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Characterization of site effects in Montreal, Canada

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Abstract Recent destructive earthquakes have clearly shown that near-surface geological conditions play a major role in the level of ground shaking in urban areas. 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 and most of its infrastructure is old and deteriorated. A seismic risk project that includes a combined methodology for site effects zoning in large cities, using microtremor measurements (*H*/*V* method) coupled with 1D numerical modelling (SHAKE91), has been initiated. The experimental approach gives good estimates of the fundamental frequency of soft deposits, while the numerical approach provides good estimates of the soil response in terms of amplification factor related to frequency. Main mechanical properties of soft soils were compiled from various data available, and a sample of input rock motions from real and synthetic earthquakes was used to compute soil response. The influence of marine clays on soil response is significant and is well correlated with thickness of these deposits. PGA amplification factors range from 2 to 4 at frequencies from 2 to 7 Hz, with some occasional larger values. The results demonstrate that the methodology used for our study is both fast and efficient to determine the influence of soft soils in urban environments. Such studies are essential for the effective deployment of seismic instrumentation, land-use planning and seismic mitigation.

Keywords Seismic site effect · Ambient noise method · 1D modelling · Microzonation · Montreal · Mitigation

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1 Introduction

It is generally recognized that soft soil deposits have a major influence on seismic ground motions and cannot be ignored in seismic zoning. Classic examples of the role of surface geology on seismic vibrations are the 1906 San Francisco and the 1985 Mexico City earthquakes. In both cases, soft soils amplified ground shaking at certain frequencies which resulted in damage to buildings and consequently important human and economic losses. Significant spatial variations in ground motions were again illustrated during several recent destructive earthquakes: Northridge (1994), Kobe (1995), Colombia (1999), Turkey (1999) and Bam (2003).

The initiation of the seismic hazard analysis for the city of Montreal coincides with an increased awareness among governments relative to any kind of hazards. Seismic hazard is considered the primary concern among all natural and man-made catastrophes; it is prone to affect the largest proportion of a given territory, and it represents the most stringent test for the robustness of existing infrastructures and for the responsiveness of emergency management agencies. Based on exposed population and on the probability of earthquake occurrence, Montreal ranks second in Canada (around 20% of national risks) after Vancouver for seismic risk (Adams et al. 2002). The city is particularly vulnerable to seismic events since most of its infrastructure is old and deteriorated or has been designed according to standards that predate modern seismic design codes and that did not account for local site effects associated with unconsolidated soils from quaternary marine and river episodes of deposition.

In the first section, the geological history of Montreal Island is briefly reviewed to explain the presence of soft soils such as clay, sand and peat. This is followed by a description of the seismic setting surrounding Montreal, and in particular of the Western Quebec Seismic Zone. The methodology used to estimate local site effects in urban environment is presented in the second section. It is based on the combination of analyses using ground ambient noise (*H*/*V* spectral ratio) and numerical 1D response of soil columns. The third section illustrates the results on hundreds of sites in the island of Montreal. Fundamental modes of soil resonance and amplification factors are estimated for different input ground motions. Finally, fundamental modes of resonance obtained by both methods are compared for several sites and a general relationship between the thickness of soft soils and the fundamental frequency of resonance is proposed for zones where clay deposits are predominant.

2 Geological setting and seismic context

The basement of Montreal Island is constituted of igneous and metamorphic rocks of Precambrian age covered by Ordovician sedimentary rocks (Limestone of Trenton 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 thickness is up to 20 m. Fluvial sand and gravel deposits occur widely over the Island of Montreal. The thickness of deposits is also highly variable but does not exceed 10 m. A detailed description of glacial and sedimentary episodes is provided by Prest and Hode-Keyser (1977). The geological map of Fig. 1 shows the distribution of the different deposits in the island.

