Development of V_{s30} and Fundamental Site Period Maps for Seismic Hazard Estimation in Ottawa, On

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ABSTRACT

In spring of 2009, the Geological Survey of Canada, in partnership with Carleton University, released maps of the City of Ottawa that depict the distribution of 2005 National Building Code of Canada (2005 NBCC) seismic site categories (A through E) and fundamental site periods across the city. The maps were compiled using subsurface geology derived from 28,000 boreholes, and shear wave velocity (V_s) data from 685 reflection/refraction sites, 25 kilometres of shallow seismic landstreamer data, and nine downhole V_s logs. The seismic site categories map has a borehole database at its core, and was compiled by applying V_s-depth functions derived from shear wave reflection surveys to post-glacial deposits, and V_s ranges for glacial deposits and bedrock. These relationships allow for each borehole record to be converted into a shear-wave velocity profile, whereby the travel-time-averaged V_s for the upper 30 m of the ground surface (V_{s30}) could be determined for each borehole site. Fundamental site periods were calculated using the 2005 NBCC equation of $4*h/V_s$, where h is the depth to 'firm ground', or the primary impedance contrast in the stratigraphic sequence, and V_s is the average shear wave velocity at this depth. To produce the map products, GIS techniques were applied to the spatial interpretation of the complex dataset. Targeted end users of the map are the geotechnical engineering community and municipal officials for emergency preparedness and land use planning purposes.

RÉSUMÉ

Au cours du printemps 2009, la Commission géologique du Canada, en partenariat avec l'Université Carleton, a publié des cartes de microzonage de la ville d'Ottawa illustrant la répartition des périodes fondamentales de zone et des catégories (de A à E) de zone sismique du CNB de 2005. Ces cartes ont été dressées d'après de données géologiques de subsurface recueillies à partir d'au moins 25 000 trous de forage, de données sur la vitesse d'ondes transversales (Vs) recueillies depuis 680 sites de réflexion et de réfraction, ainsi que de données sismiques recueillies à faible profondeur sur 25 km avec un système de géophones de type landstreamer. La carte des catégories de zone sismique est fondée sur une base de données sur les trous de forage et a été dressée en appliquant des fonctions de vitesse-profondeur tirées de levés mesurant la réflexion d'ondes transversales depuis des sédiments postglaciaires, ainsi qu'en utilisant des plages de vitesse liés à des sédiments glaciaires et au substratum rocheux. Les liens établis permettent de transformer chaque forage en profil de la vitesse des ondes transversales, afin de déterminer pour chaque site de forage une vitesse pondérée en fonction du temps de déplacement pour les 30 m supérieurs de la surface (Vs_{30}). Les périodes fondamentales de zone ont été calculées d'après l'équation $4*h/Vs$ du CNB de 2005, selon laquelle « h » correspond à la profondeur du « terrain résistant » ou au contraste d'impédance principal de la séquence stratigraphique et « Vs », à la vitesse moyenne des ondes transversales à cette profondeur. Les produits cartographiques ont été élaborés en appliquant des techniques de SIG à l'interprétation spatiale du jeu de données complexe. La carte a pour utilisateurs finaux principaux des ingénieurs géotechniques et des responsables municipaux chargés de la préparation aux situations d'urgence et de la planification de l'utilisation des terres.

1 INTRODUCTION

The factors which influence the ground motion at a site during an earthquake include site location relative to the source(s), the seismicity of the source(s), the wave travel paths to the site, and the site effects controlled by the near-surface geological conditions. The presence of thick accumulations of soft soils overlying the bedrock can greatly amplify ground motions caused by earthquake shaking. The 2005 National Building Code of Canada (NBCC, 2005) defines amplification at a site primarily in terms of a V_{s30} value, which is the travel time-weighted average shear wave velocity profile through the top 30 metres of the ground. The 2005 NBCC adopted the descriptions of soils and rocks given by the National Earthquake Hazard Reduction Program (NEHRP) of the United States, wherein five zones (A through E) are classified based on ranges of V_{s30} values (Table 1).

This paper provides an overview of the methods used to produce V_{s30} and fundamental site period (FSP) maps of Ottawa, where thick deposits of Champlain Sea sediments (Leda Clay) are known to overlie thin glacial deposits and bedrock. The maps have a 28,000 borehole database at their core, and were compiled by applying shear wave velocity-depth functions derived from shear wave (V_s) reflection surveys to post-glacial deposits, and V_s interval velocities of glacial deposits and bedrock.

Surface seismic surveys were conducted at 685 sites across the city by the Geological Survey of Canada (GSC) and Carleton University over four field seasons. This work represents a contribution to the Reducing Risk from Natural Hazards Program of Natural Resources Canada (NRCan), and maps, details of the work, and data appendices can be found for download in the Open File report by Hunter et al., 2009: (http://esic.ess.nrcan.gc.ca/screens/gscpubs-eng.html).

Table 1. V_{s30} site classification for seismic site response as defined by NEHRP (1994) and adapted by the 2005 NBCC (Finn and Wightman, 2003).

