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SEISMIC MICROZONATION OF MONTREAL AND OTTAWA, CANADA

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ABSTRACT

In regards to regional population and seismic hazard, Montreal and Ottawa are ranked second and third, respectively, behind Vancouver. Major portions of both cities are underlain by very soft, low shear velocity, postglacial sediments that, in turn, overlie very high shear velocity glacial till or bedrock, resulting in extremely high seismic impedance contrasts at shallow depths. In order to provide reliable and robust shear wave velocity-depth profiles within the study areas, several methods including seismic refraction/reflection, multi-channel analysis of surface waves (MASW), horizontal-to-vertical ambient noise spectral ratios (HVSR), borehole measurements and high-resolution seismic shear wave reflection profiling have been applied. The high impedance contrast between sediments and firm bedrock allows refracted and reflected shear waves, as well as surface waves, to be interpreted from engineering seismic records, leading to reliable shear wave velocity-depth profiles for soil site classification.

In Montreal, potential soil site amplification on a local scale has been estimated using fundamental resonance frequencies and amplitudes from microtremor HVSR techniques. In Ottawa, estimates of the shear wave velocity from the ground surface to a depth of 30 metres (Vs_{30}) have been obtained using surface shear wave refraction/reflection site analyses. In both cities, MASW, downhole shear wave measurements, and high-resolution Minivib/landstreamer shear wave reflection profiling has been done to obtain shear wave velocity-depth functions for correlations with other methods. As well, extensive borehole databases of unconsolidated overburden materials, as well as bedrock, have been developed for both cities: these serve as the framework on which the regional hazards models were developed.

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1. INTRODUCTION

Major cities in the St. Lawrence lowlands of Eastern Canada, such as Montreal and Ottawa, are mainly located on loose postglacial sediments with very low shear wave velocities (<200 m/s) overlying very firm bedrock with high shear wave velocities (>2000 m/sec) (Hunter et al., 2007). The potential for seismic soil amplification is one component considered in the specifications for earthquake design loads in the 2005 National Building Code of Canada (NBCC) (National Research Council of Canada, 2005). The NBCC seismic site classifications follow the system developed by the National Earthquake Hazard Reduction Program (NEHRP) in the 1990s for the United States (Building Seismic Safety Council, 1994; Building Seismic Safety Council, 1995). The NBCC (2005) emphasizes the importance of the travel time weighted average shear wave velocity from the ground surface to a depth of 30 metres, the so-called Vs_{30}. Recently, it has been recognized that V_{s30} may not represent the entire seismic soil amplification phenomenon, and there is a trend towards inclusion of the fundamental frequency/period of soil (f_0) in the calculation of seismic soil amplification factors (Abrahamson, 2009; Cassidy, 2009). This is particularly appropriate to the St. Lawrence lowlands, where large amplifications at the fundamental site period may be expected. Current research in Eastern Canada is focused on nonlinear soil response modeling, leading towards revised soil amplification factors.

2. SEISMICITY AND LOCAL GEOLOGY

Montreal and Ottawa are located within the Western Quebec Seismic Zone (WQSZ), which includes parts of eastern Ontario, the Adirondack Mountains in northern New York State, the Ottawa Valley from Montreal to the Temiscaming area, and the Laurentian Mountains north of the Ottawa River. The extent of the WQSZ is based on the distribution of measured small magnitude earthquakes as well larger historical events of M 5.5 to 6.2 (Lamontagne et al., 2008). Most earthquakes in the WQSZ, however, occur within two areas: a southeast-northwest band from Montreal to the Cabonga Reservoir in the upper Gatineau River watershed, and a less active sub-zone underlying the Ottawa-Bonnechere Graben (Lamontagne et al., 1994; Adams and Basham, 1989).

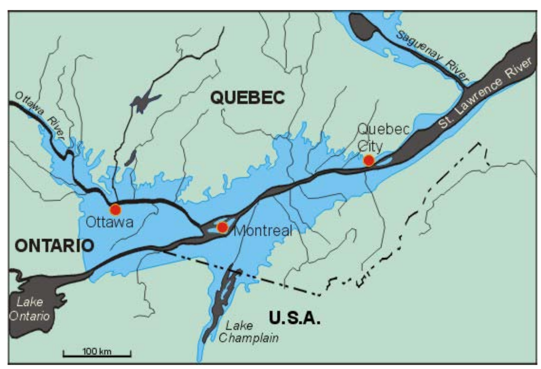

Figure 1. Areal extent of the Champlain Sea, much of which is covered by soft sediments.

