Shear Wave Velocity Measurements for Soft Soil Earthquake Response Evaluation in the Eastern Ottawa Region, Ontario, Canada

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ABSTRACT

The new National Building Code (NBC, 2005) of Canada has been amended to improve predicted earthquake accelerations on soil and rock sites. As a basis, such estimations utilize the description of soils and rocks as given by the zones defined by the National Earthquake Hazard Reduction Program (NEHRP) of the U.S.A.; these zones are primarily based on the measured travel-time-weighted average shear wave velocity of a site from surface to a depth of 30 m (Vs_{30}). NEHRP zone maps are being considered for major cities in high earthquake hazard zones in Canada. As a demonstration project, a combined research team from Carleton University and Geological Survey of Canada are surveying the Ottawa, Ontario area. Within the city boundaries, NEHRP zones are estimated to vary between NEHRP A (firm bedrock) and NEHRP E (> 30 m of soft low Vs soil).

Although a substantial database of subsurface geological information has been previously compiled based on water-wells, geotechnical boreholes and shallow P-wave refraction seismic studies, very few subsurface Vs measurements of soil or rocks exist.

For this work, surface refraction/reflection methods are currently being applied in a reconnaissance manner throughout the study area to obtain regional estimates of average Vs profiles versus depth. The technique requires a 24-channel seismograph, a polarized shear wave surface source, and horizontal axis geophones oriented in SH mode. To date, approximately one half of the city has been surveyed with 184 surface seismic sites situated at approximate 2 km spacing interval or less. Many of the sites were positioned in city parks in densely urbanized areas, and along roadsides in suburban regions. As expected, high Vs_{30} values (> 2000 m/s) have been obtained in areas of thin overburden overlying Paleozoic bedrock, and very low Vs_{30} values (<180 m/s) have been obtained in areas of thick Holocene clay. In addition, a buried bedrock valley filled with soft sediments has been identified and delineated for future 3-dimensional resonance studies.

INTRODUCTION

In the autumn of 2005, the National Building Code of Canada (NBCC) was changed to reflect the growing body of knowledge on the response of soft soils to earthquake shaking. The approach taken by the NBCC followed the National Earthquake Reduction Program of the United States (NEHRP, 1994) recommendations with some modifications (Finn and Wightman, 2003). The NEHRP site classifications based on average shear wave velocity and/or other geotechnical parameters was adopted without change (see Table 1), whereas the short- and long-period amplification factors F_a and F_v were modified so that all values are 1.0 for the reference site class C for all intensities of shaking; these factors are summarized in Tables 2 and 3 after Finn and Wightman (2003) and annotated by John Adams (GSC, pers. comm., 2005) for various values of probabilistic spectral accelerations at two periods: short (T=0.2 s) and long (T=1.0s) respectively.

TABLE I

Site Classification for Seismic Site Response

Site Class	*Soil* Profile Name	Average Properties in Top 30 m as per Appendix A		
		Soil Shear Wave Average Velocity, V_s (m/s)	Standard Penetration Resistance, N_{60}	*Soil* Undrained Shear Strength, s_u
A	Hard *Rock*	V_s > 1500	Not applicable	Not applicable
B	*Rock*	760 < V_s 1500	Not applicable	Not applicable
C	Very Dense *Soil* and Soft *Rock*	360 < V_s < 760	N_{60} > 50	s_u > 100kPa
D	Stiff *Soil*	180 < V_s < 360	15 < N_{60} < 50	50 < s_u < 100kPa
E	Soft *Soil*	V_s <180	N_{60} < 15	s_u < 50kPa
E		Any profile with more than 3 m of *soil* with the following characteristics: • Plastic index PI > 20 • Moisture content w >= 40%, and • Undrained shear strength s_u < 25 kPa		
F	(1) Others	Site Specific Evaluation Required		

(1) Other *soils* include:
a) Liquefiable *soils*, quick and highly sensitive clays, collapsible weakly cemented *soils*, and other *soils* susceptible to failure or collapse under seismic loading.
b) Peat and/or highly organic clays greater than 3 m in thickness.
c) Highly plastic clays (PI > 75) with thickness greater than 8 m.
d) Soft to medium stiff clays with thickness greater than 30 m.

Table 2. Values of F_a as a Function of Site Class and T= 0.2 s Spectral Acceleration.

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Ottawa

Site Class	Values of F_a				
	Sa(0.2) ≤ 0.25	Sa(0.2) = 0.50	Sa(0.2) = 0.75	Sa(0.2) =1.00	Sa(0.2) = 1.25
A	0.7	0.7	0.8	0.8	0.8
B	0.8	0.8	0.9	1.0	1.0
C	1.0	1.0	1.0	1.0	1.0
D	1.3	1.2	1.1	1.1	1.0
E	2.1	1.4	1.1	0.9	0.9
F	Site specific investigation required				

Non-Linear effects on soft soils

Deamplification

Table 3. Values of F_v as a Function of Site Class and T= 1.0 s Spectral Acceleration.

