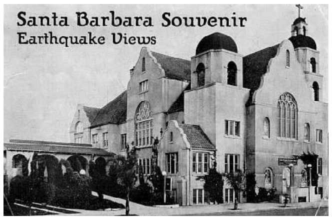

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MICROZONATION OF MONTREAL, VARIABILITY IN SOIL CLASSIFICATION

Chouinard Luc
McGill University
Montreal, QC
CANADA

Rosset Philippe
WAPMERR
Geneva,
Switzerland

ABSTRACT

Montreal ranks second in Canada (around 20% of national risks) after Vancouver for seismic risk based on exposed population and on the probability of earthquake occurrence. Site response of Champlain Sea and Saint-Lawrence River deposits was investigated using micro tremor techniques, numerical simulations, seismic surveys and borehole data. Since 2001, two approaches were investigated for microzonation purposes. The first approach is based on correlating the resonant frequency F_0 obtained from microtremor measurements with the maximum amplification factor obtained from equivalent linear seismic response analyses for a set of input strong motion records. The second approach is based on Vs_{30} derived from relationships between shear wave velocity Vs, depth to bedrock and F_0 for a set of typical sites. A relationship between F_0 and Vs_{30} is proposed for zones with highest expected site response. Both approaches indicate that regions where site responses are most significant correspond to locations where Leda clays and river sand deposits are predominant. Differences between microzonation maps are mainly related to the spatial extent of the soil type zones which are found to be sensitive to the interpolation procedure and the models used to represent the properties of soft soil layers.

INTRODUCTION

The urban area of Montreal has a population of 1.7 millions. It is located in a moderately seismic zone where several earthquakes of intensity higher than VI occurred in the recent past (Lamontagne, 2008). The largest historical event occurred in 1732 with an estimated magnitude of 5.8 and reported damage to 300 houses (Leblanc, 1981). PGA deaggregation analysis shows that the main contribution to seismic hazards at the 2% in 50 years level is due to earthquakes of magnitude 6 at a distance of 30km (Adams and Halchuk, 2003). In 1988, the Mw 5.9 Saguenay earthquake located at 350km from Montreal caused severe damage to the masonry cladding of the former Montreal East City Hall. Mitchell et al. (1990) concluded that the damage was the result of the combined effect of soil amplification due to 17 m of Leda clay and the poor condition of the structure. Soft soil layers on the island of Montreal are mainly associated with Leda clay deposited during the Champlain Sea era and more recently deposited sand from the Saint-Lawrence River. These considerations make the Montreal urban area subject to high seismic risks and justify the elaboration of a microzonation map for civil protection and mitigation purposes.

Since 2001, several methods were investigated to estimate site response across the island. Interpolated maps derived from the resulting datasets show similar site responses but with some variability in the contours lines defining the various soil types zones. The derivation of the different maps is described followed by a discussion of the variability between the maps.

METHODS FOR SITE RESPONSE ANALYSIS

H/V spectral ratio (HVSR) analyses were performed using ambient noise records for more than 2000 sites. These were combined with 1D pseudo linear analyses of site response at more than 700 sites selected from a dataset of more than 26600 boreholes (Rosset and Chouinard, 2009). The study has shown a good correlation between the predominant frequencies derived from the H/V peak amplitudes and the thickness of Leda clay deposits that range from a few meters to 20m at the eastern tip of the island. Maps were derived as a function of the expected amplification factor for various earthquake scenarios in terms of frequency content which has a significant influence on site response. Figure 1 shows the map of interpolated amplification factors for earthquakes records with intermediate frequency contents (2-10 Hz) which is the range that was judged to be most appropriate for the Montreal area. Amplification factors range from 1 to 3.5. The first proposed microzonation map combines the information from the predominant mode of resonance (F_0HVSR) and the associated amplification factor (Chouinard and Rosset, 2007) (Figure 2).

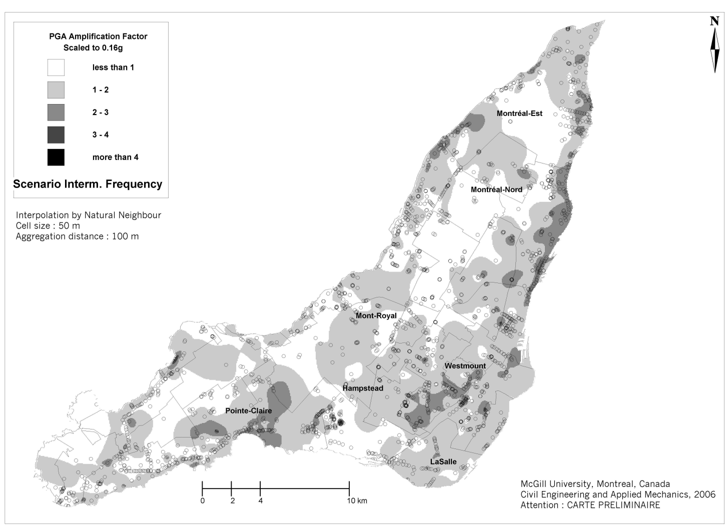


Fig. 1. Microzonation of Montreal related to PGA amplification factor. The interpolated values are based on 1D calculation performed with earthquake records having an intermediate frequency contents (2-10Hz) and scaled to 0.16g (from Rosset and Chouinard, 2009).

