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SEISMIC SITE EFFECTS AND SEISMIC RISK IN THE MONTREAL AREA - THE INFLUENCE OF MARINE CLAYS

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ABSTRACT

In Canada, Montreal is ranked second for seismic risk after Vancouver considering its population and regional seismic hazard. The city is largely built on recent unconsolidated marine and river deposits that are known to amplify seismic waves and a large proportion of its infrastructure is old and deteriorated. The conjunction of site effects and vulnerable infrastructures could result in significant damage if a major earthquake, such as a repeat of the magnitude 6 event of 1732, would occur in proximity to the city. In order to improve estimates of seismic hazards, a seismic microzonation of the city was performed by combining field investigations using ground ambient noise records (H/V method) and numerical simulations of seismic wave propagation. Field investigations were performed at over 700 locations distributed across the Island of Montreal to estimate the fundamental frequency of resonance of soil deposits. Numerical simulations were performed using compiled data from over 2000 boreholes to obtain estimates of the spectral response of soil deposits and site amplifications. The resulting seismic microzonation maps are the most detailed and comprehensive to date for Montreal. Critical areas are identified along the southeast shore of the St-Laurent River as well as west of downtown. Both are well correlated with the presence of thick marine clay deposits. The maps have been used in collaboration with the Sécurité Civile of Montreal to develop seismic hazard mitigation plans for critical infrastructures such as water filtration plants and to validate emergency response plans through earthquake simulation exercises.

Introduction

It is generally recognized that soft soils have a major influence on seismic ground motion and are a major consideration in seismic zoning. Classic examples of the role of surface geology on seismic waves are provided by the 1906 San Francisco and the 1985 Mexico City earthquakes. In both cases, soft soils amplified ground shaking at frequencies close to those of existing buildings which resulted in important human and economic losses. Significant spatial variations in ground motions were again illustrated during several recent destructive earthquakes; e.g. Northridge (1994), Kobe (1995), Armenia and Colombia (1999), Turkey (1999) and Bam (2003).

The initiation of the seismic hazards mitigation program for Montreal coincides with an increased awareness among governments relative to hazards in general. Seismic hazards are often a major

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concern since out of all natural and man-made catastrophes, it affects the largest proportion of a given territory and represents the most stringent test for the robustness of existing infrastructures and the responsiveness of emergency management agencies (Adams et al. 2002). Montreal ranks second in Canada (20% of national urban risk) after Vancouver for seismic risks based on population at risk and probability of seismic events (Adams 1989).

The regional seismicity of Montreal is dominated by two main active zones within the Western Quebec Seismic Zone (Adams and Basham 1991); One band follows the Ottawa River and is the site of 3 major earthquakes; a magnitude 6 event near Montreal in 1732 (Leblanc 1981); a magnitude 6.2 event near Timiskaming in 1935 (Bent 1996a) and a magnitude 5.6 event near Cornwall-Massena in 1944 (Bent 1996b). These earthquakes correlate with a normal faulting zone from the Paleozoic or later periods along the Ottawa River that may represent a failed rift. The second band is oriented NW-SE and extend from Montreal to the Baskatong Reservoir (200 km north to Ottawa). Although the relationship between epicentres and local tectonics is not clear, the hypothesis of a crustal displacement over a hot spot has been proposed. The previous National Building Code of Canada (NBCC 1985) indicated that Montreal can expect horizontal PGA of 0.16g for a probability of non-exceedence of 10% in 50 years. The new version (NBCC, 2005) gives normative values up to 0.49g for a probability of non-exceedence of 2 % in 50 years.

The sub-soil of Montreal is constituted of igneous and metamorphic rocks of Precambrian age covered by Ordovician sedimentary rocks (Trenton Limestone and Utica Shale). The chronological sequence of glacial deposition is described as Malone Till, Middle Till Complex and Fort Covington Till during the Wisconsinan period (ca 125,000 –10,000 years BP). Tills are composed of boulders, gravel, sand and silt in varying proportions. All superficial deposits (clay, sand and silt) originate from the Champlain Sea and subsequent wanderings of the St-Lawrence riverbed. The characteristics of the marine clay vary from massive to silty depending on the depositional history. The location of clay deposits is variable and thicknesses range from one to tens of meters. Fluvial sand and gravel deposits occur widely over the Island of Montreal. The thickness of these deposits is also highly variable but does not exceed 10m. Prest and Hode-Keyser (1977) give a detailed description of glacial and sedimentary episodes for the island of Montreal.