Current knowledge of the earthquake activity in the WQSZ is based on less than 200 years of reported felt effects and approximately 100 years of instrumental recordings. During this period, the area experienced moderate shaking from earthquakes in the range of M 5.0 to 6.2. In addition, evidence based on site investigations and radiometric dating indicates that the lower Ottawa Valley experienced two geologically destructive earthquakes in the Holocene (Aylsworth et al., 2000). One, which occurred circa \ 4550 years BP, caused widespread landsliding of sensitive marine clays along the sides of paleochannels located east of Ottawa. The other, at 7060 years BP, caused irregular surface subsidence, lateral spreading, sediment deformation in thick deposits of marine clay, and sand infilling a small deep bedrock basin at Lefaivre, Ontario. Magnitudes of these ancient earthquakes probably exceeded M 6.5 (Aylsworth and Lawrence, 2003) and may have exceeded M 7 (Adams and Halchuk, 2004; Aylsworth and Hunter, 2003). Both the Montreal and Ottawa areas were inundated by the Champlain Sea between approximately 12000 and 10000 years BP (Figure 1). The underlying bedrock is mainly composed of Paleozoic sedimentary limestone, dolostone, shale and sandstone, which overlie Precambrian crystalline basement rock. In the Ottawa area, Late Quaternary deposits generally consist of glaciogenic gravel and diamicton (till) that underlie glaciomarine silty clays and prodelta 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. The thickness of postglacial sediments in the Ottawa area ranges from a thin surface veneer (<1 metre thick) to over 100 metres thick, where it has accumulated in bedrock depressions and valleys. Glacial sediments are generally thin (1-3 metres thick), but may be thicker (>5 metres) within bedrock depressions.In the Montreal area, the thickness of Quaternary deposits can reach 35 metres. The thickness of Champlain Sea sediments is up to 20 metres and that of the overlying recent fluvial deposits of the modern St. Lawrence River can reach 10 metres (Rosset and Chouinard, 2009).

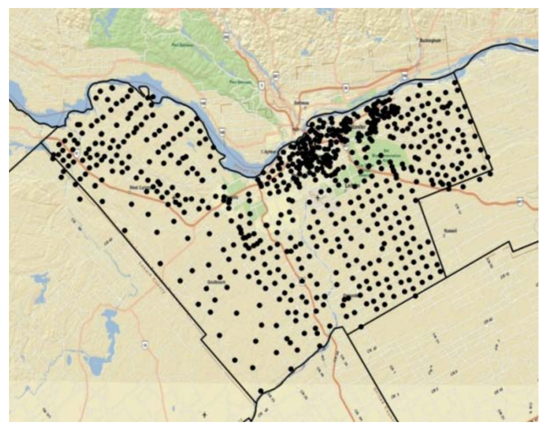

Figure 2. Location of the 685 surface shear wave refraction/reflection sites within the city of Ottawa.

3. GEOPHYSICAL/GEOTECHNICAL MEASUREMENTS

Our microzonation activities have recently been directed towards geophysical measurement techniques for estimation of Vs_{30} and f_0 (fundamental resonant frequency of the soil) based on guidelines established by the 2005 NBCC. The development of near surface geophysical techniques, the interpretation methodology, and their application to sites have been designed to address shear wave and geological structural issues that may arise in future building codes when improved knowledge of the near surface factors affecting ground motion response to earthquakes becomes available. In addition, our research group is also working to provide a region-specific model of seismic soil amplification for Eastern Canada. This is particularly important in this area where large amplification at the resonant frequency of the soils may be expected.

The geotechnical/geophysical methods used in the study of the Montreal and Ottawa areas are briefly described.

- *Borehole Shear Wave Measurements*. The downhole seismic survey method was employed at 10 boreholes sites in Ottawa and three sites in Montreal. Most boreholes were drilled through thick postglacial sediments, and most were drilled to bedrock. Downhole shear and compressional velocity techniques were previously developed for near surface applications in soils and rock (Hunter et al., 1998).

- *Vs_{30} Sites*. A seismic surface array of shear wave horizontal geophones and a shear wave source was designed for the survey area, guided by known geological stratigraphy as well as previous seismic velocity data for the postglacial, glacial and bedrock units measured in the Ottawa area (Hunter et al., 2007). Figure 2 shows the location of the 685 surface shear wave sites.