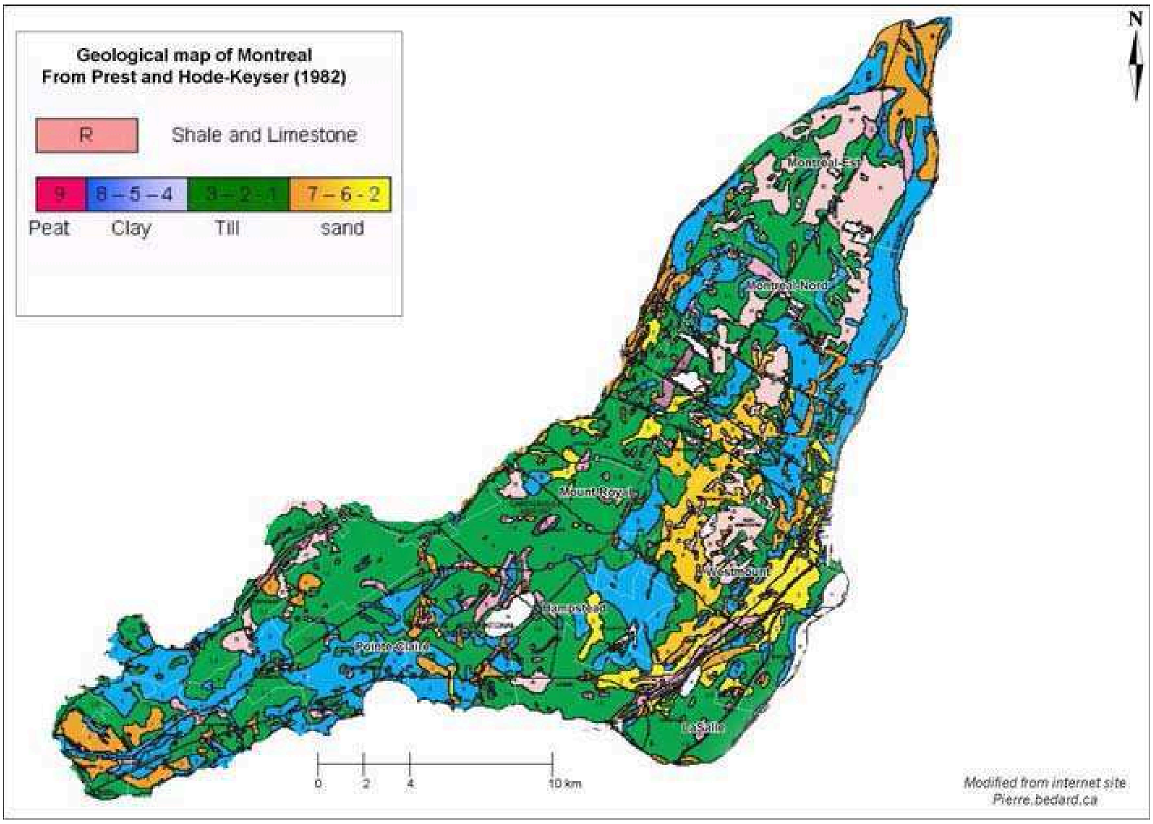

Fig. 1 Geological map of the island of Montreal (modified from Pierre.Bedard.ca)

A simplified layered model was defined to represent the typical quaternary geology of Montreal (Rosset et al. 2003a, b; Madriz 2004). It is derived from the chronology of soft soil deposition described previously and was also adopted by Jacques (1985, 1980) for detailed studies in two areas (Montréal-Est and plateau Mont-Royal). An exhaustive compilation of existing boreholes and their geological description is used to define 1287 soil profiles with the proposed layered model. As in situ geotechnical data are missing, the same average unit weight and shear-waves velocity are associated to a given formation throughout the city. The unit weight values are based on available laboratory measurements and previous compilations. The estimate of S-wave velocity V_s is trickier. Two deep instrumented boreholes in the Saint-Lawrence Basin in Ottawa region are used to constrain V_s for clay and sand (National Resource Canada 2003). Benjumea et al. (2001) investigated site amplification effects near Alfred in Ottawa region, with near-surface seismic methods, and gave an approximate V_s value for Fort Covington Till and rock formations. For the other soil layers, V_s is derived from values commonly used for similar formations. The classification and properties of the different layers are summarized in Table 1. This simple layered model is coherent with the different episodes of quaternary deposition in the Montreal region.

Seismicity around 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 three major historical earthquakes: a magnitude 6 near Montreal in 1732 (Leblanc 1981), a magnitude 6.2 near Timiskaming in 1935 (Bent 1996a) and a magnitude 5.6 near Cornwall-Massena in 1944 (Bent 1996b). These earthquakes appear to have occurred through reactivation of ancient (Paleozoic or later periods) normal rift faults along the Ottawa River, as thrust or strike-slip events in the current compressive stress field. The second band is oriented NW–SE and extends from Montreal to the Baskatong

Table 1 Selected geological layer models used to build up 1D simulation

Episode of deposit	Nomenclature	Type of deposit	Unit weight (kg/m^3)	S-Wave velocity (m/s)	Ref.
Late	Bog–pond deposit	Peat, muck, filled ground	2000	150	(a)
Fluvial	St-Lawrence deposits	Sand, gravel	2054	400	(a, b, f)
Marine	Offshore sediments	Clay-silt, marine shells	1720	150	(a, d)
Glacial	Fort Covington Till	Undifferentiated tills	2080	600	(a, c, e)
	Intermediate Till	Sand, gravel, silt, cobbly	2160	800	(a)
	Malone Till	Boulders, sand, silt	2400	1000	(a)
Rock	Trenton Limestone	Limestone	2730	2300	(a, c, e)
	Shale of Utica	Shale	2670	2100	(a, c, e)

Note: (a) Prest and Hode-Keyser (1977); (b) Robert (1980); (c) Decroix (1984); (d) Nixon (1993); (e) Benjumea et al. (2001); (f) Sharpe (2001)

Reservoir (200 km north to Ottawa). Although the relationship between epicentres and local tectonics is not clear, the hypothesis of a crustal displacement of North America over a hot spot has been proposed (Adams and Basham 1991). The National Building Code of Canada (NBCC 1985) indicates that Montreal can expect horizontal peak ground acceleration PGA of 0.16 g with a probability of exceedence of 10% in 50 years, 475-year return period (Adams and Atkinson 2002; Adams and Halchuk 2003). The new code (NBCC 2005) is more stringent regarding the return period T and proposes PGA values of 0.43 g for $T = 2475$ years (2% probability of exceedence in 50 years).

3 Description of the methodology

As shallow seismic prospecting data are not often available in urban contexts, alternative methods have to be used. A methodology for characterizing the seismic response of surface soil deposits was specifically developed for applications in urban environments. The approach retained here combines information obtained from the geological setting of Montreal Island, data from ground ambient noise measurements and from 1D wave propagation models. To demonstrate its efficiency, the method was first applied to several pilot study zones across Montreal and then extended to the entire island.