An illustration of the importance of site effect in Montreal is provided by the magnitude 5.9 Saguenay earthquake of 1988. Despite an epicentral distance exceeding 300 km, the external masonry wall of the the Montreal-East City Hall was extensively damaged. An analysis of the event concluded that failure was due to the state of deterioration of the building and local amplification associated with a thick layer of marine clay (Mitchell et al. 1990).

The objective of the paper is to present the results of 3 years of research on the seismic microzonation of Montreal. Maps have been produced that indicate the most critical areas of Montreal relative to seismic site effects. This information is being used in collaboration with the City of Montreal to develop seismic mitigation plans for critical infrastructures such as water filtration plants and to generate seismic scenarios for emergency preparedness simulation exercises.

Methodological Aspects

A methodology for characterizing the seismic response of surface soil deposits was specifically developed for applications in urban environments. The use of shallow seismic wave prospecting techniques is often not feasible in urban environments. The method developed for the project combines information obtained from the geological setting, empirical data from ground ambient noise and analytical simulation results using one dimensional wave propagation models (Rosset et al. 2003). It was first applied to several pilot study zones to demonstrate the efficiency of the procedure (Rosset 2003) and extended the following year to the entire island (Madriz 2004; Chouinard et al. 2004).

The empirical approach uses ground ambient noise records to estimate the fundamental period of a site. The approach, known as the H/V method (Nakamura 1989), characterizes site effects by the ratio of the horizontal and vertical components of surface ambient noise records in the frequency domain. The maximum of this ratio is used to identify the fundamental period of the site; however, there is currently no consensus on the relationship between the magnitude of this ratio and site amplification (Bard 1999 ; Nakamura 2000 ; Faeh et al. 2001; Bonnefoy-Claudet 2004). The validity of the approach for estimating the fundamental frequency of a surface deposit has been extensively demonstrated by comparison with other established techniques (Lachet and Bard 1994; Lermo and Chavez-Garcia 1994). In our application, data was recorded with a 24 bit ORION digitizer from Nanometrics Ltd. connected to a 3-components seismometer Guralp CMG-40T/30 sec. Field experience showed that recording sessions of 5 to 7 minutes after stabilization of the instrument were sufficient to obtain stable and repeatable results. Software with a user-friendly interface was developed in order to process efficiently multiple sets of records (Rosset 2002). Over 700 measurements were performed across the island of Montreal.

The analytical approach is based on numerical simulations of one dimensional shear wave propagation using Shake91 (Idriss and Sun 1992). The geology under a site is idealized as an horizontal, homogeneous and isotropic multi layers model. Each layer is characterized by its thickness, density, shear wave velocity and damping factor. The analysis provides the spectral amplification and the related frequencies of the fundamental and harmonic mode of resonance of the site. More than 700 multi-layer models were generated at locations across the island from the compilation of over 2000 boreholes. Input strong motions records from five intra-plate earthquakes were used representing low, intermediate and high period scenario earthquakes. A "broadband" scenario was added consisting of synthetic signals generated specifically for the Montreal area (Atkinson and Beresnev 1998). A regional soil layer model was defined for the various types of soil deposits on the island of Montreal (Table 1) and a software application was developed to allow processing of multiple sites and earthquake scenarios (De la Puente and Rosset 2002).

Table 1. Regional soil layer model considered for numerical simulation.

Episodes of deposit	Nomenclature	Type of deposit	Unit Weight kg/m^3	S-Wave Velocity m/s
LATE DEPOSIT	Bog-pond deposit	Peat, muck, filled ground	2000	150
FLUVIAL DEPOSIT	St-Lawrence deposits	sand, gravel	2054	400
MARINE DEPOSIT	Offshore sediments	Clay-silt, marine shells	1720	150
GLACIAL DEPOSIT	Fort Covington Till	Undifferentiated till	2080	600
	Intermediate Till	Sand, gravel, silt, cobble	2160	800
	Malone Till	Boulders, sand, silt	2400	1000
ROCK	Trenton Limestone	Limestone	2730	2300
	Utica Shale	Shale	2670	2100