Site Class	Generic Description	Range of Vs_{30}
A	Hard rock	>1500 m/s
B	Rock	760 – 1500 m/s
C	Very dense soil and soft rock (Firm horizon)	360 – 760 m/s
D	Stiff Soil	180 – 360 m/s
E	Soil profile with soft clay	<180 m/s
F	Site specific geotechnical investigation required	

2 STUDY AREA

The study area is situated within the Ottawa-St Lawrence Lowlands, which were inundated by the Champlain Sea between approximately 12000 and 10000 years BP (Figure 1). The underlying bedrock is composed of Paleozoic sedimentary limestone, dolostone, shale and sandstone, which overlie Precambrian crystalline basement rock. Late Quaternary deposits generally consist of glaciogenic gravel, and diamicton (till) that underlie glaciomarine silty clays and pro-delta silts deposited within the Champlain Sea. The Champlain Sea deposits are locally known as 'Leda clay' and are composed of glacially-ground, non-clay minerals held together in a loose structural framework (Torrence, 1988). These materials can be geotechnically sensitive, and if disturbed, can lose strength and collapse. Within this report, all geologic materials have been classified as either 'post-glacial' (i.e. Champlain Sea deposits), 'glacial', or 'bedrock', based on differing shear wave characteristics in each of these units.

The thickness of post-glacial sediment in the Ottawa area ranges locally from a thin surface veneer (<1m thick) to over 100 m thick where it has accumulated in bedrock depressions and valleys. Glacial sediments are generally thin (1-3 metres thick), but may be thicker (>5 m) within bedrock depressions.

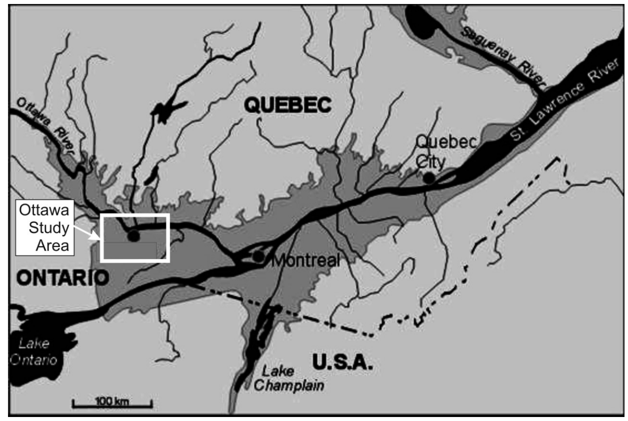

Figure 1. Extent of Champlain Sea deposits within the St. Lawrence Lowlands.

2.1 Seismic Setting

The Ottawa area is subject to local seismic activity originating from the Western Quebec Seismic Zone (Adams and Basham, 1989). The occurrence of two major paleo-earthquakes in the immediate Ottawa area at approximately 7060 and 4550 yr BP has been inferred by Aylsworth et al. (2000), based on the coincidental radiocarbon ages of a cluster of large-scale earthflows in the Bourget, Ontario area, and the presence of heavily disturbed fine-grained marine silt and sand deposits near Lefaivre, Ontario, 20 and 50 km east of Ottawa respectively. The disturbed deposits exhibit irregular surface subsidence, minor lateral spreading, and sediment deformation to a depth of 50 m. Although earthquakes measured in the Ottawa area between 1980 and 2000 generally recorded magnitudes between M2.0 and M4.0, the magnitudes of these paleo-earthquakes are estimated at M6.5 or higher (Adams, pers. comm.), indicating that the region has been subject to high magnitude earthquakes in the past (Aylsworth and Hunter, 2004).

3 METHODOLOGY

3.1 Seismic Reflection/Refraction Methods

Data were collected at 685 surface reflection/refraction sites across the city between the 2004 and 2008 field seasons (Figure 2). At each location, a 24-channel array of 8-Hz horizontal axis geophones oriented in horizontal shear (SH) mode was laid out at either a 3 metre or 5 metre spacing. Geophone separation was influenced by the space available at each site, and the inferred depth to bedrock based on a review of available borehole logs in the vicinity. The seismic source consisted of a steel I-beam plate with one edge dug into the ground in SH orientation and a 10-lb hammer connected to a piezometric trigger system. The data were recorded using a Geometrics Strataview or Geode seismograph. Source points were chosen at 1 and 1½ geophone spacings off each end of the array, and one centre shot was taken between geophones 12 and 13. This configuration allowed for trace-to-trace correlation of wide angle reflections from the glacial or bedrock interface, while permitting sufficient source-geophone spacing to detect the bedrock refractor at depths up to 30m.

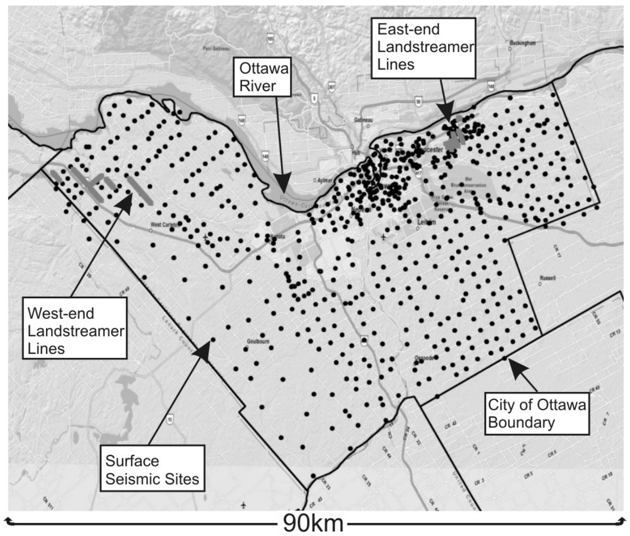

Figure 2. Location of 685 shear wave reflection/refraction sites and 25 line-km of landstreamer data within the city.

