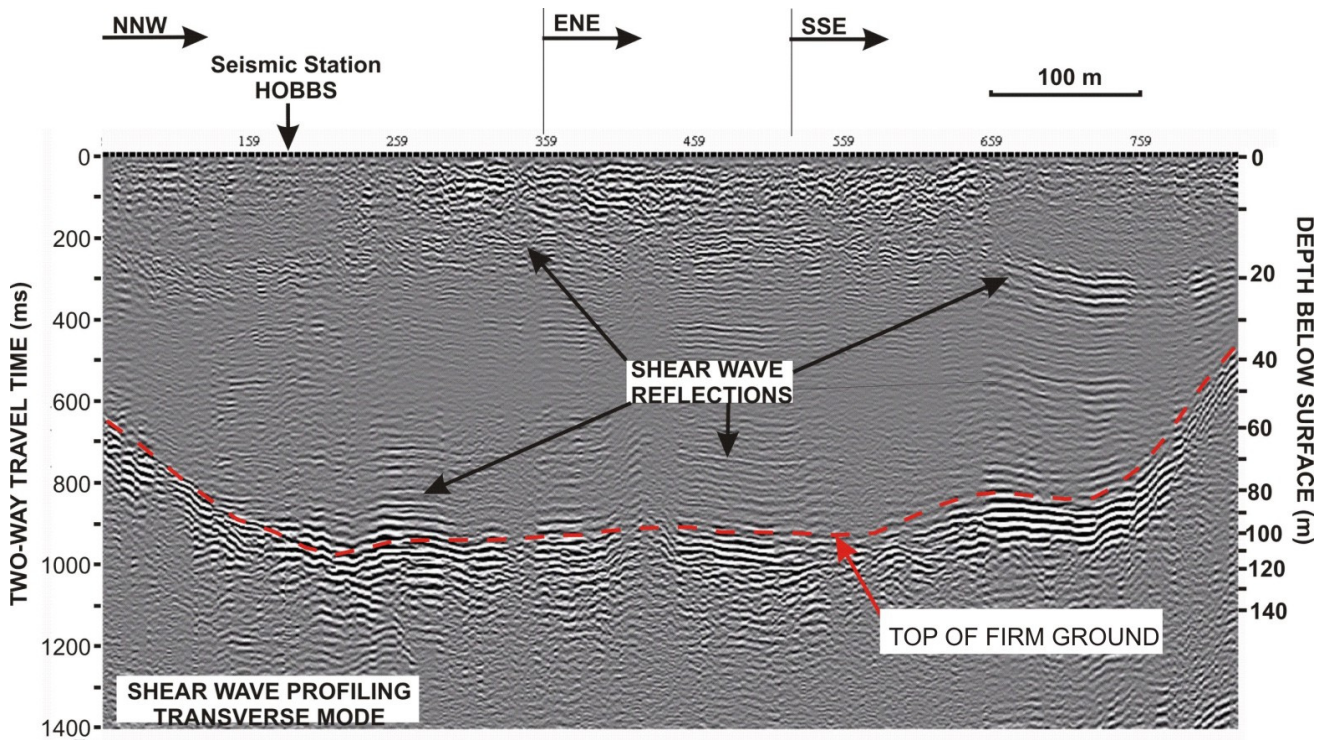
Figure 3. Shear wave reflection profile adjacent to a temporary seismograph station (HOBBS) showing significant buried topography (~60 m) on the soil-bedrock interface.