Seismic Microzonation of Montreal

The spatial location of ambient noise measurements was selected using existing surface geology maps, increasing the density of measurements in zones of clay and sand deposits. Measurements were classified into three categories depending on the quality of the peaks in the H/V spectra. The best category corresponds to records that exhibit a single clear peak and accounts for 62% of the sites. The second category corresponds to records with two (or more) peaks and accounts for 33% of the sites. Finally, the last category corresponds to records with no distinctive peak (5% of the cases) and comprises mainly sites on rock. Estimates of predominant frequencies were spatially interpolated using the natural neighborhood technique (Fig. 1). The map shows low frequencies zones close to the St. Laurent River and in the vicinity of ancient riverbeds. In the north-eastern part of the island, frequencies are below 2 Hz close to the river and increase regularly to the SW. In other zones, spatial variability in frequencies may reflect the irregularity of depth to bedrock or heterogeneity of soil layers.

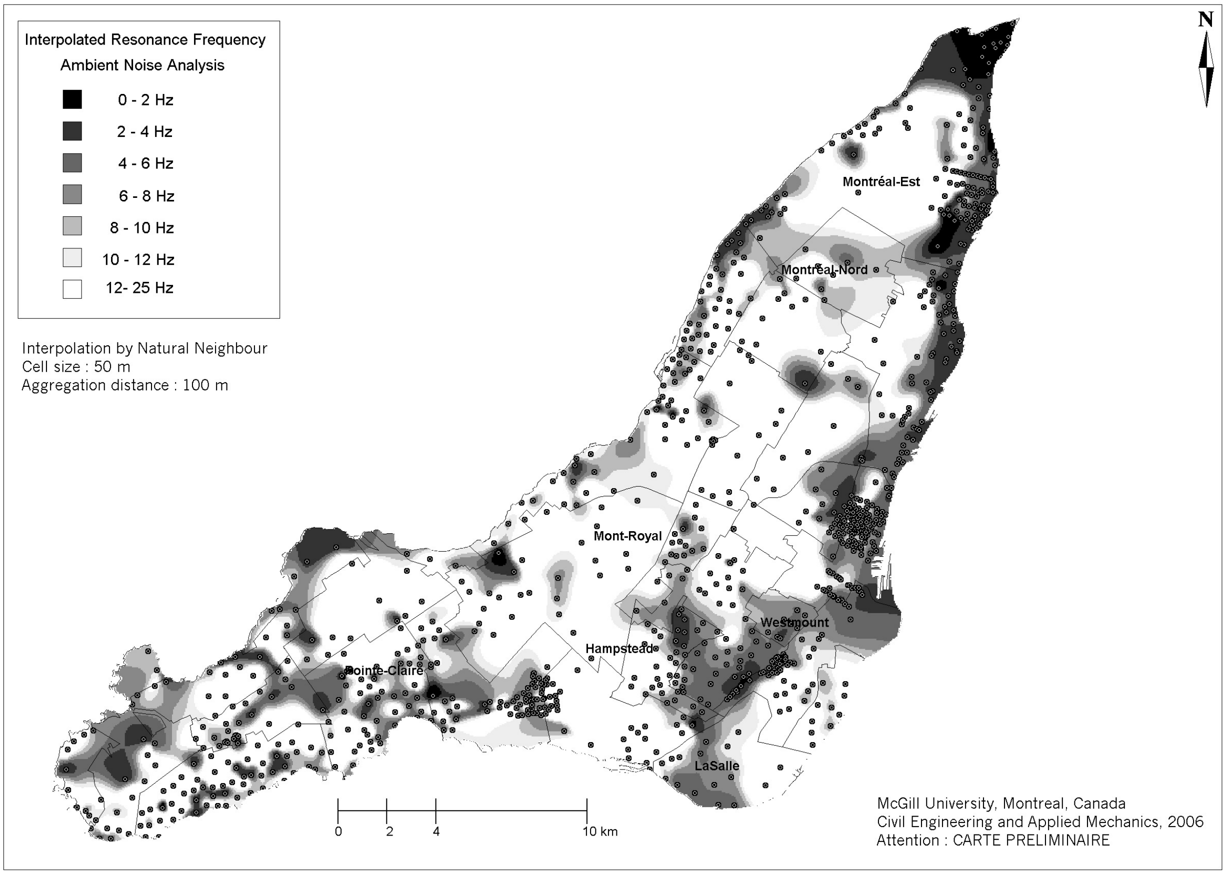

Figure 1. Interpolated map of the predominant frequency response of soil obtained with ambient noise analysis. Black dots indicate the location of measurements.