The experimental approach, also known as the *H*/*V* method (Nakamura 1989), uses ground ambient noise records to estimate the fundamental frequency of soft soils. Site effects can be characterized by the ratio between the Fourier spectra of the horizontal and vertical components of microtremors at the same station. The ratio is used to identify the fundamental frequency of the instrumented site; however, there is currently no agreement about the corresponding amplification (Bard 1999; Nakamura 2000; Faeh et al. 2001; Bonnefoy-Claudet 2004). The reliability of the approach has been demonstrated by comparison with other well-established techniques (Lachet and Bard 1994; Lermo and Chavez-Garcia 1994; Rodriguez and Midorikawa 2002).

For the Montreal survey, the recordings were acquired using a 24-bit ORION digitizer from Nanometrics Ltd. connected to a 3-component velocimeter Guralp CMG-40T/30 s. Field experience showed that recording sessions of 5–7 min with a sampling rate of 100 Hz after stabilization of the instrument were sufficient to obtain stable and repeatable results for the investigated sites. Software with a user-friendly interface was developed to process efficiently multiple sets of records (Rosset 2002). All signals have been checked from the screen to detect those where transients are too numerous and would not allow keeping the most stationary parts of ambient vibrations. Over 700 sites were investigated in the island, which were selected on the basis of the surface geology as given by the Prest and Hode-Keyser map (1977) of Fig. 1. Areas with clay, peat and sand outcropping are more densely surveyed than zones with tills and rock outcrops.

The analytical approach is based on numerical simulations of 1D response of soil columns to an incoming shear wave using Shake91 (Idriss and Sun 1992). Input soil parameters are obtained from borehole data belonging to the City of Montreal. Table 1 describes the layer types, with the S-wave velocity and unit weight chosen for the calculation. Damping values and shear modulus are provided from literature and laboratory tests in similar clay deposition conditions.

Input strong motions were chosen as the most representative for Montreal seismicity context. The 17 selected accelerograms come from five intra-plate earthquakes recorded on rock sites at distances ranging from 40 to 150 km. They cover a wide range of possible events depending on the predominant frequency of the signal; the records were grouped into three sets corresponding to low, intermediate and high predominant frequencies in the response spectra (Table 2). A fourth set was added since it consists of synthetic signals specifically generated for the Montreal area (Atkinson and Beresnev 1998), with broadband frequencies ranging from 3 to 25 Hz. They were derived from several trials simulating two representative earthquakes for Montreal: a magnitude 6 at a distance of 30 km and a magnitude 7 at 70 km. All time histories are scaled at a reference PGA of 0.16 g to be in accordance with the NBCC (1985) specifications for Montreal, in vigour at the time of the work. They provide with a consistent set of possible events for Montreal at different frequency ranges. Figure 2 shows the acceleration response spectra calculated for both real and synthetic time histories after PGA scaling.

Procedures that automatically generate input data files in the SHAKE91 format were developed to speed up the processing and updating of the large number of numerical simulations required for the microzonation (De la Puente and Rosset 2002).

Table 2 Selected earthquake records to build up seismic scenarios

Event name	Date	Depth (km)	Magnitude (M_w)	Faulting type	Station ID. Ep. distance	Pred. F (Hz)	Scenario
Saguenay	1988/11/25	29	5.9	Thrust with a s–s comp.	5 NS records 43–150 km	4–20	High Freq.
Izmit	1999/08/17	16	7.4	Right-lateral s–s	Gebze NS 42 km	1.5–3	Intermed Freq
Duzce	1999/11/12	14	7.1	Right-lateral s–s	Murdunu NS 34 km	2–4	
El Centro	1940/05/18	≈10	6.9	Right-lateral s–s	Diamonds Hts NS	1	Low Freq.
Loma Prieta	1989/10/18	17	6.9	Right-lateral s–s and reverse slip	Belmont EW 64 km	1–1.5	
Model 1			7.0		70 km	3–25	Synthetics
Model 2			6.0		30 km		

Note: s–s, strike-slip; Pred. F, predominant frequency content of the response spectra

Data sources: Peer (2000), Munro and Weichert (1989) for the Saguenay event, Atkinson and Beresnev (1998) for Models 1 and 2