Picking and analysis of the first arrivals from the records was carried out using the Interpex IXSEG2SEGY software. This software allows the interpreter to use a variety of bandpass filters and gain enhancements, including AGC, trace max, and user specified constant gains to enhance different features in the record. The most prominent event on the sections is generally the direct arrival through the Champlain Sea sediments, or 'post-glacial' materials. The refraction from bedrock and/or till surface, if visible as a first arrival, can generally be brought out by increasing gain levels to heighten the trace amplitude. Forward and reverse arrival data were analysed separately and time-distance slopes were inverted to estimate interval velocities and t_o intercept times for each layer (Figure 3a). Interval velocities and intercept times determined from the refraction interpretation were used to calculate layer thickness of the units lying above the bedrock.

Prominent reflections observed on the seismic records were fitted with hyperbolic curves using the IXSEG2SEGY software. The reflection fitting algorithm provides a t_o, average velocity, and depth value for each reflector fit. Average velocity and depth values were copied to a spreadsheet and used to produce velocity-depth charts. If firm ground was sufficiently deep (i.e. >30m), V_{s30} could be interpreted from this graph directly. In areas of relatively thick Champlain Sea deposits, two prominent (i.e, high-amplitude) reflection events were often observed, and have been interpreted as glacial material overlying the bedrock surface. The sharp impedance contrast between the post-glacial soils and the glacial tills produces a high-amplitude reflection which may be more prominent than the reflection from the till-bedrock interface. Due to the compact nature of the glacial till and its high velocities (500 – 800 m/s), the glacial material is considered the 'firm' horizon and is not distinguished from the bedrock for the purposes of the site period calculation (Figure 3b).

By applying a time-weighted average calculation over the thicknesses derived from the refraction interpretations, the interval velocities were converted to average velocities and combined with the reflection data to produce an average velocity versus depth plot (Figure 3c) for each of the 685 sites. The V_{s30} value for each site is then easily determined from this database of shear wave velocity profiles (Figure 3c).

3.2 Borehole database and V_{s30} Calculation

The core of the V_{s30} and FSP maps is based on a digital borehole database containing stratigraphic information derived from a combination of borehole engineering logs and water well logs (Belanger, 1998). Each borehole log was reviewed and stratigraphic materials were classified as either 'post-glacial', 'glacial', or 'bedrock' units, based on the deposit description, stratigraphic position, and inferred depositional environment using the GSC's Surficial Materials and Terrain Features Map (Richard et al., 1978). This distinction between these units was made for the purpose of calculating a shear wave velocity profile at each borehole location.

To predict shear-wave velocities in the post-glacial soils at sites where geophysical surveys had not been carried out, velocity-depth relationships were developed on city-wide and site-specific levels. A city-wide velocity depth function was derived by compiling all the V_s reflection data from the surface seismic sites and nine downhole V_s logs in the 'post-glacial' sediments (5400+ data points from 150+ geophysical sites). The soft sediments are known to have a high velocity layer on surface, typically extending ~5m below surface. Eden et. al. (1957) identified this effect throughout the city and attributed it to post-glacial freeze thaw cycles when the seabed was exposed, or drying and cracking of the seabed in areas where marine sediments became raised. This velocity increase can also be seen in urban areas when surveys were performed on artificially consolidated roadbeds or areas containing fill, such as city parks. Due to the elevated velocities in the very near-surface materials, developing a curve to predict the shear wave velocity with depth would require the fitting of a complex polynomial function through the data. An important consideration for the average velocity-depth function was that it remain simple in form so that it could be easily applied widely in engineering practice. As the velocities presented in Figure 4 are average velocities, they show the average, or cumulative, velocity over a depth range and contain contributions from the measurements above. The average velocities at 10m already contain a contribution from the elevated velocities closer to the surface. Therefore, it was decided to simplify the curve fitting by using a linear fit through the data, creating a velocity depth function which is valid for Leda Clay sites with thicknesses of 10m to 100m (Eqn [1]). In this way, the effect of the elevated data could be taken into account at greater depths but the curve would be simpler in form.