4.3   Borehole Shear Wave Measurements

Shear wave velocities have been obtained in 13 boreholes from the analysis of travel times of shear waves from a near-borehole surface polarized source (horizontal hammer and I-beam plate) down to a three-component well-locking geophone sonde in a plastic-cased and grouted hole. Travel time measurements are made with successive locations of the sonde at 0.5 meter intervals. Figure 4(a) shows a compilation of shear wave interval velocities measured in 13 boreholes in post-glacial sediments along with the 2 standard error limits of a previous study by Hunter *et al.* (2007) for 17 boreholes between Ottawa and Montreal. Anomalous velocity values associated with the overconsolidated surface layer have been removed for clarity. Figure 4(b) shows the compilation of average shear wave velocities of post-glacial sediments for the same 13 boreholes, derived from total travel time from ground surface to the sonde (i.e. including the effect of the high velocity surface layer). Also shown in this figure are the estimated limits of the range of observed values from the previous regional survey by Hunter *et al.* (2002). Note that Vs_{30} estimates are < 180 m/s (i.e. NEHRP Zone E or F).
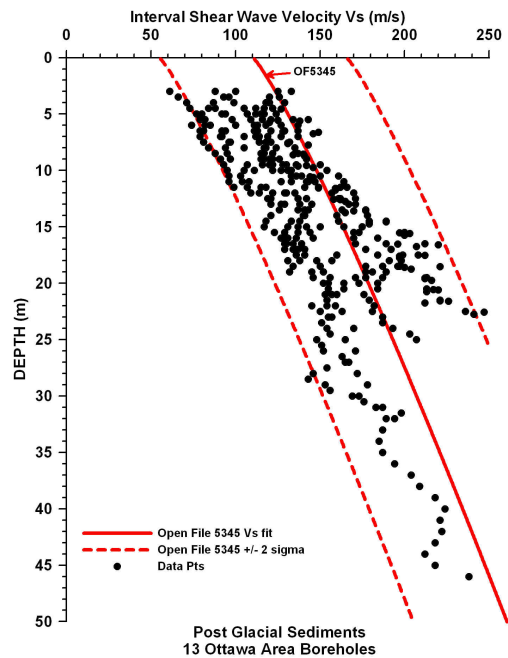

Figure 4(a). Borehole shear wave interval velocities measured in the Ottawa area. The curves shown are from a regional Ottawa-Montreal study by Hunter *et al.* (2007).
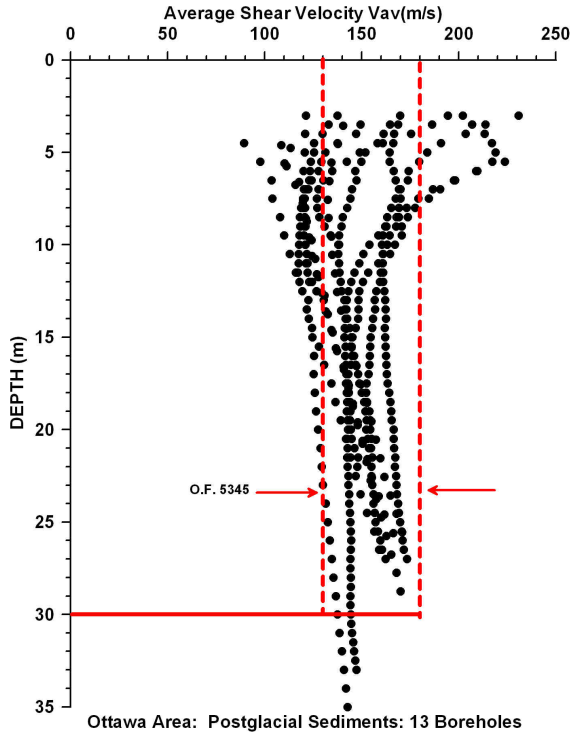
Figure 4(b). Borehole shear wave average velocities measured in the Ottawa area. The dashed line limits are those from Hunter *et al.* (2007)