- *Horizontal-to-Vertical (H/V) Ambient Noise Spectral Ratios*. More than 2,000 sites in Montreal and 400 sites in Ottawa have been occupied for horizontal and vertical (H/V) measurements using background noise. Figure 3 shows the location of H/V sites in the Montreal region.

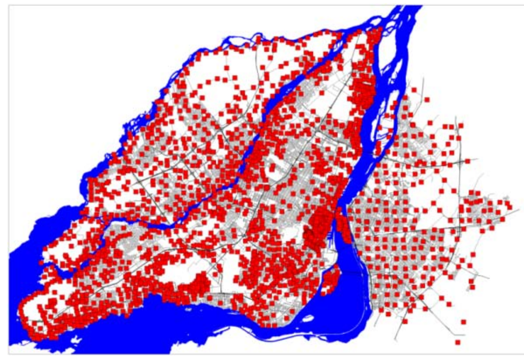

Figure 3.Location of more than 2000 sites in the Montreal area.

- *MiniVib/Landstreamer Seismic Reflection Profiling*. Recent research by the Geological Survey of Canada has focused on the design of geophone sleds and associated sources to allow data acquisition to take place at higher rates and with variable swept frequency vibrator sources (Pugin et al., 2007). Landstreamer seismic lines were selected where thick Champlain Sea sediments were known or suspected and where detailed profiling of complex bedrock topography was required. A total of 25 line-kms in Ottawa and 7.5 line-kms in Montreal were surveyed using this technique.

- *Multi-Channel Analysis of Surface Waves (MASW)*. MASW methods were employed at 35 sites within the City of Ottawa and 29 sites in Montreal. The field procedure of MASW for microzonation studies was applied in three different manners: active, remote passive, and roadside passive.

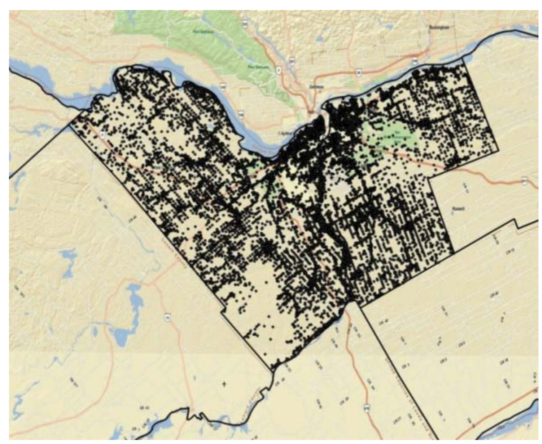

Figure 4. Map showing the location of ~21,000 water well and engineering boreholes in the greater Ottawa area.

- *Estimates of Q (or Damping)*. Borehole experiments are currently being carried out in the Ottawa area, using two downhole 3-component geophones and a mono-frequency vibrating source. A variation on the spectral ratios processing technique is being examined to obtain reliable estimates of Q (or damping) in situ.

Results of the combined geophysical/geotechnical methods will be used in advanced soil modeling, which will lead to an improved understanding of soil behaviour during weak motion events and eventually lead to strong motion estimation/modelling.

4. Vs_{30} MAP

For the city of Ottawa, velocity-depth relationships in the postglacial soils were developed at city-wide and site-specific levels. These analyses were carried out with the reflection data set, which consisted of an interpreted data set of 279 surface reflection sites, 1,281 velocity-depth measurements from landstreamer lines in sediment filled bedrock depressions, and 390 velocity-depth measurements from downhole shear wave velocity logs through soft postglacial soils. These reflection-derived velocities allowed the development of a city-wide velocity-depth function in postglacial soils and shear wave velocity (Vs) ranges for glacial deposits and bedrock.

Within the Ottawa area, the subsurface geological data has been interpreted from approximately 21,000 water well and engineering boreholes (Figure 4). The borehole stratigraphy was summarized into three units based on Vs characteristics: postglacial deposits, glacial deposits, and bedrock. Hunter et al. (2007) found that the Vs of the postglacial sediments could be reasonably represented by a linear average Vs-depth function, while Motazedian and Hunter (2008), and Benjumea (2008) found that glacial depositis and bedrock are reasonably representated by average Vs values. These velocity relationships, developed using the reflection/refraction data collected across the city, allow for each borehole record to be converted into a shear wave velocity profile, whereby the travel-time-averaged Vs for the upper 30 metres of ground surface (Vs_{30}) could be determined for each borehole site.