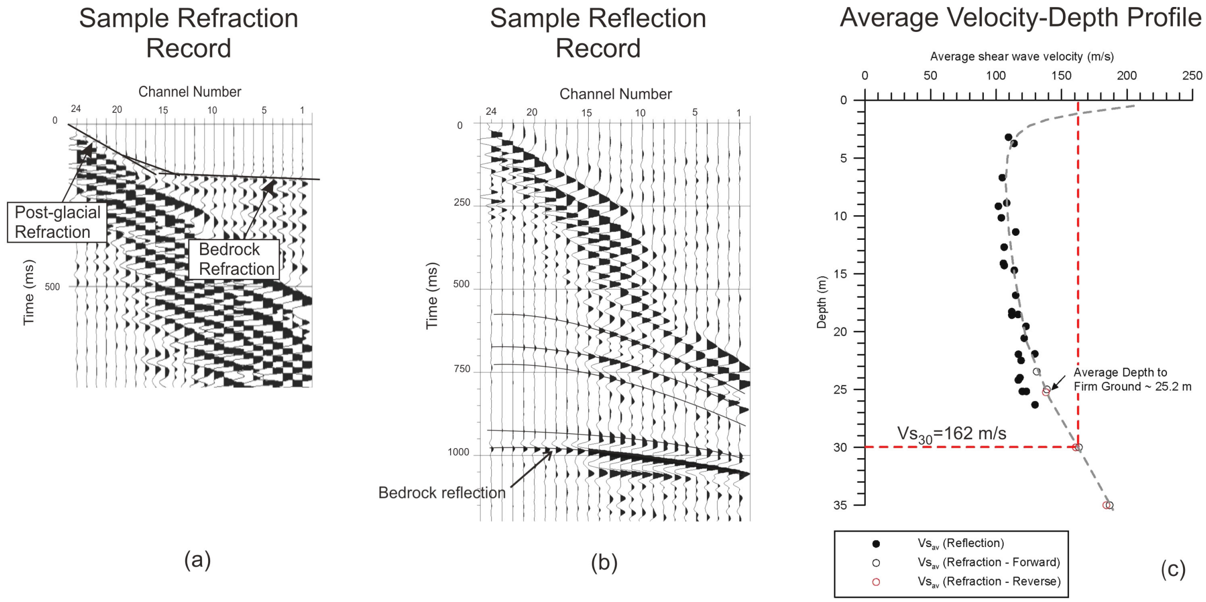

Figure 3. Sample seismic records (a) refraction interpretation from a shallow bedrock site and (b) reflection interpretation from a deep (80m) bedrock site. (c) Interpex software was used to interpret reflection velocities (closed circles) which were displayed directly on an average velocity-depth plot. Interval velocities derived form refraction interpretations were converted to average velocities (open circles) by applying a time-weighted average calculation. Results were combined to produce an average velocity versus depth plot down to 30m (example shown in from a site where the top of firm ground was determined to be 25 m).

This is our best estimate of a city-wide velocity-depth function applicable to Champlain Sea deposits.

$V_{s(av)}$=123.86 + 0.88$*$Z (+/- 20.3 m/s). [1]

To further refine the estimation of shear wave velocity as a function of depth, the reflection data from the seismic test sites were analysed one site at a time, creating 150 linear velocity-depth equations in areas of thickest Champlain Sea deposits within the city. Using these 150 relations, a unique velocity-depth function was determined for numerous borehole locations based on their spatial location from the geophysical site (or sites) within a specified search radius. This led to an improved estimate of variation in V_{sav} with depth in soft soil across the city. Where no geophysical sites were found within the borehole's search radius, the city-wide equation [1] was used.

For the 'glacial' and 'bedrock' units, interval velocities were calculated from the refraction data where breakovers were interpreted through the materials. With GIS software, the locations of the boreholes were intersected through the bedrock geology map to determine the type of bedrock below each borehole. These bedrock V_s values are made available in the GSC Open File published by Hunter et al, 2009.

By using a combination of an average velocity-depth equation (city-wide or site-specific) for the soft soil (post-glacial materials), interval velocities for the glacial and bedrock materials, and knowing the thicknesses of the stratigraphic units down to 30m from the borehole database, V_{s30} values were calculated at each borehole location (Figure 5). To provide a measure of potential variation of V_{s30} at each borehole location, upper and lower V_{s30} values were also calculated using plus/minus one standard deviation for glacial/bedrock units, and two standard deviations within the soft soil unit.

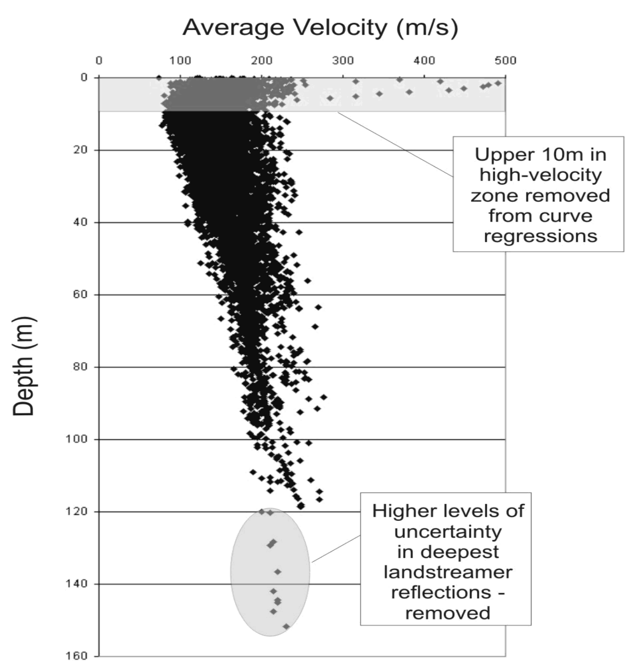

Figure 4 – City-wide reflection data collected in Leda Clay, used to develop average velocity depth function.