Credit for better sites

Ottawa

Site Class	Values of F_v				
	Sa(1.0)< 0.1	Sa(1.0) = 0.2	Sa(1.0) = 0.3	Sa(1.0) =0.4	Sa(1.0) > 0.5
A	0.5	0.5	0.5	0.6	0.6
B	0.6	0.7	0.7	0.8	0.8
C	1.0	1.0	1.0	1.0	1.0
D	1.4	1.3	1.2	1.1	1.1
E	2.1	2.0	1.9	1.7	1.7
F	Site specific investigation required				

Non-Linear effects on soft soils

Less amplification

Significant earthquake hazard exists in eastern Canada (Adams and Halchuk, 2003). One particular region of interest is that encompassing highly populated area around Ottawa and Montreal, resulting from historical seismic activity associated with the West Quebec Seismic zone (See Figure 1a). The hazard is further accentuated by the presence of thick loosely consolidated post-glacial deposits formed by the post-glacial Champlain Sea (see Figure 1(b); these sediments are composed mainly of silty clays, silts and fine sands which were deposited in a marine or brackish-water environment and can reach measured thicknesses of 120 m. Water contents are unusually high, and where salt leaching of cohesive materials has occurred, the sediments are geotechnically sensitive and prone to retrogressive earth flow land-sliding or in-situ deformation when sheared to failure. Ample paleo-evidence exists of large scale earthquake-triggered ground deformation (Aylsworth et al, 2000).

The surficial geology map of the Ottawa area (population 1.09 Million people) shown in Figure 2 indicates significant areal extent of bedrock outcrop, glacial deposits as well as post-glacial (Champlain Sea) sediments. Hence within the Ottawa city limits ground conditions might vary between firm and very soft.

Prior to this current work, very little shear wave velocity information was available in the public domain, within the Ottawa-Montreal area (Hunter et al, 2006). Hence, only rough estimates of shear wave velocities can be associated with the three material types mentioned. This paper discusses the early phases of a survey of the Ottawa area to establish NEHRP site classification zones utilizing emerging near-surface seismic technologies and correlation of these results with an existing geological/geotechnical data base consisting of >28000 boreholes.

The new NEHRP-based NBCC emphasizes the importance of the travel-time weighted average shear wave velocity from ground surface to 30 m depth at a site, the so-called Vs_{30}. One of the main goals of the present work is to establish typical velocities or velocity-depth ranges for the three broad categories using combined shear wave refraction and reflection high-resolution techniques. As well, by strategic placement of geophysical test sites, the interpreted structural information can be used to improve the knowledge of 3-dimensional structure of the sediments in areas where borehole information is lacking. Future phases of the project will test other active and passive seismic techniques, including surface wave dispersion and background noise measurements in the development and field testing of 3-dimensional ground response modeling for typical subsurface surficial geological structure.

SEISMIC REFLECTION/REFRACTION METHODS

We have designed the seismic array geometry so that it can be used for both SH refraction and SH reflection surveying in the particular surficial geology structure within the Ottawa area as follows:

Commonly, the thickness of post-glacial sediments can range from a thin veneer to 30-40 m with extremes as much as 95 m. The glacial sediments (tills, and till-derived gravels and sand) beneath the post-glacial sediments are relatively thin in most areas (1-3 m) but tend to be slightly thicker (~5 m or more) in bedrock topographic lows. Where the glacial sediments outcrop on surface, the depth to bedrock is commonly shallow (~5 to 10 m). Bedrock at depth, or in outcrop consists either of Pre-Cambrian granite gneiss or lower Paleozoic dolostone, limestone, sandstone or shale.

Hence, the geophone array consisted of 24 horizontal 8 Hz geophones at either 3m or 5m spacing depending on the available space at a particular field site (see Figure 3). Seismic source positions were occupied at ½ and 1½ geophone spacings off each end of the array as well as a source location between geophone #12 and #13. For low shear wave velocity post-glacial sediments (100-200 m/s) overlying high velocity bedrock (~2300-3000 m/s) this geometry allowed sufficient trace-to-trace correlation of wide-angle reflections from bedrock (or top of glacial sediments) while also allowing sufficient source-geophone spacing to detect the bedrock refractor at depths to 30 m.

The seismic source consisted of a steel I-beam plate with one edge dug into the soil in SH orientation and a 10 lb neoprene hammer with electronic trigger. The data was recording using a Geometrics Geode seismograph.

Figure 4 (a) shows an example field record showing both refraction first arrivals in the overburden and bedrock as well as wide-angle reflections. Commonly there is a thin high-speed surface layer that interferes with the direct overburden wave near the origin. This is interpreted to be associated with either the roadbed (if the site is on the side of the road), or artificially consolidated surface materials in parks, etc. However, natural over-consolidation of the upper few meters of the Champlain Sea sediments has been found throughout the Ottawa area (Eden and Crawford, 1957), and may be associated with post-glacial paleo-freeze-thaw cycles when the seabed was exposed.