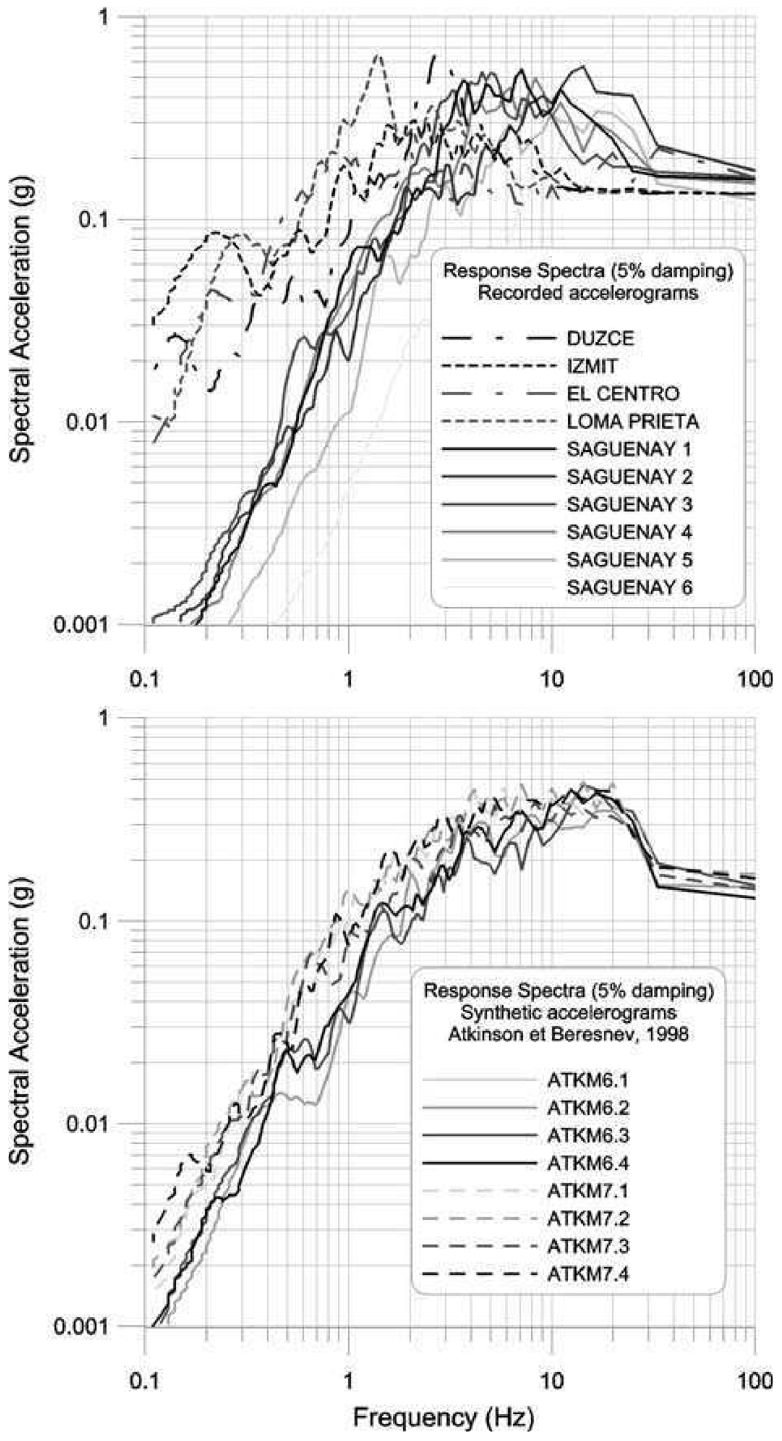

Fig. 2 Calculated response spectra with 5% damping for real (top) and synthetics records (bottom) used as input records for the 1D modelling. Time histories are scaled to a PGA of 0.16 g as proposed in the 1985 NBCC

4 Experimental site response estimates

Over 350 measurements were first performed over predetermined areas of the city representing a total surface of 20 km^2 (Rosset 2003a, b) and then the entire island was covered with up to 350 additional sites (Madriz 2004). A clear peak can be associated to the resonance frequency on the *H*/*V* ratios for two-thirds of the measured sites. The analysis for the other sites is more tricky and hypothetical. Some measurements had to be rejected due

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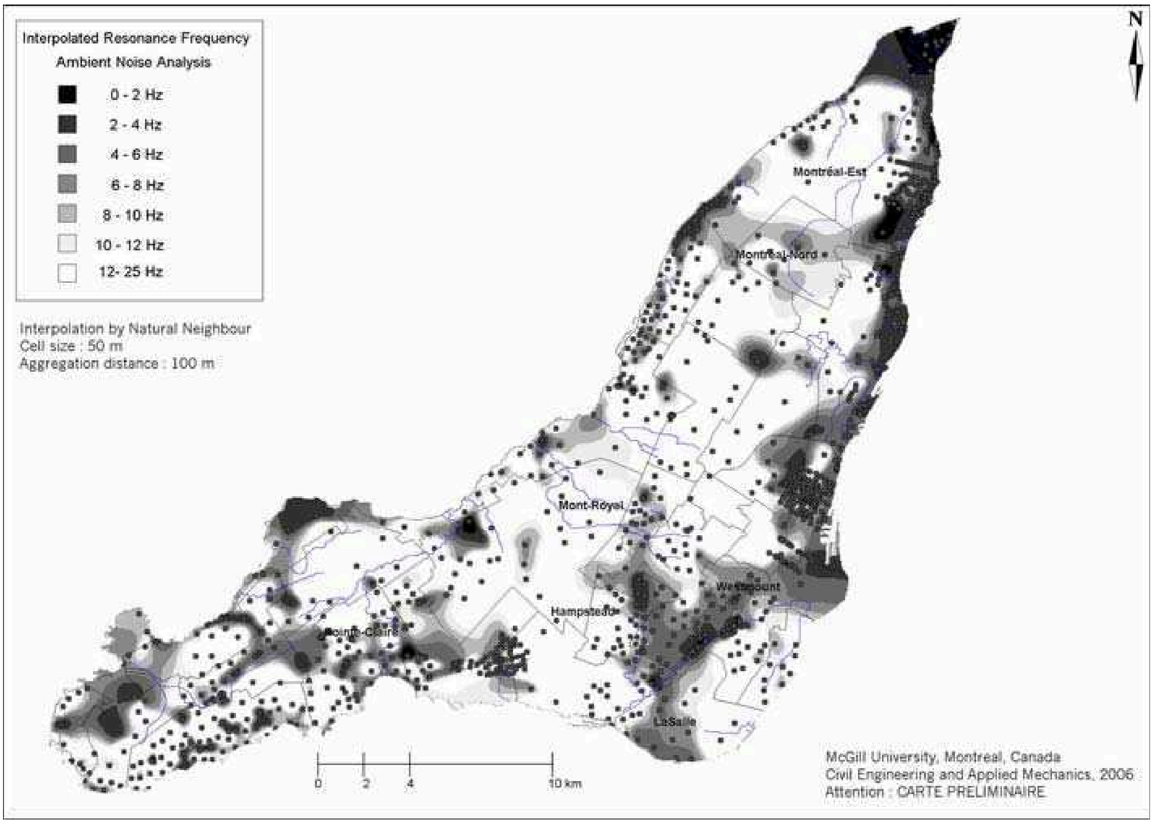