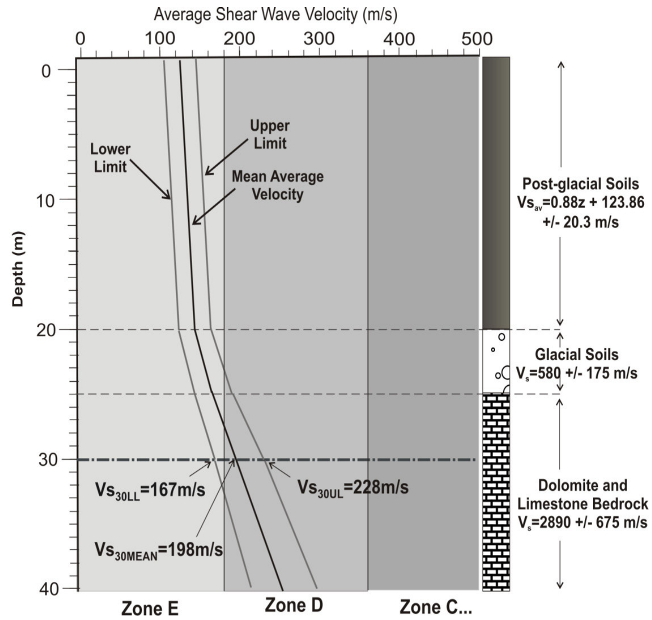

Figure 5. Typical average shear wave velocity profile for the Ottawa area, calculated using stratigraphic thicknesses provided by the borehole database. Average velocity-depth functions for the post-glacial materials are combined with interval velocities from the glacial and bedrock materials to calculate a travel-time weighted V_{s30} value. This calculation is repeated three times using the mean, upper, and lower velocity limits of the materials to provide a measure of error on the V_{s30} value. It is not uncommon to have the upper and lower ranges straddle two seismic site categories as shown in this figure.

3.3 Landstreamer Lines

Shallow seismic reflection techniques using a vibratory source and landstreamer receiver array are well suited for collecting seismic data in urban environments. Towing an array of geophones behind a vehicle avoids the need to plant geophones in busy urban areas, and data collection can be achieved more quickly than with conventional roll-along methods. Up to 3 line-km/day of reflection data can be obtained with this data acquisition system (Pugin et al. 2007). The vibrating source (‘Minivib’) transmits a swept-frequency wave of 6 to 7 seconds duration into the ground which is cross-correlated with the theoretical input sweep or a measured sweep pulse on the vibrating plate. The frequency and duration of the signal and array length can be changed in order to optimize the parameters for various near surface velocity characteristics and depths of investigation.

Twenty-five line km of landstreamer data were collected over the 2006 to 2008 field seasons along alignments where complex bedrock topography was known to exist in the east and west ends of Ottawa. Shear wave reflection sections indicate various seismic impedance contrasts at depth as well as significant lateral changes in V_s within the post-glacial and glacial sediments. Commonly the most prominent reflector on the section is the top of bedrock, or the surface of glacial sediments in areas where significant till overlies bedrock. Figure 6 displays a seismic section collected over an area of deep (>60m) soft sediments overlying a highly variable bedrock surface. A model of average shear wave velocity allows for a V_{s30} profile to be calculated along the survey alignment. This technique was extremely effective in identifying areas of rapid variation of average velocity due to anomalous subsurface bedrock topography.

4 RESULTS

4.1 V_{s30} and NEHRP Classification

The database of shear-wave velocity depth information determined for the Ottawa area from surface seismic sites, landstreamer lines, and downhole geophysical logs, and estimated for the 28000+ boreholes was used to produce a V_{s30} map for the Ottawa area (Figure 7). The V_{s30} map is presented using contours based on the NEHRP site classification categories shown in Table 1. Due to the improved definition of post-glacial soil thickness contributed by the seismic surveys and landstreamer lines, a greater area of the map falls into Zone E (<180m/s) than was previously identified by the borehole dataset alone. Look-up tables in the 2005 NBCC provide the amplification factors (based on NEHRP Zones A - E) for spectral acceleration at periods of 0.2 sec and 1.0 sec at a site.

4.2 Fundamental Site Period (FSP) Estimation

The fundamental period (T) of a soft soil site approximates the period of vibration at which the greatest soil amplification is anticipated (Kramer, 1996). The motions experienced by a structure during an earthquake can be amplified significantly when the natural resonance period of the structure matches (or approaches) that of the underlying ground. In the approach used by the 2005 NBCC, the period is governed by the main seismic impedance contrast caused by the post-glacial-to-glacial or post-glacial-to-bedrock boundary, and is given by:

$$T=(4*Z) / V_{s(av)} \qquad [2]$$

where Z is the depth to the boundary, and $V_{s(av)}$ is the average velocity of the overlying post-glacial sediments. The basic assumptions for equation [2] are that a single shear wave velocity layer represents the total soft soil column, and that this equation is valid for small strains in the linear range. Figure 8 presents the results of site period calculations carried out at all borehole (28000+) and seismic test site locations (685) using the shear-wave velocity-depth information described in this paper. The FSP calculations for the City of Ottawa area are depicted in five ranges between 0.1 and 2.0 s. Figure 8 shows that the majority of the city falls within the 0.1-0.4s range, which coincides with the areas of thin to negligible overburden. The ranges >1.0 sec coincide with the seismic site class E, which reflect locations of greater overburden thickness.