4.4 Surface Wave Methods

The Rayleigh wave surface seismic technique is an additional tool that is being used by Carleton University to provide estimates of soil and rock shear wave velocity structure, particularly in areas of the city with restricted access and high ambient noise levels. The applications follow that given by Park *et al.* (2005) which utilize both passive (ambient noise) and active (hammer and plate) recording methods of Rayleigh wave phase velocities as well as various mathematical inversion approaches to solve for a best-fitting shear wave velocity-depth model. Figure 5 shows an example interval velocity inversion model of field data compared to borehole shear wave measurements at the National Research Council Geotechnical Test Site #1 in Ottawa. This method can provide accurate estimates to at least 30 m depth throughout the project area; it can also be used to detail the thin surface high-velocity zone.
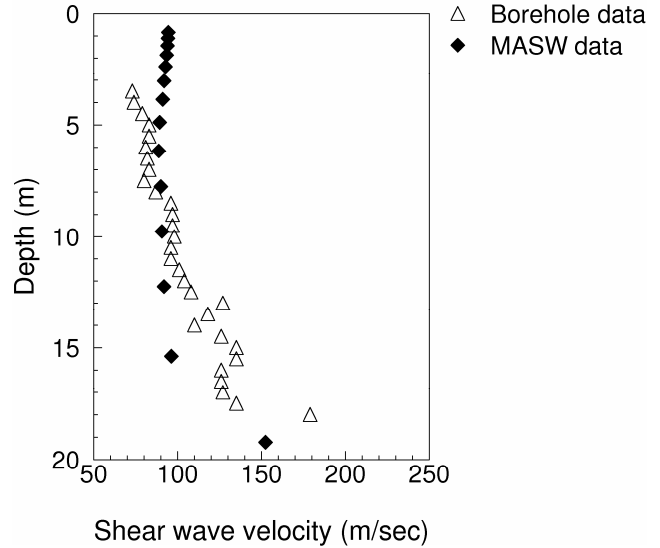

Figure 5. A comparison of borehole and Rayleigh wave inversion (MASW) results for a site in the Ottawa area.

4.5 Horizontal to Vertical Spectral Ratio Method (HVSR)

The Horizontal to Vertical (H/V) spectral ratio method can help define some dynamic characteristics of unconsolidated deposits, mainly the natural fundamental resonant frequency (Sesame 2004). Ambient teleseismic background 3-component ground motion has been recorded at a number of soft-soil sites that were monitored with a seismograph equipped with a three-component broad band seismometer. Using the Sesame (2004) freeware, the data were analyzed and the fundamental frequency computed. Figure 6 shows the results at Heritage Park, a site known to have 95 m of unconsolidated deposits. Results show a clear peak, indicative of a sharp velocity contrast between the overburden and bedrock. The fundamental frequency at that site was found to be about 0.73 Hz (1.36 s), a peak seen in the unsmoothed values as well as in the curve smoothed using the recommended Konno and Ohmachi filter. The H/V peak amplitude of >15 does not correspond to the amplification factor, however, world-wide experience suggests that it generally underestimates the actual site amplification (Sesame, 2004). Most sites analyzed to date show clear peaks which range from 0.6 to 3 Hz or higher. A few sites that did indicate wider peaks, two peaks, or were unclear, are probably affected by either local noise sources or 3-D soil heterogeneity in shear wave velocity structure.
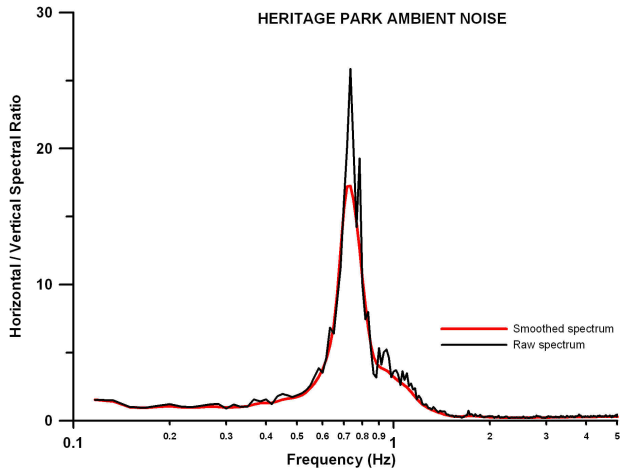
Figure 6. Horizontal to Vertical (H/V) spectral ratio as a function of frequency (only shown between 0 and 3 Hz) for a site located at Heritage Park, Orléans, Ontario. The peak is clear and centered at around 0.73 Hz, and is visible in either unsmoothed or smoothed data.
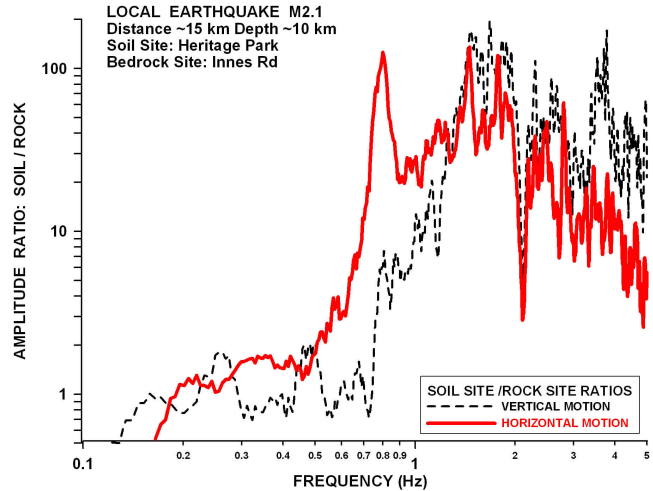