Fig. 3 Interpolated map of the predominant frequency response of soil obtained with ambient noise analysis. Black dots locate sites with ambient noise records. Old streams and the limits of districts are drawn

to difficulties in interpretation or ignored due to strong local perturbations during recording process. The values of resonance frequencies have been interpolated following the natural neighbourhood technique into the whole island. Figure 3 shows the interpolated map for ranked resonance frequencies. The NE terminal of the island has the lowest resonance frequencies that begin around 2 Hz close to the St-Lawrence River to more than 10 Hz where tills and rock outcrop. Low resonance frequencies are also encountered along the Eastern border of the island close to the River and values increase westward. The southern flank of the Mont-Royal, Westmount, the Hampstead, Mount Royal and Lachine “corridor”, the Pointe-Claire area and Montreal-Nord zone also have low frequency site responses. Some sites have singular low values that are well correlated with ancient riverbeds. It is the case for old mapped channels located in west of Pointe Claire and south of Westmount. A good correlation is found with interpolated map of bedrock depth (2159 boreholes reaching the basement), particularly in zones where clays are predominant.

For sites where boreholes are well documented, an attempt is made to correlate the predominant frequency of H/V ratios with the thickness of soft soil layers. Figure 4 shows the correlation for 115 sites where a single layer of clay overlies rock or till basement and the distant to the closest borehole is less than 500 m. The depth to basement refers to the top of the till formation rather than the bedrock (limestone and shale) as it constitutes the first predominant impedance contrast. Sites are divided in three datasets based on the distance to the closest borehole (<10 m, 100–300 m and 300–500 m). As expected, the results indicate that the resonance frequency decreases with the increase of the clay layer thickness. The general relationship $F = V/4H$, where H is the soil thickness, is plotted for shear-wave velocities V of 100, 200 and 300 m/s. For the sites at short distance to a borehole, points are within the lower and upper V intervals except for two outsiders.

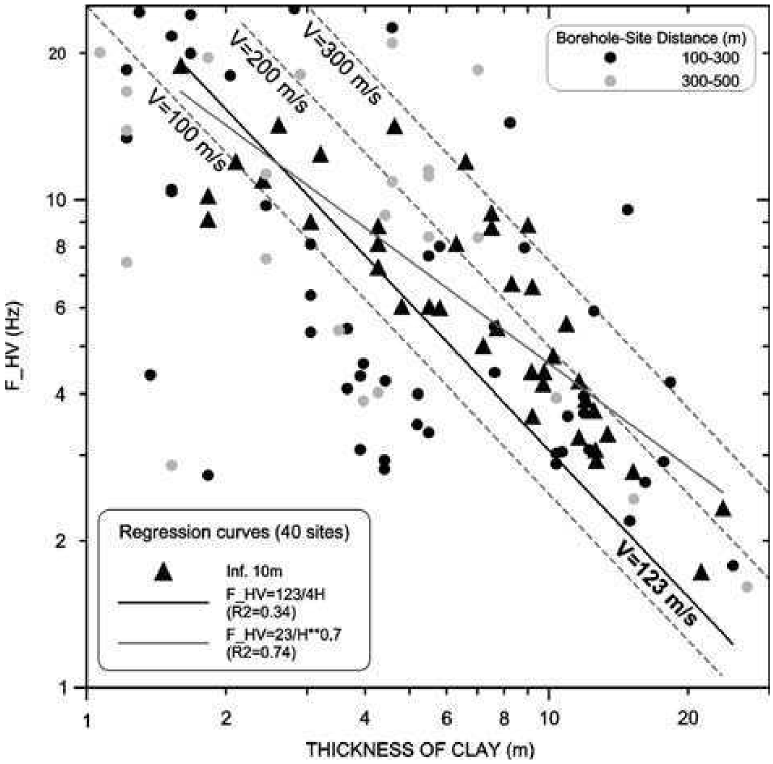


Fig. 4 Predominant frequency of resonance derived from the *H*/*V* polarization peak (F_HV) versus the thickness *H* of clay overlying tills (logarithmic scales). Sites are divided in three datasets based on the distance to the closest borehole. Grey dash lines represent a constant velocity *V* following the relationship $F = V/4H$. The black line is the best estimate of *V* using the dataset for sites with short distance to a borehole (filled triangle) and grey line is the power law fitting these samples (equations and *R*-square are given bottom-left)

For distant sites to boreholes (more than 100 m), one-third of the points have expected *V* values lower than 100 m/s but the deviation is still reasonable with few metres difference in thickness. A regression performed on the 40 sites of the short distance dataset results in an average shear-wave velocity *V* of 123 m/s with a coefficient of determination R^2 of 0.34. This result justifies the chosen average V_s for clay of 150 m/s if we down-weight the two outsider sites that are located in a clay lens bordered by sand and considers thickness uncertainty.