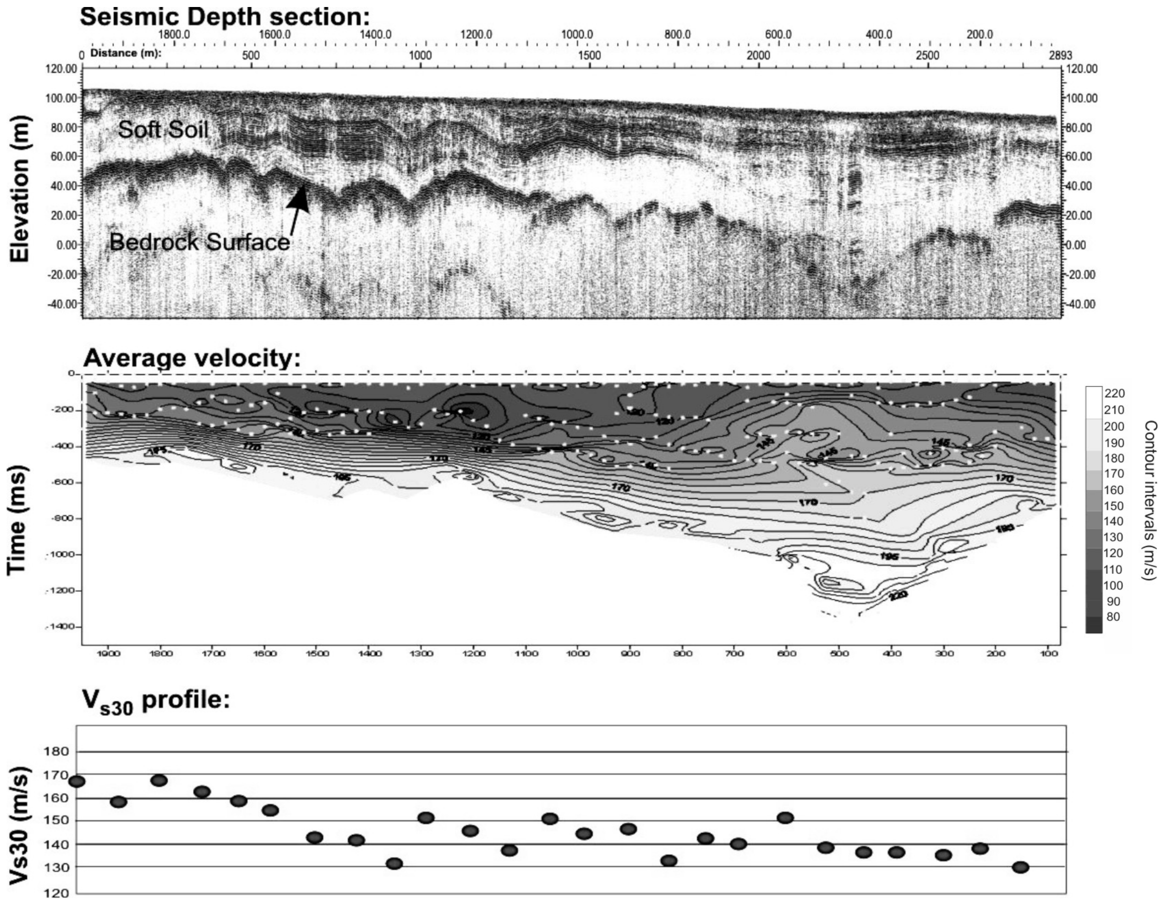

Figure 6. A shear wave "Landstreamer" seismic section along Highway 17 near Arnprior, Ontario (upper panel) showing the bedrock topography as well as stratigraphic structure within the soil. Average shear wave velocity variations within the postglacial Champlain Sea sediments (central panel) have been determined from velocity analyses of the multi-channel reflection data. A V_{s30} 'profile' can be computed from the average velocity section (lower panel).

Ongoing research at the GSC is also investigating FSP estimation using the principles of Nakamura's method, introduced in 1989. This approach estimates the fundamental site period, T_0, or site frequency, f_0, using ambient seismic noise in the same frequency range as earthquake energy (Nakamura, 1989). The ratio of spectral horizontal-to-vertical motion (HVSR) can indicate a peak frequency equivalent to the resonant frequency. Comparison of the results from both methods indicates different fundamental periods in the later times (>1.5 seconds). Therefore, the reader is cautioned that the calculated values from the single layer approximation as shown on the map (Figure 8) should be only utilized as a guide to areas where significant long period fundamental resonance can occur. Further details of these results can be found under Hunter et al., 2009.

5 DISCUSSION AND FUTURE WORK

Amplified seismic ground motions from a modest- to large-scale earthquake are of concern in large, soft-sediment filled basins. The identification and delineation of numerous bedrock depressions across the city from this work highlights the value of carrying out surface geophysical surveys when creating microzonation maps of cities in high and moderate earthquake risk zones. Shear wave seismic surveys fill in gaps between boreholes and provide broad coverage of geological trends in the soil and bedrock surface using non-invasive, cost-effective methods. The seismic site surveys and landstreamer reflection profiles provide shear wave velocity data down to important impedance boundaries. By using these methods and extending the shear-wave estimates to the extensive borehole database, the GSC has developed a shear wave database of Ottawa which extends from surface down into the bedrock. This database forms a critical input for current and future assessments of seismic hazard in the area.