First arrival picks are made on the surface high velocity layer, on the main overburden refractor, and on the bedrock refraction (if visible as a first arrival) using Interpex IXSEG2SEGY software. The main overburden refraction event can be relatively weak if the surface high velocity layer is predominant (seismic energy trapped in the surface layer) and if lower velocity sediments occur beneath; on the other hand, the main overburden refraction can sometimes be picked to its farthest offset where higher velocities are evident, even though it occurs later in time than the bedrock refraction (not shown here). It has been our experience that higher velocities associated with the basal portion of the post-glacial sediments as well as the glacial sediments occur as "hidden" layers, due to the very high velocity contrast between the upper overburden and the bedrock velocities. Evidence for this can be seen where the bedrock refraction intercept time occurs later than the bedrock reflection intercept (see Figure 4b). A layered-case interpretation is shown here for the first arrival refractions; if the overburden arrival can be picked on a sufficient number of traces as a later event, velocity-depth conversion of the travel-time gradient using VELDEP (Hunter, 971) can also be made as well. Refraction velocities of the bedrock (as well as glacial sediments) provide important parameters required to estimate the primary impedance contrast for ground response modeling and to confirm depth estimates obtained from shear wave reflection analyses.

Time-averaged shear wave velocities, required for NEHRP zonation, are obtained from hyperbolic fitting of reflection travel times. The reflection-fitting algorithm contained in the IXSEG2SEY interactive software is used to obtain average velocity estimates of prominent reflectors visible on the field record. To enhance the reflection events, the record is commonly band-pass filtered and automatic gain control with varying window lengths is applied. The refraction interval velocity and reflection average velocity information is then merged on the same plot, as shown in Figure 4 (c).

SOME PRELIMINARY RESULTS

Although the project is on going at the time of writing, some preliminary results have been obtained. For the 2005 field season, we concentrated our surface seismic work on the eastern part of the Ottawa area where thick post-glacial sediments occur, as outlined in Figure 2. In the urban centers, we chose areas where seismic data could supplement the overburden structural variations given by the borehole data; for lower ambient seismic noise we were restricted to open areas (schoolyards and city parks) where we could lay out the array without being in the immediate area of high-traffic roads. In rural areas, we worked along the edges of roads and did our recording in between passage of vehicles; here we spaced the sites more uniformly to obtain regional estimates of average velocity-depth values. The locations of shear wave seismic sites as well as existing borehole information is shown in Figure 5. To date 184 seismic sites have been occupied.

In the suburb of Orleans in the northeastern portion of the city, the borehole information indicated that a substantial bedrock depression might exist, although there was no indication of it from the surface topography. The occurrence of such a structure is of interest since the area associated with the buried valley could be the source of anomalously large and complex ground motion during earthquake shaking. We strategically placed our shear wave sites so as to fill in spaces in the borehole distribution as well as to provide us with velocity information for future ground response modeling. The location of the detailed work is shown in Figure 5 and the resultant overburden thickness map, from combined borehole and seismic information, is shown in Figure 6.

Cross-sections of the bedrock depression shown in Figure 7 indicate an elongate valley with very steep sides; if this bedrock topography is part of a pre-existing inter-glacial river system, the valley depth would be approximately 3 times that of the Niagara River gorge. Figure 8 shows a plot of average velocity versus depth for the post-glacial sediments filling the “Orleans valley” obtained from interpretation of seismic data in the area.

CONCLUSIONS AND DISCUSSIONS

A reconnaissance field program consisting of strategic shear wave velocity refraction-reflection sites is being conducted in the Ottawa area to measure the shear wave velocity structure of the unconsolidated overburden. To date, the eastern portion of the city has been examined, where areas of thick post-glacial soft sediments occur. Although NEHRP zonation is not yet complete, since data is currently being processed, from preliminary examination of field results, it is possible that NEHRP zones A through E and F occur. A significant buried bedrock valley has been outlined by a combination of borehole and seismic information; the necessary parameters of valley shape and shear wave velocity structure have been obtained for future input to 3-dimensional earthquake ground response modeling.

Plans for the 2006 field season include: short and long duration passive monitoring of select sites (including the Orleans valley) to obtain representative variations in values of fundamental site periods across the area, occupying shear wave seismic sites in the western portion of the Ottawa area, and testing of MASW techniques at selected sites.