Various interpolation techniques were examined to create a contoured Vs_{30} map and the nearest neighbour approach was found to fit the data best. All five of the NBCC site classes are present, indicating that there are significant differences in seismic hazard across the city of Ottawa. In particular, the map reveals that class D and E areas, representing the more amplification susceptible terrains, are present beneath built-up areas of the city. The occurrence of classes D and E primarily relates to the presence of thicker deposits of soft postglacial sediments (or Leda clay) that locally are up to 100 metres thick. Reflecting the steeply sloped margins of the buried valleys, the transitions from classes A to E can occur over distances of less than 0.5 km (e.g. in the east Ottawa suburb of Orleans) (Motazedian and Hunter, 2008).

The distribution of the seismic site classes is directly relevant for emergency response planning and seismic mitigation strategies, because the built-up urban areas on the D and E class terrains are likely to experience more damage than the A, B and C areas during a significant earthquake, all factors being considered equal. For reasons mentioned above, the shaking pattern will not be uniform within the site classes; thus, the map represents a first approximation of the seismic hazard. Nevertheless, it does provide a framework for qualitative assessments to be made for the prioritization of buildings for seismic retrofitting, the siting of new critical infrastructure, as well as assessing the vulnerability of linear utilities (e.g. gas lines, water mains, power lines) and linear transportation corridors (Levson et al., 1998). The map is also relevant to the insurance industry for better assessment of their exposure to earthquake risk and to aid in calculating ‘fair’ premiums that better the reflect variability of local seismic hazards (Clark and Khadilkar, 1991; Smolka and Berz, 1991; Finn et al., 2004).

Further applications of this map include provision of the amplification factors required for analyses of potential losses (deaths, property damage) from earthquake events using risk assessment software, such as Hazards U.S. Multi-Hazard (HAZUS-MH). These analyses take into account many variables in order to portray the vulnerability of a study area, such as the characteristics and location of the built environment (buildings, essential facilities, transportation and utility lifelines), population densities, and building occupancy (based on the time of day). Many specific details are compiled and integrated into the analysis to allow a rigorous determination of loss, for example, of the physical properties of the building inventory (building age, height, foot print, building materials, load bearing system, etc. (Finn et al., 2004)). The loss estimate can be modeled for selected scenarios of earthquake magnitude, spectral characteristics and distance from the study area. The data on the scale and pattern of loss from a risk analysis allows the consequences of a hazard event to be quantified and mapped, which can greatly aid in emergency response planning and decision making about mitigation strategies. These analyses can also allow the cost-effectiveness of mitigation to be quantitatively assessed.

5. FUNDAMENTAL SITE PERIOD (T_0) MAP

In addition to the Vs_{30} map, a fundamental site period map for Ottawa (Figure 5) was produced using the equation given in the 2005 National Building Code of Canada (NBCC): $T_0 = 4*H/ V_{av}$, where T_0 is the fundamental site period, H is the thickness of soft soil over firm ground, and V_{av} is the average shear wave velocity down to this interface. For seismic refraction-reflection sites where the velocity-depth function was known to firm ground, the travel time from surface to this interface was computed to obtain the fundamental site period as given above by Equation 1. Additional information was acquired from borehole shear wave surveys where travel times from the surface to the firm ground interface could be measured directly.

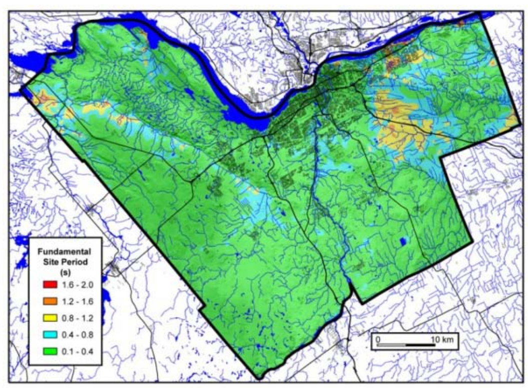

Figure 5. Map depicting ranges of the fundamental site period of the ground within the city of Ottawa area. See text for how fundamental site period was calculated.

For Montreal, a compilation of about 26,000 geotechnical boreholes were used to determine the bedrock depth and among them 2,000 soil profiles were defined to compute transfer functions using one-dimensional modelling. By combining the numerical approach with H/V ambient noise spectral ratios, a preliminary f_0 map was produced. This map is under revision following a recent survey of downhole measurements, MASW, and shear wave reflection profiling using the Minivib/landstreamer system. The data from these surveys will be used to update the soil layers model for the Montreal area and to revise site classifications and amplification factors.