A compilation of 2000 boreholes was used to estimate depth to bedrock across the island of Montreal and to compute transfer functions and scenarios using the 1D analytical approach. In addition, depth to bedrock was established accurately for approximately half of the sites where ambient noise measurements were performed. Figure 2 shows a comparison of predominant frequencies for sites where both estimation procedures could be used and indicates good agreement. One can notice that the lower bound for frequencies is around 2Hz in accordance with the maximum thickness of soft soils in the Montreal area.

Seismic scenarios were produced using a selection of 17 strong motion records classified into 4 categories. The reference peak ground acceleration (PGA) for each record was scaled to 0.16g and corresponds to the reference value for Montreal (NBCC 1985). The PGA amplification factor, defined as the ratio between the PGA of the signal with site effects and the reference PGA, was calculated. The 4 selected scenarios are shown to illustrate the range of PGA amplification as a function of predominant frequency. These are labeled “low frequency”, “intermediate frequency”, “high frequency” and “broadband frequency” earthquake scenarios.

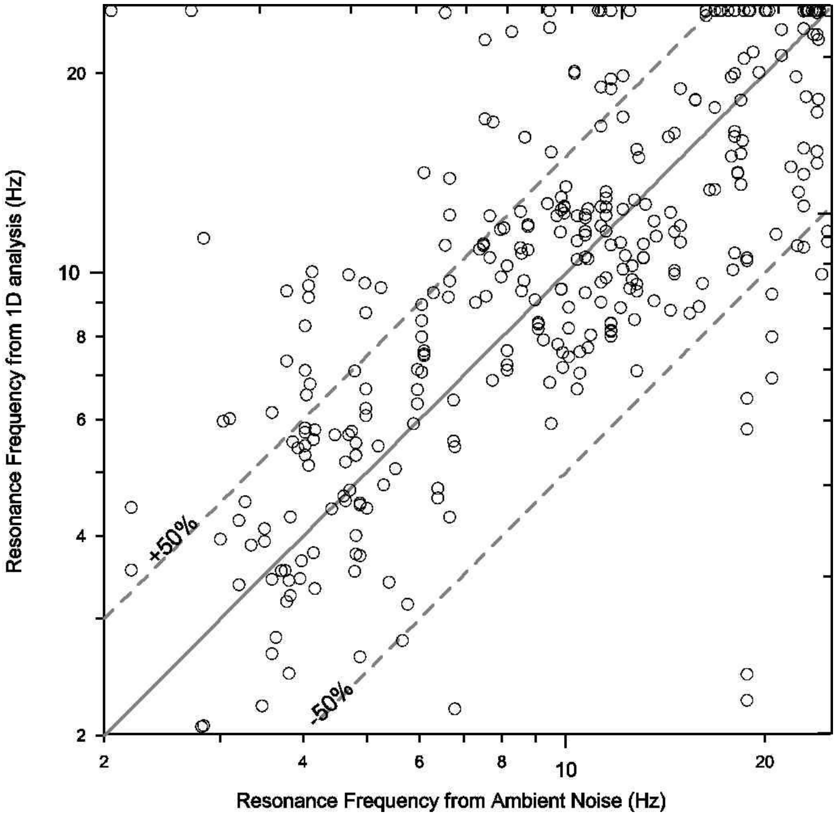

Figure 2. Predominant frequencies of resonance derived from ambient noise analysis versus those calculated with the analytical approach. The black line represents perfect agreement between the methods and the dash lines the ±50% deviation intervals.

Figure 3 shows the PGA amplification factor as a function of the predominant frequency for each site and the four earthquake scenarios. The results show a large range of amplifications at a given frequency especially for intermediate frequencies (2-10 Hz). This can be explained by the variability of soil layers between sites with similar frequencies. The Low and broadband/high frequency earthquake scenarios provide lower and upper bounds respectively for frequencies between 2 and 7 Hz, while the intermediate frequency earthquake scenario represents an “average” of the other scenarios. A regression curve into points for each scenario is drawn in order to define zones with similar amplification factor.