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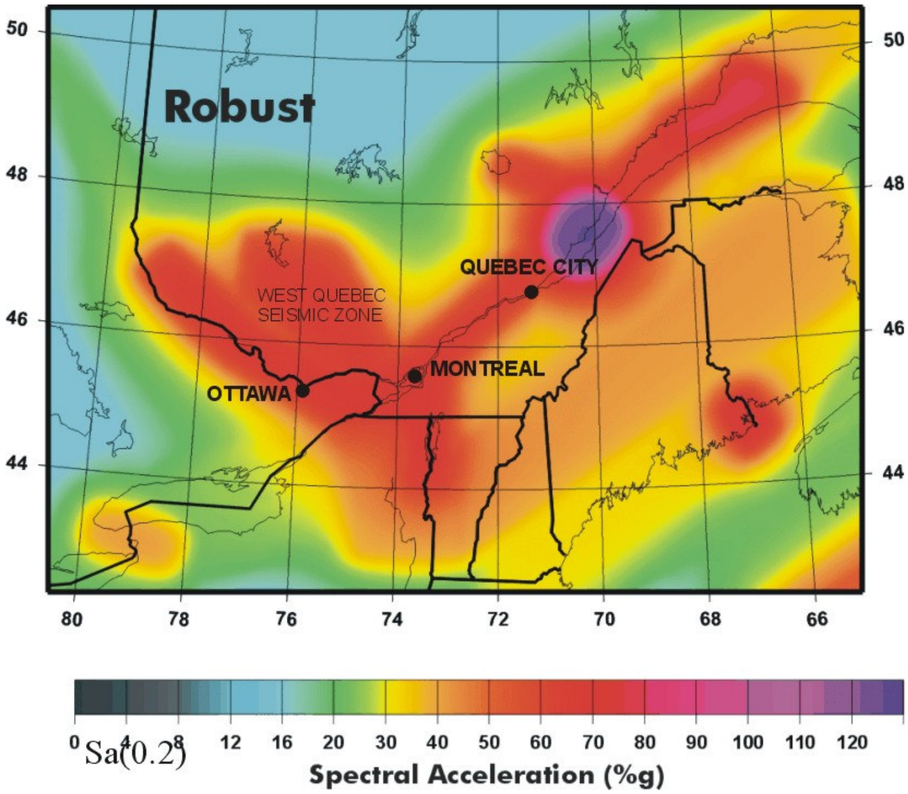

Figure 1(a) Probability of exceedence of 2% in 50 years for 5% damped pseudoacceleration at a period of 0.2 seconds for NEHRP class C in the West Quebec Seismic zone, which includes the Ottawa region study area (after Adams and Halchuk,2003).

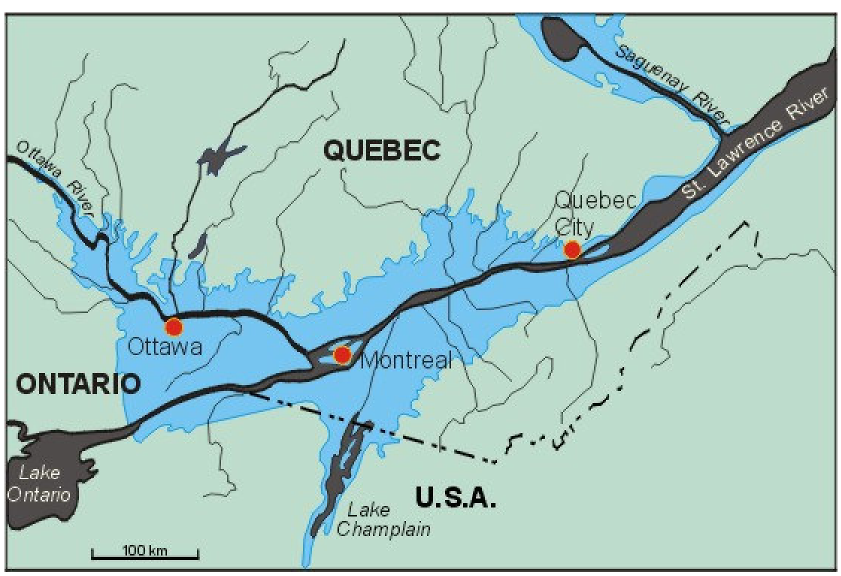

Figure 1(b). Areal extent of Champlain Sea, much of which is covered by soft sediments.