A power-type regression has been tested on the same dataset that gives a good R^2 of 0.73. It is of the form:

$$F = 23/H^{0.7} \qquad (1)$$

where *H* is the thickness of the clay layer overlying basal till (in m). Using *H*/*V* ratios from microtremor measurements, the Eq. 1 could be used to predict the thickness of clay for any other site in the same context of deposition.

5 Numerical site response analyses

Based on the compilation of thousands of boreholes, 1D response of soil columns was simulated for 1287 sites among the island. Of these sites, 363 are located at distances <50 m from sites investigated with ambient noise records. Figure 5 plots the sites where both predominant frequencies obtained with ambient noise records F_HV and the ones

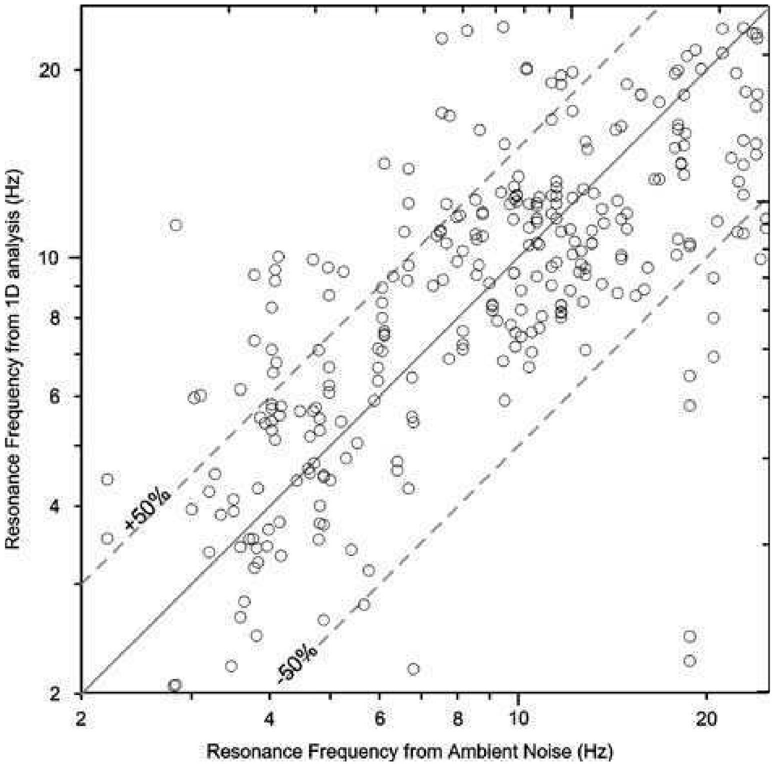


Fig. 5 Predominant frequencies of resonance derived from ambient noise analysis (F_HV) versus those calculated with the analytical approach (F_1D). The black line represents perfect agreement between the methods and the dash lines the ±50% deviation intervals

calculated with the 1D model F_1D are available. Straight lines showing the equivalence between both values as well as ±50% deviations are represented. There is an overestimation of the fundamental frequency derived from ambient noise analysis greater than 50% for 44 of the 363 sites. There is a good coherence between frequency values obtained with both approaches in 90% of the cases. Significant disagreement between experimental and numerical results in several zones of the island was observed. Some of these zones are characterized by modes of deposition that are inhomogeneous and disturbed by early river channels. In those cases, experimental method is not able to characterize these particular site conditions since it reflects the polarization of Rayleigh waves at the interface with the highest contrast of impedance that not necessarily fits the proposed 1D soil columns based on available geological data. Other discrepancies can be attributed to the lack of information on dynamic soil properties and in particular on the depth-dependant shear wave velocity and unit weight of the different layers which can have a major influence on soil response results.

The four sets of time histories (i.e. low, intermediate, high frequencies, synthetics, Table 2) scaled to a PGA value of 0.16 g are used as input motions for simulating soil responses. Results from 1D simulations are given in terms of PGA amplification factor, averaged over the input motions for a given set. The microzonation maps of Figs. 6 and 7 are the interpolated representation of the calculated mean PGA amplification factor at each site for the four sets of input motions. One can notice the large variability from one set to another. Depending on the chosen set, extreme values range from 3.5 to 6.8 as the mean values range from 1.4 to 3.5. High amplification factors calculated with the synthetic and high frequencies input records (Fig. 7a and b) are observed in zones with high *H*/*V* resonance frequencies (Fig. 3). The intermediate (Fig. 6) and, in less degree, the low (Fig. 7c) frequency scenario earthquake reflect the expected ground amplifications for representative