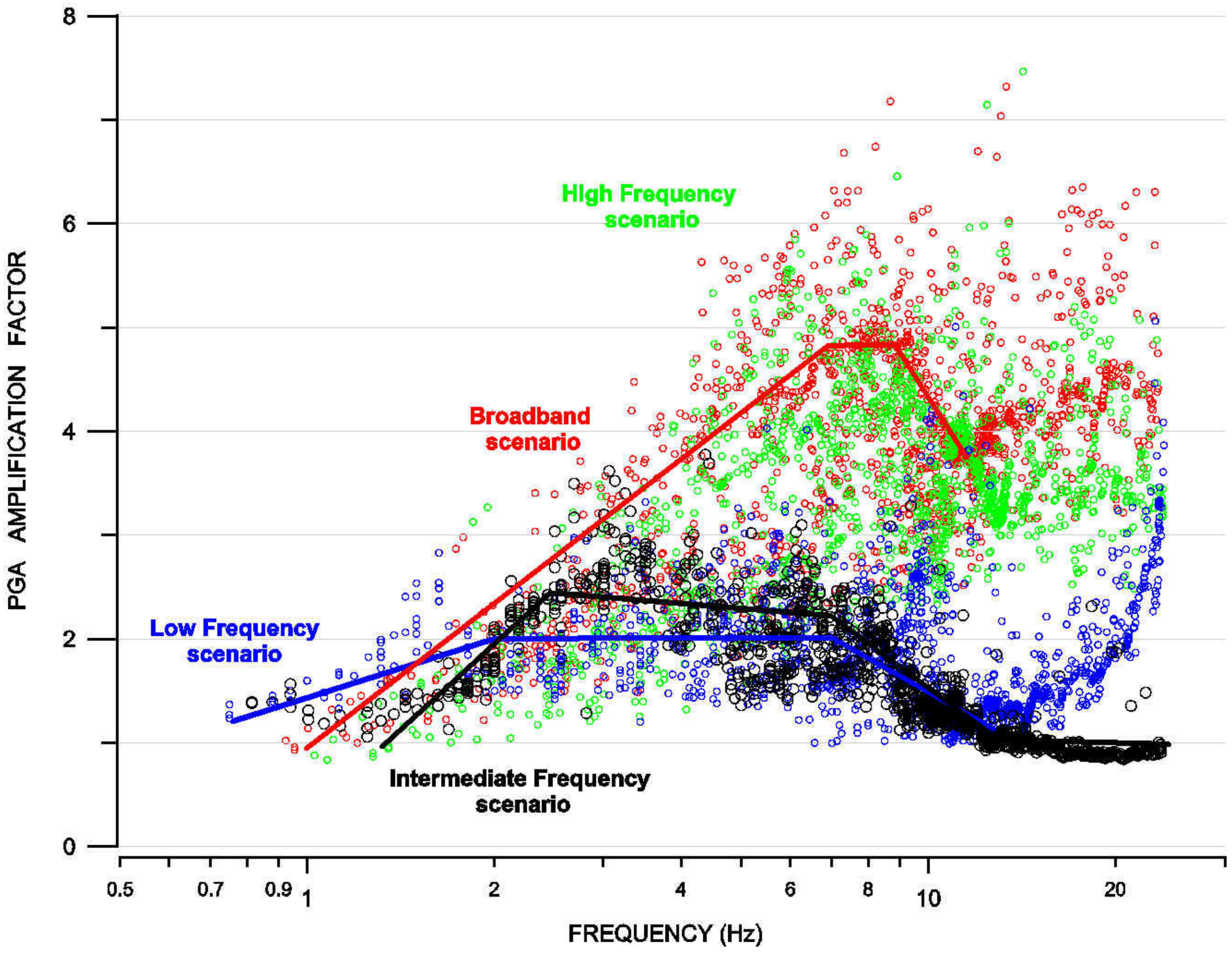

Figure 3. Peak ground acceleration amplification as a function of predominant frequency for the four earthquake scenarios (low, high, intermediate and broadband frequency) for sites in Montreal.

The intermediate frequency scenario of the Figure 3 was selected to generate the seismic microzonation map. Zones of the map are characterized in terms of predominant frequency of resonance and expected relative amplification of seismic waves. Figure 4 (top) shows a proposed diagram with zones corresponding to four frequency ranges. Amplifications are low for frequency ranges A, intermediate for frequency ranges B and D, and high for frequency range C.