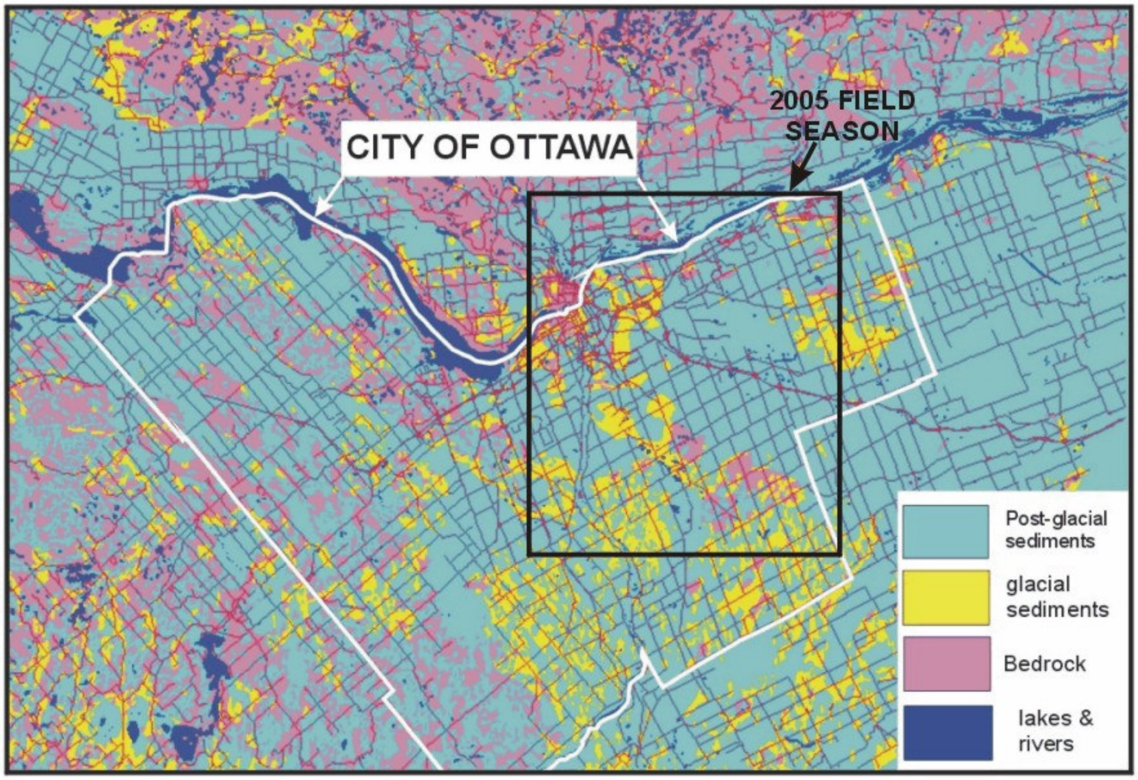

Figure 2. Simplified surficial geology of the Ottawa region. Post-glacial sediment are usually soft, and glacial sediments are relatively firm. Bedrock consists of firm Precambrian granite gneiss or competent lower Paleozoic rocks.

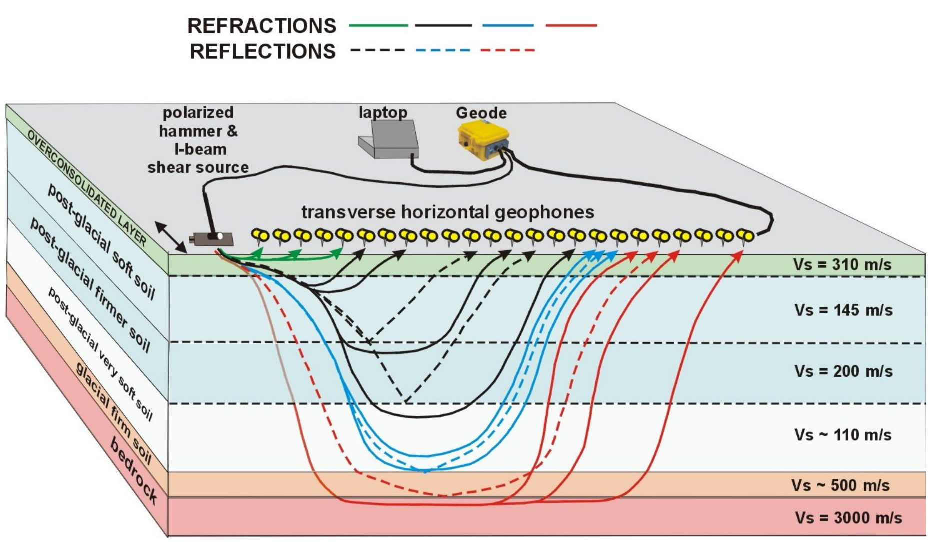

Figure 3. Shear wave seismic wave propagation through a typical overburden section in the Ottawa area. Refractions are shown as solid lines; wide-angle reflections are shown as dashed lines. Note the effect of a high velocity surface layer. The glacial sediments constitute a “hidden” layer.