Figure 6 shows the preliminary f_0 map for the city of Montreal and the South shore. The Northeast part of the island has lower frequencies that begin around 2 Hz, adjacent to the St. Lawrence River, up to 10 Hz, where tills and rock outcrop. Low frequencies are encountered in the eastern part of the island near the river and values increase westward. The southern flank of Mont Royal, Westmount, Hampstead, the Mont Royal and Lachine "corridor", the Pointe-Claire area and the Montreal-Nord zone also have low frequency site responses. Some sites have singular low f_0 values that could be correlated with thick overburden in ancient riverbeds. Good correlation was found for f_0 with the interpolated map of bedrock depth, particularly in zones where clays are predominant. For sites where boreholes are well documented, the predominant frequency of polarization of ambient noises was correlated with the thickness of soft layer (Chouinard and Rosset, 2007, Rosset and Chouinard, 2009).

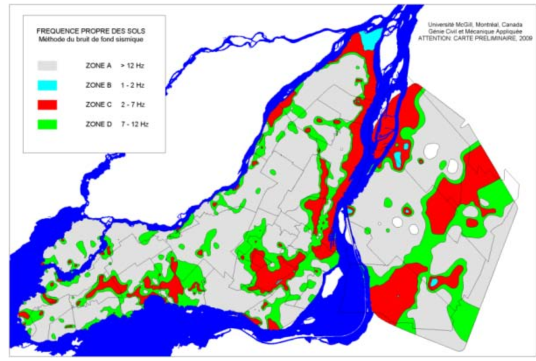

Figure 6. Soil fundamental frequencies for Montreal and the South Shore.

6. CONCLUSIONS AND RECOMMENDATIONS

Because of the unique variability of near surface soil and rock configurations within the cities of Ottawa and Montreal, the shaking levels will vary considerably over relatively short horizontal distances, in the order of 500 metres or less. To examine the variable shaking conditions, a combined geological/geophysical/geotechnical approach was adopted for regional surveying.

In Ottawa, over 21,000 boreholes, both water wells and geotechnical borings, were examined to establish the basic geological units that could be related to geophysical/geotechnical units. By using the shear wave velocity measurements obtained from 685 surface refraction/reflection sites, as well as 9 downhole shear wave surveys and 35 MASW surveys, the geophysical/geotechnical units were assigned shear wave velocity-depth functions for all 21,000 boreholes. These functions included average velocity structure throughout the postglacial Champlain Sea sediments, as well as shear wave velocities assigned to both the Pleistocene sediments and the various types of bedrock. From the velocity-depth functions assigned to the boreholes, as well as the velocity-depth functions computed from the geophysical sites, Vs_{30} values were computed throughout the city of Ottawa. Using the Vs_{30} boundaries associated with the site classifications given in the 2005 NBCC, a contoured map of the site class zones was developed for classes A through E. We conclude that the special NEHRP class F cannot be distinguished from NEHRP class E based on shear wave velocities, since 30 metres of most class

F materials would exhibit a Vs_{30} < 180 m/s (the upper boundary of NEHRP zone E). Furthermore, shallow thicknesses of class F materials overlying high shear wave velocity bedrock could result in a Vs_{30} value equivalent of that of class D and possibly of class C (e.g. related to the presence of amounts of organic materials, sensitive clay or soft clay, as specified in the 2005 NBCC). Hence, it is recommended that the NEHRP zones as shown on the map should be used only as a guide, and the reader is cautioned that zones E, D or C could possibly include areas of class F.

For both cities, estimates of the fundamental response period (or frequency) of a site consisting of postglacial sediments overlying bedrock (where the glacial sediments are relatively thin) have been made. In Montreal, the H/V method was demonstrated to be both fast and efficient in estimating the predominant mode of resonance of a site in the urban context of Montreal, which is a key parameter for determining vulnerability assessment. However, difficulties in analysis were encountered in areas where surface soil layers are non-homogeneous due to successive sequences of soil deposition and weathering. In these cases, the H/V spectra exhibit two or more amplitude peaks or a width amplitude plateau.

In summary, as a result of the considerable variation of postglacial sediment thicknesses in the Ottawa area and the correlation of these with variations in shear wave velocity structure throughout the survey area, we conclude that there are considerable lateral variations in the NEHRP zone classifications that, in turn, lead to considerable lateral variations in amplitudes and frequency content of earthquake shaking.

7. Acknowledgement

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