Figure 7. Ratio of spectral components for a local earthquake recorded on 95 m of soil at Heritage Park and at an adjacent bedrock site at Innes Rd in Ottawa. Note the correlation of the onset of high amplitude ratios with the fundamental site period at 0.73 Hz, as shown in Figure 6.

4.6 Weak Motion Earthquake Event Monitoring

Numerous small earthquake events occur along the Ottawa River or west Quebec seismic zones. These events have been recorded on both thick soil sites as well as a local bedrock outcrop site using broad-band velocity sensors. Figure 7 shows a comparison between a rock site and a soil site at Heritage Park in the eastern area of Ottawa. At Heritage Park, the post-glacial soil is approximately 95 m thick; the bedrock site located about 1.7 km away. The sites recorded an M2.1 shallow earthquake that occurred approximately 15 km away at an epicentral depth of 10 km and was equidistant from both stations. Identical velocity sensors and digital recorders were in operation at both sites at that time. The soil-to-rock spectral ratios for the seismograms are shown in Figure 7 for both combined horizontal as well as vertical components. It is interesting to note that amplification up to 100X is prevalent at frequencies above the fundamental resonance frequency (as given by the ambient noise ratio in Figure 6) for the Heritage Park site for both horizontal and vertical components. The horizontal component ratio also shows the sharp fundamental resonance peak at 0.73 Hz, whereas this peak is not evident on the vertical component ratio. For the Heritage Park soil site, amplifications greater than 1 persist to frequencies as high as 25 Hz (not shown). The anomalously large amplification ratios cannot be adequately explained from impedance contrasts alone; it is possible that there are additional 3-dimensional "buried valley" amplification effects (Bard and Bouchon, 1985) but to date we have no adequate explanation. Similar amplifications have been found for other temporary seismic stations that we have established on thick soil sites in the area.

5. CONCLUDING REMARKS

We have estimated that significant variations in earthquake amplification can occur within the city of Ottawa as a result of the changing shear wave velocity properties of the soil and rock. All NEHRP site classifications can be found within the project area and extreme lateral variations are possible.

The anomalously large amplitudes associated with fundamental resonance frequencies cannot be adequately explained despite the large seismic impedance contrasts between soils and rock. Future 3-dimensional shake modeling should be done to investigate specific regions of thick post-glacial sediments.

Figure 8 shows the data coverage within the project area as of January 2008. The planned project completion is March 31, 2009, when maps of Vs_{30}, fundamental site period, spectral amplifications and a borehole digital data base will be published for the Ottawa region.
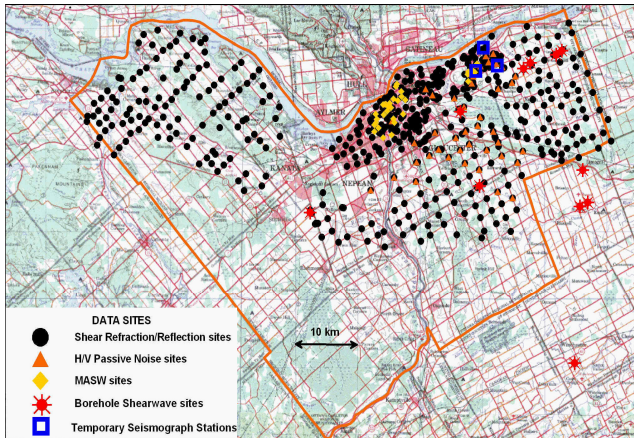
6. ACKNOWLEDGEMENTS

Figure 8. Location of seismic measurements within the city of Ottawa as of January 2008. More sites are planned for the final year of the project.

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