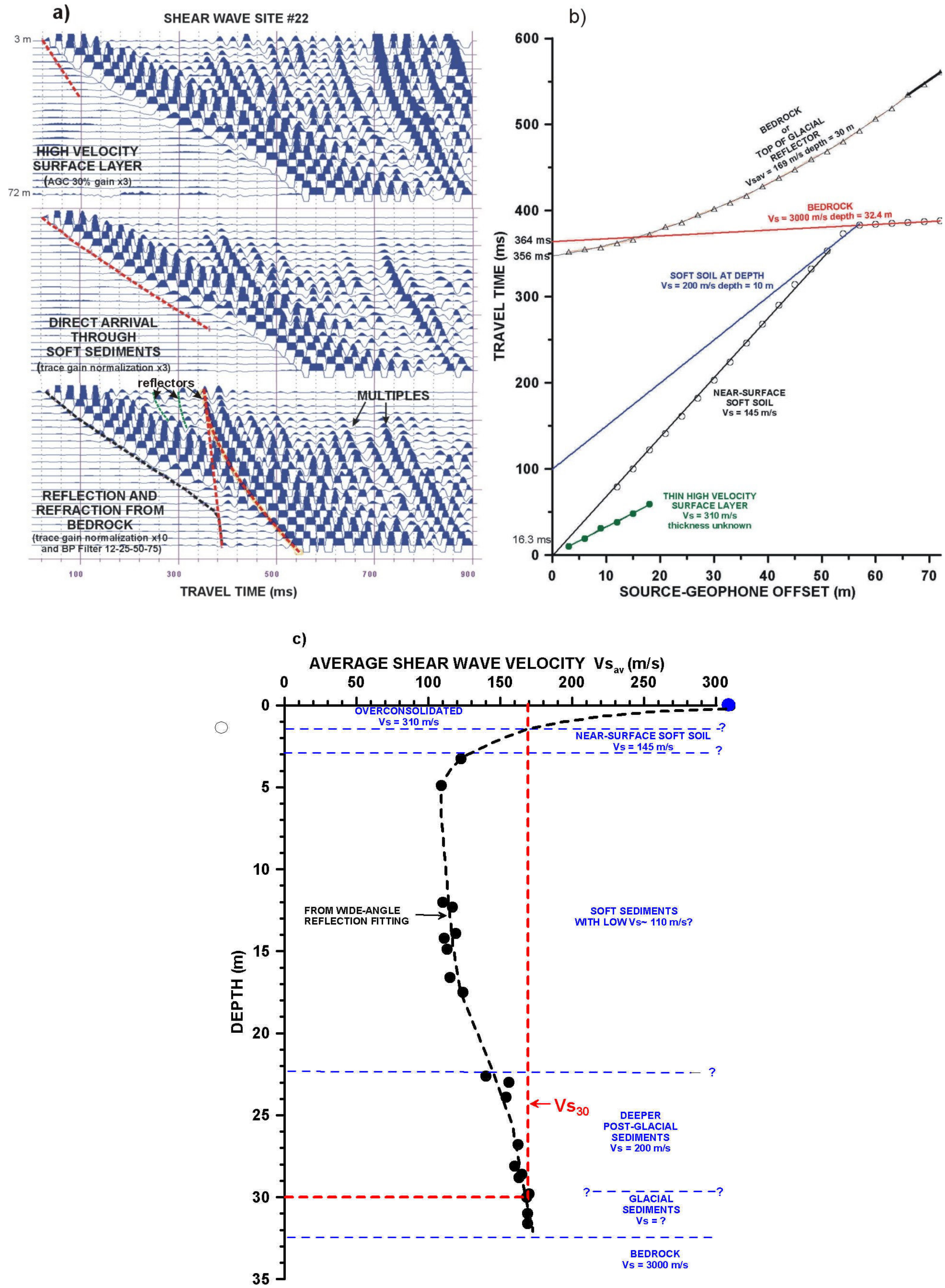

Figure 4. Shear wave seismic interpretation at a shallow bedrock site: a) field record displayed with differing gain settings, b) refraction first arrivals and main reflection event, c) combined refraction and reflection velocity model.