The four ranges of soil response frequencies are then used to produce a microzonation map based on the results of ambient noise analysis. Figure 4 bottom shows the interpolated map for Montreal related to the site response indicated in Figure 4 top. In this way, expected amplification is superposed with information on the expected frequencies for this amplification, which is of prime importance when looking at the vulnerability of buildings or infrastructures and matching building and site predominant frequencies.

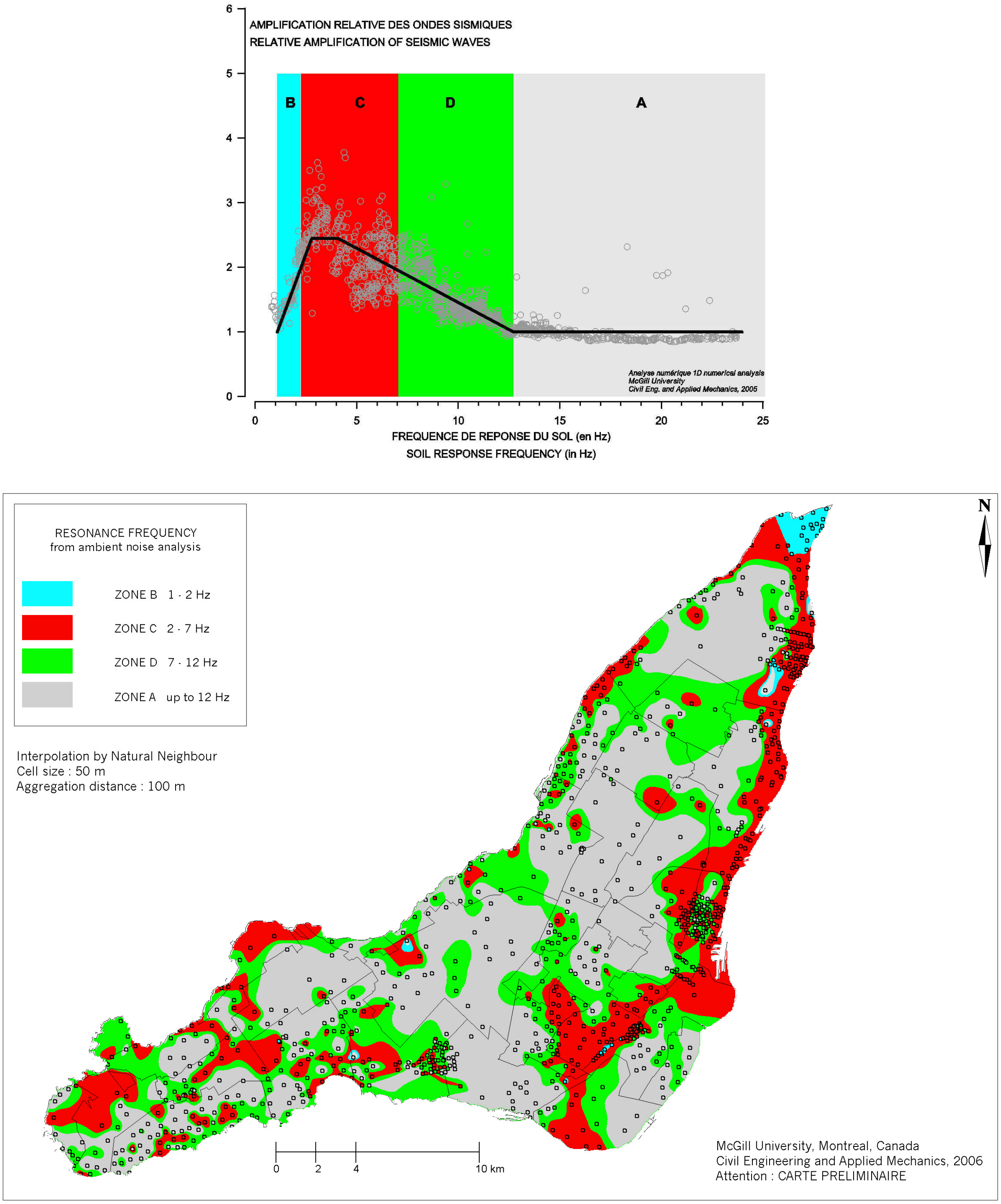

Figure 4. Seismic microzonation for Montreal. (Top) Relative amplification of seismic waves as a function of predominant frequency of soils. Four zones are defined: Zones A with low amplification, zones B and D intermediate amplification and zone C with high amplification. (bottom) Microzonation map derived from ambient noise data

The Influence of Marine Clay in the Site Amplification

The microzonation map of Figure 4 is based on frequencies obtained from the analysis of ambient noise records. It is generally recognized that soil response is inversely proportional to the thickness of soft soils deposits. For Montreal, marine clays have a significant influence on site response in vicinity to the St. Laurent River as illustrate by the damage sustained by the Montreal East City Hall during the 1988 Saguenay earthquake (Rosset 2003).