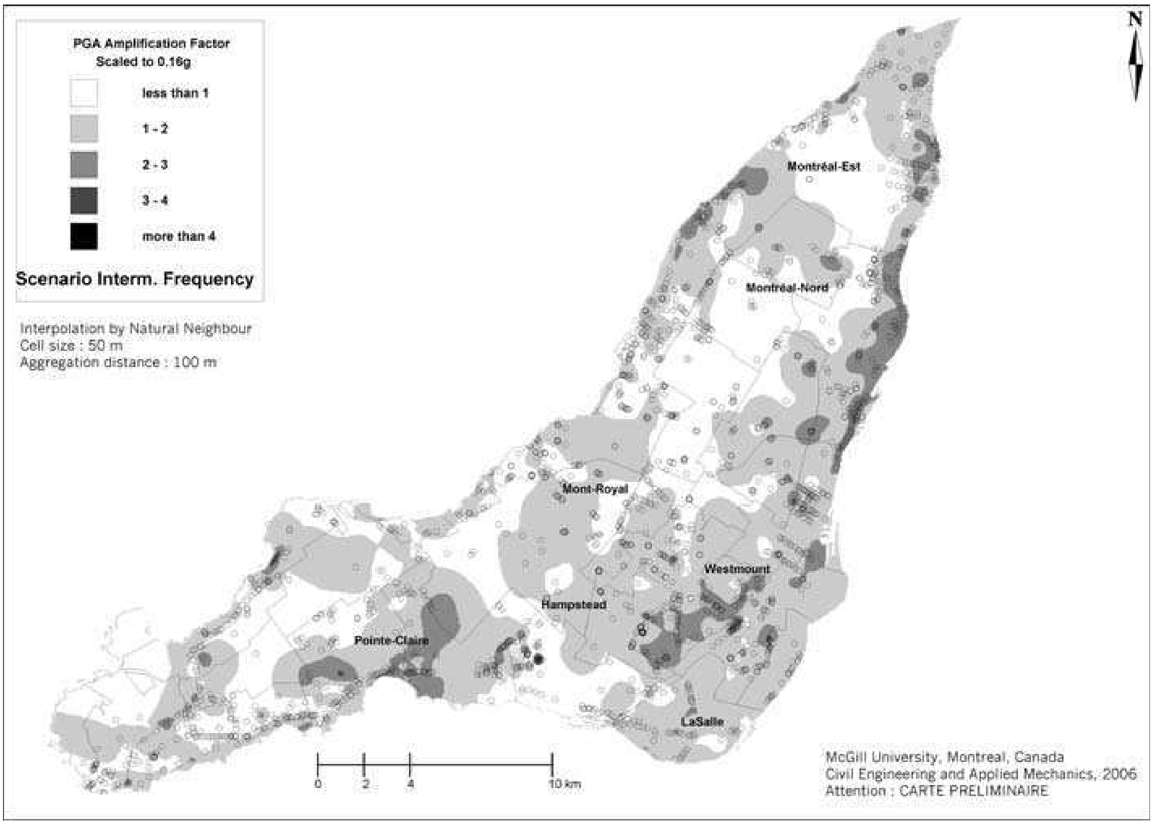


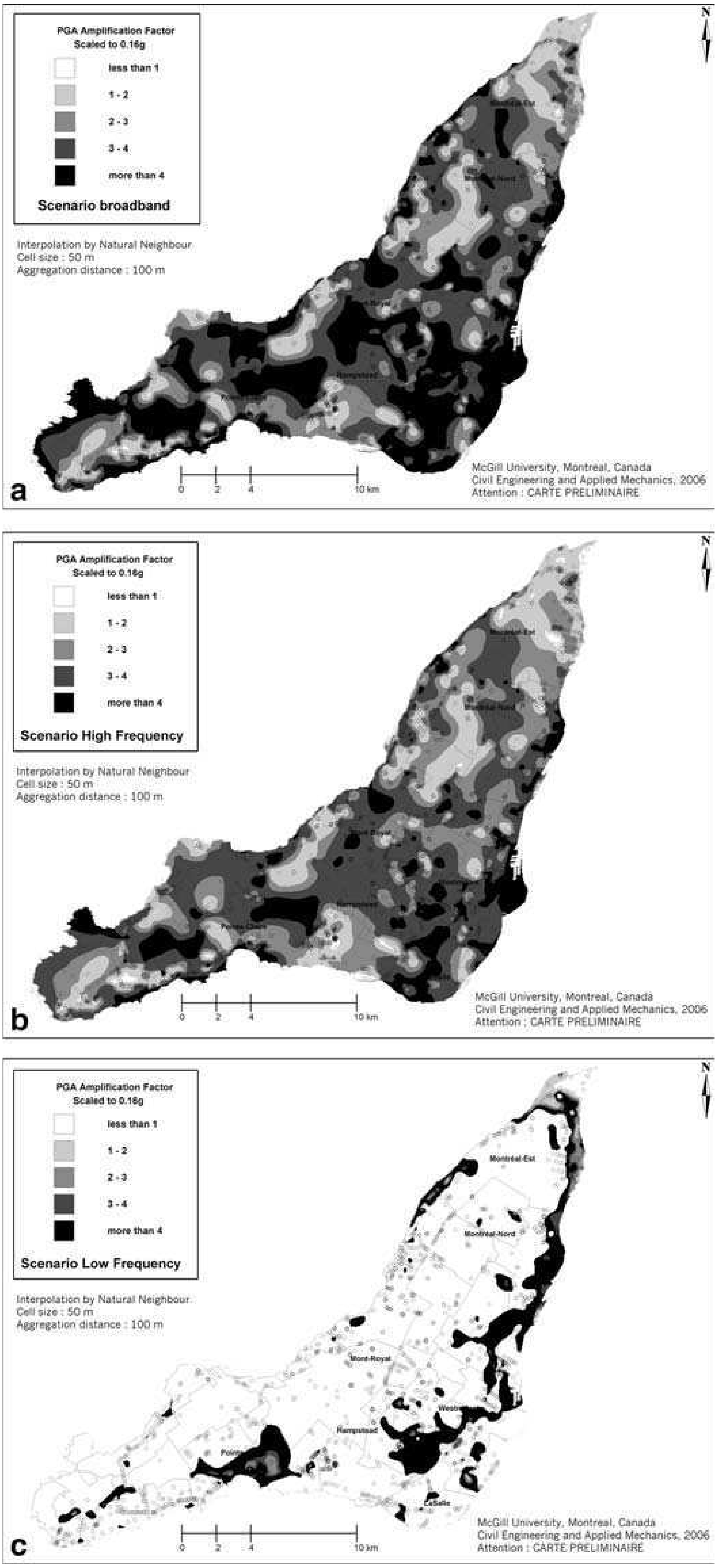
Fig. 6 Seismic scenario for Montreal. The interpolated PGA amplification factor is related to the Intermediate frequency content for one record of the Kocaeli (1999) and Duzce (1999) earthquakes. The reference PGA is 0.16 g

earthquakes in Eastern Canada. They correspond to a magnitude 6–6.5 earthquake distant of 40–100 km that should contribute more significantly in the seismic hazard of the Montreal area.