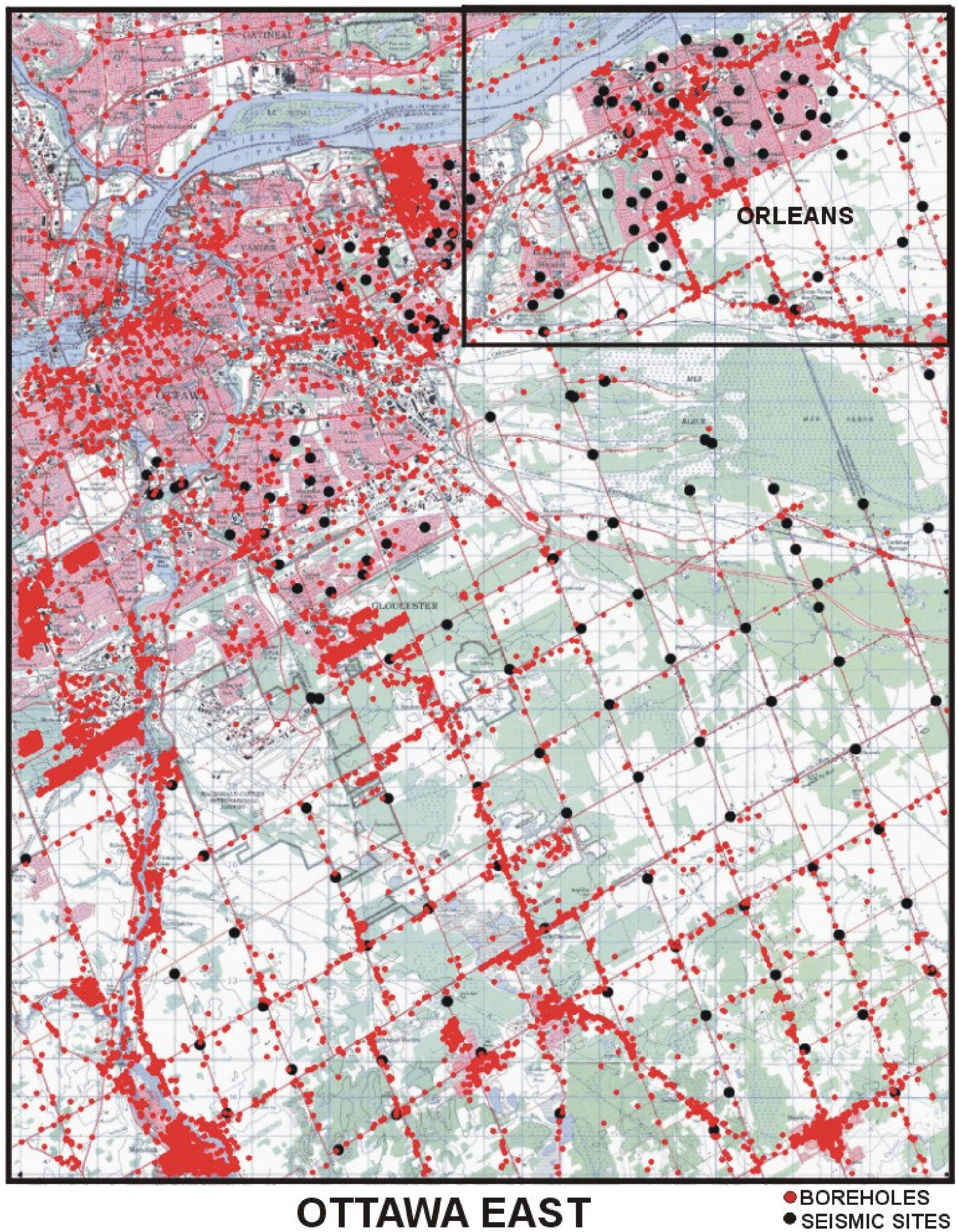

FIGURE 5. Locations of boreholes and seismic shear wave sites obtained during the 2005 field season. Seismic sites in urban areas were located in city parks.

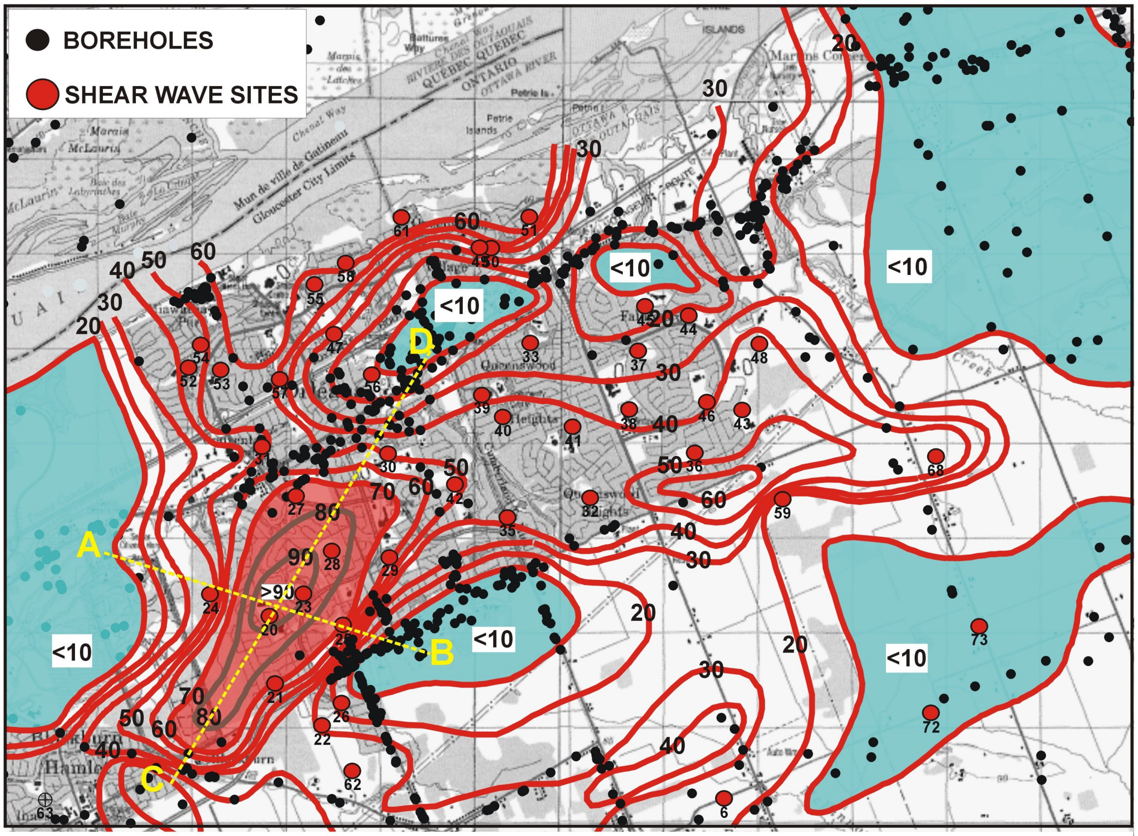

Figure 6. Overburden thickness in metres in the Orleans suburb of Ottawa, based on combined borehole and shear wave seismic site measurements.