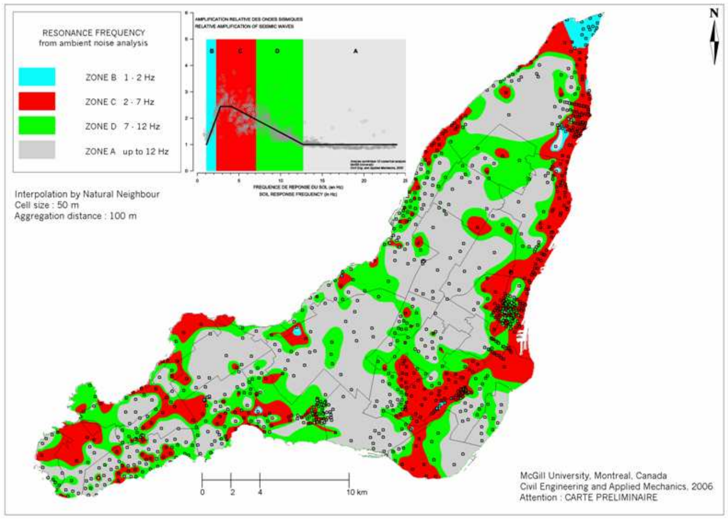


Fig. 2. Microzonation of Montreal related to PGA amplification factor and resonance frequency. Four zones are identified based on the amplification factor calculated with 1D model and the predominant frequency derived from H/V analysis (from Chouinard and Rosset, 2007).

The 2005 version of the National Building Code of Canada (NBCC2005) includes soil classifications based on the Vs_{30} parameter (Finn and Wightman, 2003). In 2008, various seismic surveys campaign were performed to measure both body and surface wave velocities at sites in the Montreal area. The surveys comprised MASW (Multichannel Analyses of Surface Waves) measurements at 32 sites, downhole seismic measurements on 3 boreholes, seismic refraction on 3 sites, and high resolution multichannel seismic reflection records using a land streamer over 3 segments for a total distance of 7.5 km. Sites were selected in zones with Leda clay, sand and peat and to cover the full range of soft soil deposit thicknesses.

Sets of active and passive MASW data were used to produce 1-D shear-velocity profiles for the different sites following the scheme developed by Spark and Miller (2008). Each site had a minimum of two active MASW field records collected with different source offset and receiver spacing and for 13 sites, one passive MASW record. Inverted 1-D shear-velocity profiles are compared to the closest geological log to attribute a Vs value for each type of soil at a given depth. Downhole shear wave arrival times were processed using running least-squares fits to the offset distance-corrected depths and travel times. Interval velocities were obtained over vertical distances and average velocities computed directly from surface to the detector at depth (Hunter et al., 2002). Standard refraction interpretations were employed using the slope-intercept refraction method, after first arithmetically averaging forward and reverse velocity segments. The use of landstreamer for shear wave reflection applications was used to obtain higher accuracy in both average and interval shear wave velocity determination (Pugin et al., 2008). A best-fit regression relation between average velocity V_{av} and depth Z was derived using 380 values derived from the dataset up to a depth of 35m which is the maximum thickness of post-glacial sediments on the island. The resulting expression is as follows and can be used to estimate average shear wave velocity at sites where only depth to bedrock is known.

$$V_{av} = 170 + 29\,Z^{0.5} \quad +/- \; 50 \text{ m/s} \qquad (1)$$

A consistent dataset of Vs values was also compiled for sites where the soil type and thickness could be determined accurately. Equations were derived for Vs as a function of depth for river sand and Leda clay (Figure 3). Ranges of Vs for till and bedrock (limestone and shale) are also derived from field data (Rosset et al., 2011). These relationships and ranges are used to estimate shear wave velocity at sites where detailed stratigraphic information is available.