6 Discussions

The *H*/*V* method demonstrated to be both fast and efficient in estimating the resonance frequency of a site in the urban context of Montreal, which is a key parameter for assessing buildings vulnerability. However, some difficulties of interpretation are encountered in areas where surface soils are non-laterally homogeneous due to successive sequences of soil deposition and weathering. In these cases, *H*/*V* ratios exhibit two or more amplitude peaks or a wide amplitude plateau. 1D numerical modelling approach is used to fill in the gaps as soon as deep data is available. Resonance frequencies for 363 sites are compared together using both the experimental and numerical results (Fig. 5). Two-thirds of the observations are within 50% of the line corresponding to perfect agreement between the two estimation procedures. Most of the differences between experimental and numerical estimates can be related to the uncertainties on input parameters for the physical properties

Fig. 7 Seismic scenarios for Montreal. The interpolated PGA amplification factor is related to (**a**) the ▶ broadband frequency content of the synthetic strong motions calculated for Montreal by Atkinson and Beresnev (1998); (**b**) the high frequency content of the Saguenay earthquakes (1988) recorded at 5 stations; (**c**) the low frequency content of the record of the Loma Prieta (1989) and Imperial valley (1940) earthquakes


PGA Amplification Factor
Scaled to 0.16g
less than 1
1 - 2
2 - 3
3 - 4
more than 4
Scenario broadband
Interpolation by Natural Neighbour
Cell size : 50 m
Aggregation distance : 100 m
N
0
2
4
10 km
McGill University, Montreal, Canada
Civil Engineering and Applied Mechanics, 2006
Attention : CARTE PRELIMINAIRE
a
Scenario High Frequency
b
Scenario Low Frequency
Montréal-Est
Montréal-Nord
Mont-Royal
Hampstead
Westmount
LaSalle
c

of soft soil deposits and the misinterpretation of *H*/*V* ratios. In a few cases, the interpretation of the polarization peak of the *H*/*V* ratio is problematic and appears to be better correlated with the second resonance frequency calculated with the numerical approach. The general good agreement between the numerical and experimental frequencies demonstrates the efficiency of the experimental approach for estimating the fundamental mode of resonance of a site.

The impedance contrast at the interface of two layers is an important criterion in qualifying site effects. Higher contrasts are correlated with stronger seismic soil responses. The available geotechnical database did not contain sufficient information to quantify the impedance contrast as a function of depth at the interface between individual soils layers (e.g. clay or sand). However, this influence was established for sites with a homogeneous layer of clay above rock or till basement by comparing the obtained empirical frequencies of resonance and its thickness (Fig. 4). The level of confidence for Eq. 1 ($R^2 = 0.7$) is relatively good to correlate the thickness of the clay layer with the site response. This correlation is used to generate zonation at large scale (1/50,000) by including information on till and rock outcropping region as well as the knowledge of surface geology to better define the contours between zones of same response pattern. It is particularly pertinent in clay zones well correlated with the 2 to 8 Hz frequency lines of Fig. 2.

The transfer function calculated with SHAKE91 is used to produce maps of PGA amplification relative to a 0.16 g reference value. Results are divided into 4 groups corresponding to reference input motions with different predominant frequencies as shown in Table 2. Table 3 gives the main statistics on the calculated values for the 689 sites. Relative PGA amplification ranges from 1 to 7 depending on the chosen set of input motions. Highest values are exceptions as 75% of the sites have values lower than 4. Intermediate, high, low frequency scenarios and synthetic one are classified in terms of the increasing median PGA amplification factor. The predominant frequency resonance map of Fig. 3 coupled with the PGA amplification factor mapping of the Fig. 6 is used as base information for seismic mitigation (Chouinard and Rosset 2007).

The integrated methodology developed for the project allows modifications to the database and maps as soon as new data or knowledge becomes available. Further improvements are needed to fit the new code regulations (NBCC 2005) and to provide a seismic zoning at different periods for engineering purposes. Uncertainties on the input physical properties values will be included in the layer models by considering a set of 250 calculations per site instead of a single one. Then, the microzonation results could be used to perform vulnerability assessment and performance analyses for lifelines and buildings, which in turn will be incorporated in emergency and seismic hazards mitigation planning (Chouinard et al. 2004).

Table 3 Statistics on PGA amplification factor for 689 sites as calculated for the 4 scenarios

Input frequency band PGA amplification factor	High frequency	Low frequency	Intermediate frequency	Synthetics
Minimum	0.9	1	0.9	0.9
Maximum	5.9	6.7	3.5	7.1
Mean	3.1	1.8	1.5	3.4
Median	3.3	1.7	1.3	3.7
First quartile	2.3	1.4	0.9	2.5
Third quartile	3.8	2.1	1.9	4.4

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