Studies comparing weak-motion ground response from small local earthquakes at a deep soil site in Heritage Park, Orleans, and a bedrock site 1.5km away indicates that amplification in Champlain Sea deposits is higher than predicted by NEHRP-based amplification factors for strong motion (Figure 9). The unusual observed broad band weak-motion amplification and the nonlinear behaviour between weak-motion and strong-motion

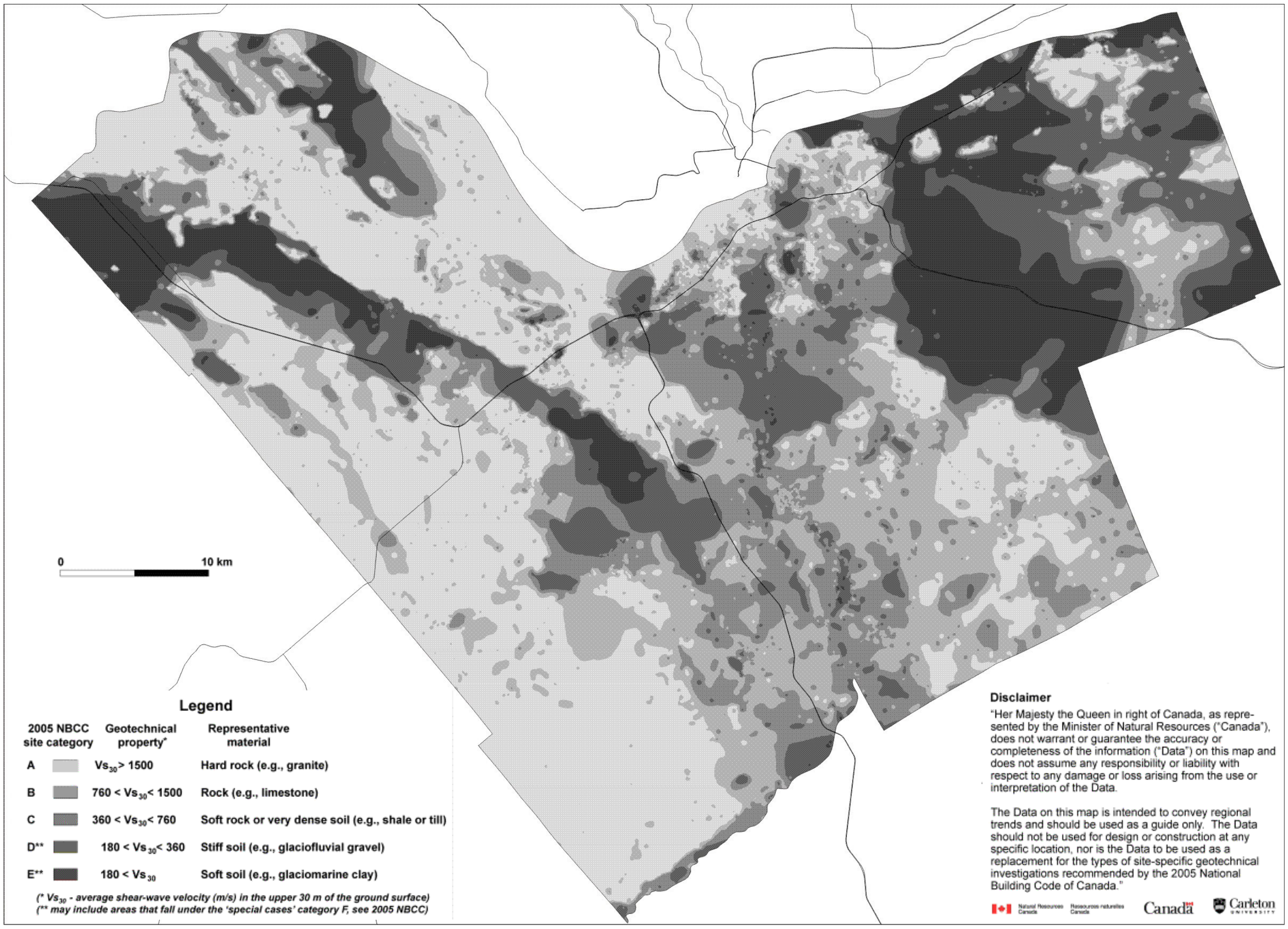

Figure 7. V_{s30} map produced from the database of shear-wave velocity-depth information discussed in this paper, depicting the distribution of 2005 NBCC seismic site classes across the City of Ottawa (see Table 1). This map is available in color for download from the NRCan website.

records remains an unresolved problem. The high impedance contrast between the Champlain Sea deposits and the bedrock in the Ottawa area is likely a strong contributing factor to this site amplification (Motazedian, 2007). Research is being carried out by the GSC and Carleton University to address these issues.

6 DISCLAIMER

Her Majesty the Queen in right of Canada, as represented by the Minister of Natural Resources ("Canada"), does not warrant or guarantee the accuracy or completeness of the maps and other data and information ("Data") contained in this report and does not assume any responsibility or liability with respect to any damage or loss arising from the use or interpretation of the Data.

The Data in this report is intended to convey regional trends and should be used as a guide only. The Data should not be used for design or construction at any specific location, nor is the Data to be used as a replacement for the types of site-specific geotechnical investigations recommended by the 2005 National Building Code of Canada.