The relationship between predominant frequency and thickness of clay is shown in Figure 5 for 118 sites where a homogeneous clay layer overlays till or rock. The S-wave velocity V that best fits the curve using a simple one layer model (F_HV=V/4H) is around 125m/s which is within the expected range for this type of clay. A regression line fitted to the data points provides the following relationship between fundamental frequency and thickness of the clay layer:

$$\mathbf{F\_HV = 21 / H^{0.6}} \tag{1}$$

where F_HV and H are the H/V peak frequency (Hz) and thickness (m) of clay respectively. Equation 1 can also be used to estimate the thickness of the clay layer for any new site using ambient noise analysis.

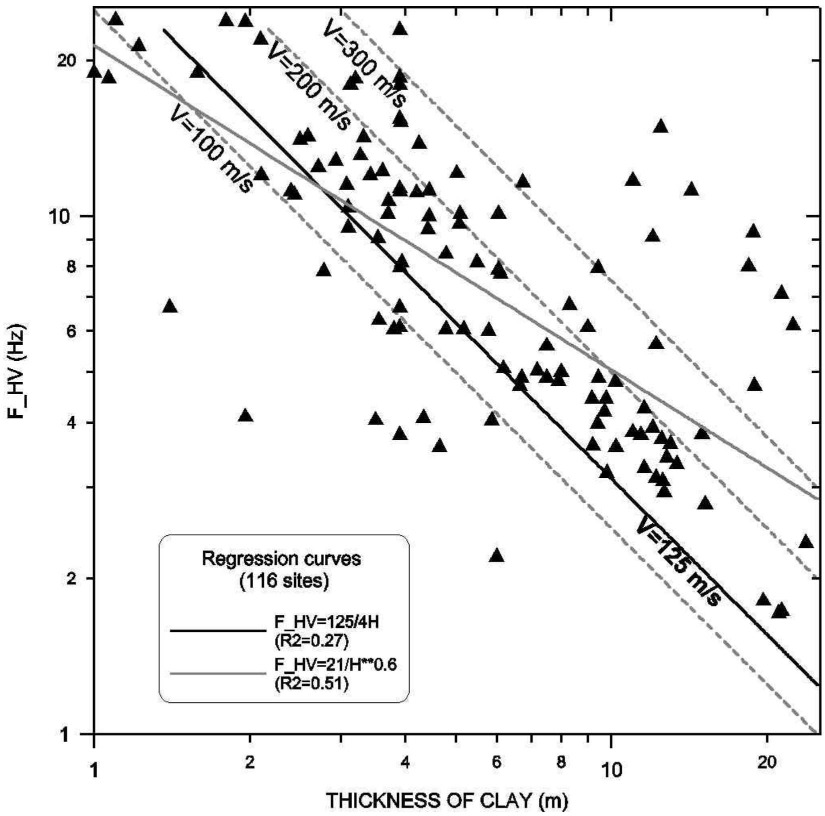

Figure 5. Predominant frequency derived from the H/V polarization peak (F_HV) versus the thickness H of clay overlying tills (logarithmic scales). Grey dash lines represent a constant velocity V following the relationship F=V/4H.

Conclusions

The seismic microzonation for the island of Montreal was obtained by the combination of two complementary approaches. The first is based on the analysis of ambient noise records for the identification of the predominant frequency of resonance from the H/V spectral ratio. The second is based on a numerical model for the one dimensional propagation of S-waves through a series of horizontal, infinite and homogenous layers of soil. The analysis is used to obtain estimates of local amplification and of the predominant frequency of resonance. Different earthquake scenarios were considered and four ranges of predominant frequency were used to define 4 zones also characterized by the expected level of amplification. The "mean" earthquake scenario used need to be improved as soon as new data regarding specific S-wave velocity for soils of Montreal are available. An effort is made now to redraw the contours of the microzonation map by considering the surface and sub-surface geological information for the different soil layers.

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