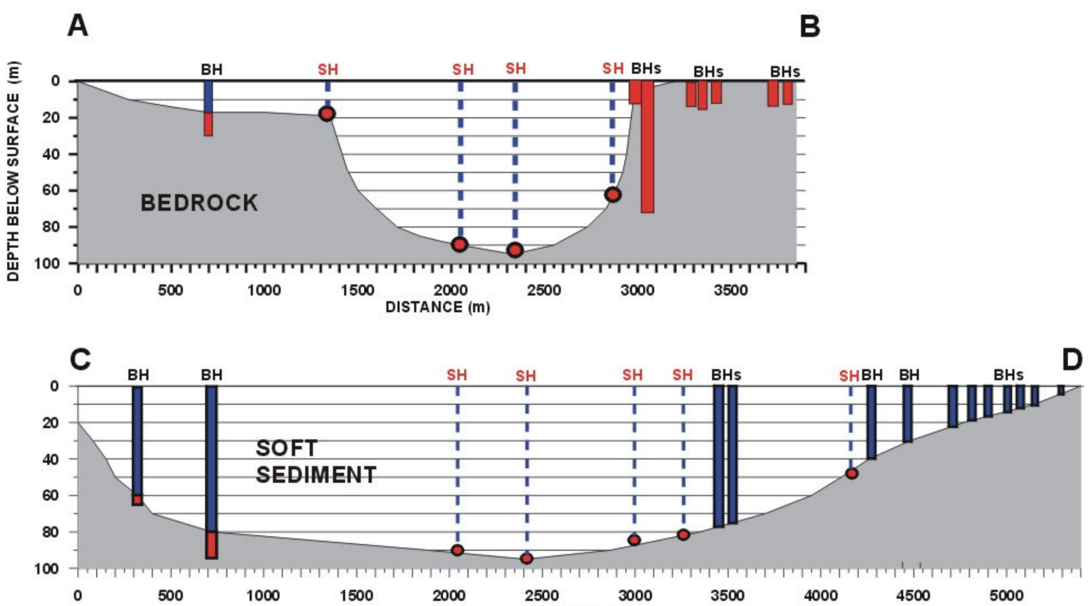

Figure 7. Transverse and longitudinal cross sections of the Orleans buried valley with a vertical exaggeration of ~10:1.

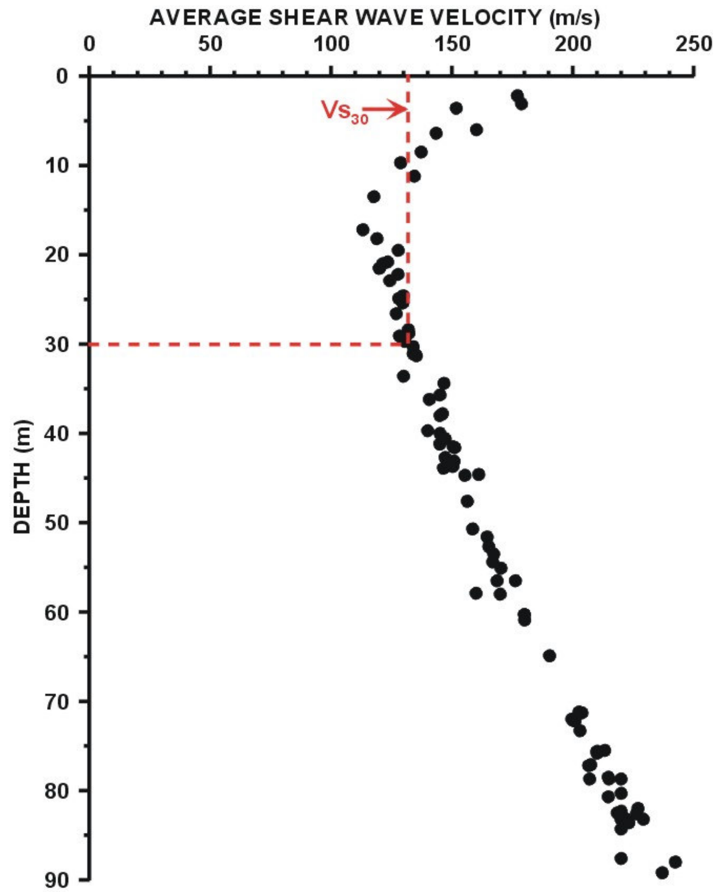

Figure 8. Travel-time-weighted average Vs values for measurements made in post-glacial soft sediments in the Orleans suburb of Ottawa. Note near-surface high velocities interpreted to be associated with over-consolidated sediments.