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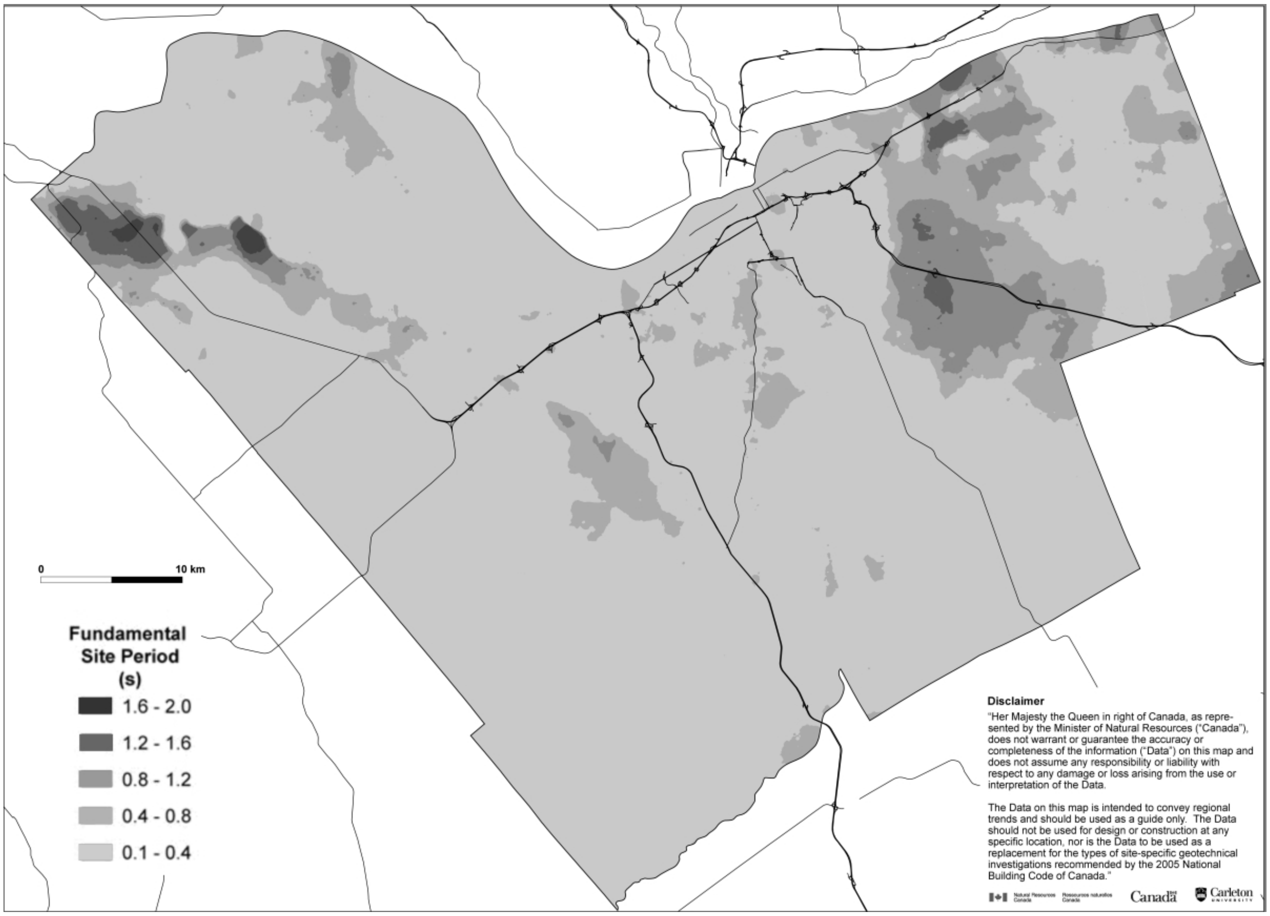

Figure 8. Map depicting ranges of calculated fundamental site period within the City of Ottawa. This map is available in color for download from the NRCan website.

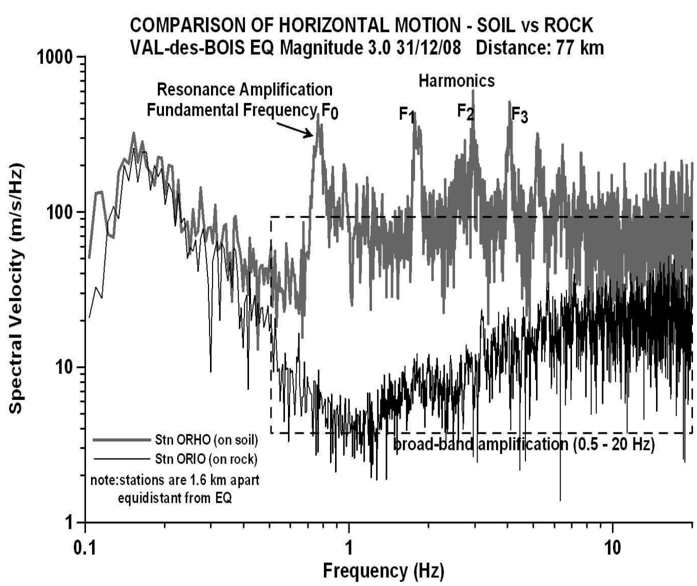

Figure 9. Comparison of spectral velocities computed from recordings of a 2008 earthquake (Val-des-Bois, M3.0, 77km N) showing broad band amplification in Orleans on rock (black) and soil sites (grey), separated by 1.5 km.

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