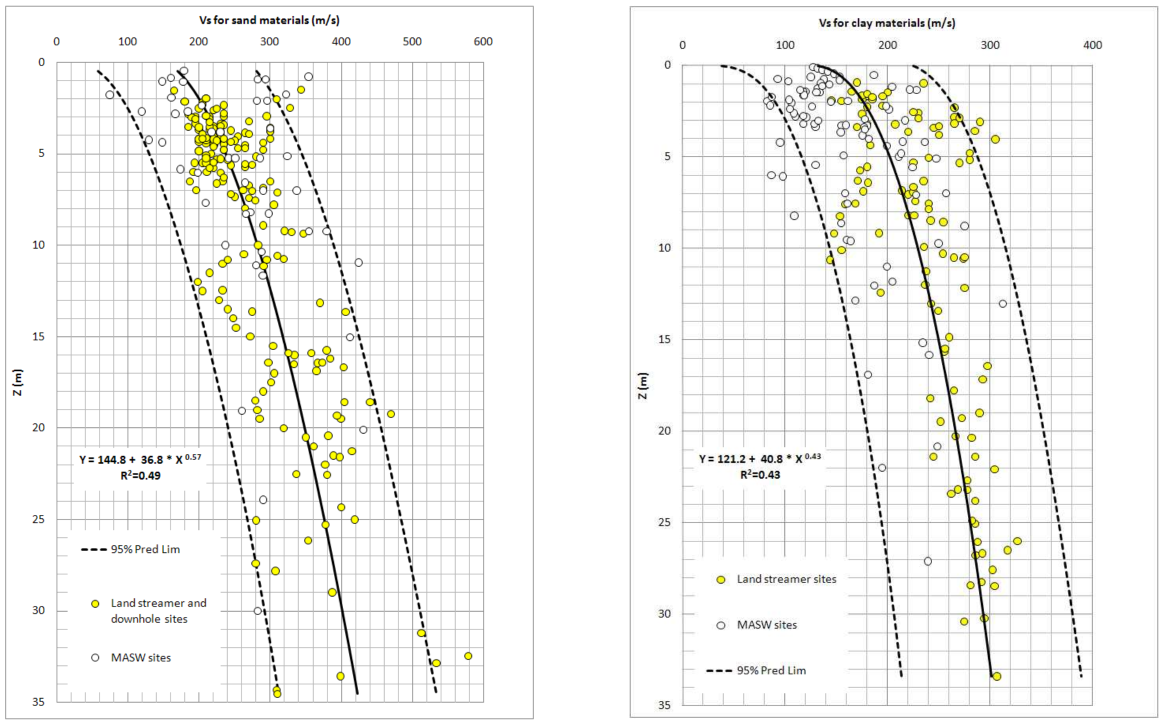


Fig. 3. Vs versus depth relations. Regressions are determined for river sand (left) and Leda clay (right) using field data (from Rosset et al., 2011).

Finally, several sites where the average Vs at 30m (Vs_{30}) had been obtained were also surveyed with the HVSR method in order to determine F_0HVSR. The regression between Vs_{30} and F_0HVSR shows good agreement up to 10Hz (Figure 4). The following relation is proposed to estimate Vs_{30} in zones with Leda clay:

$$Vs_{30} = 177 + 44.7\, F_0 \pm 89\text{m/s} \tag{2}$$

An excellent correlation up to 0.7s is also obtained between the T_0HVSR and the value derived from the double travel time using 2D high resolution seismic profiles at 33 sites (Chouinard and Rosset, 2011).

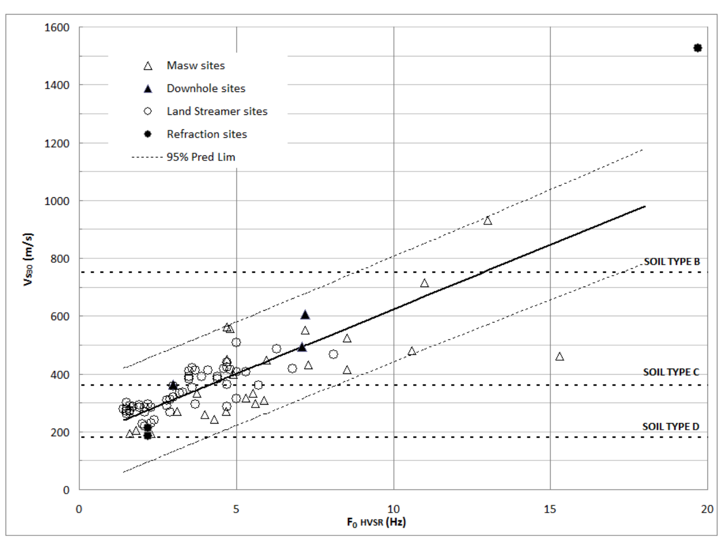


Fig. 4. Comparison of estimated Vs30 values and predominant frequency F_0 from HVSR. Limits for the soil classes used in the NBCC2005 are indicated

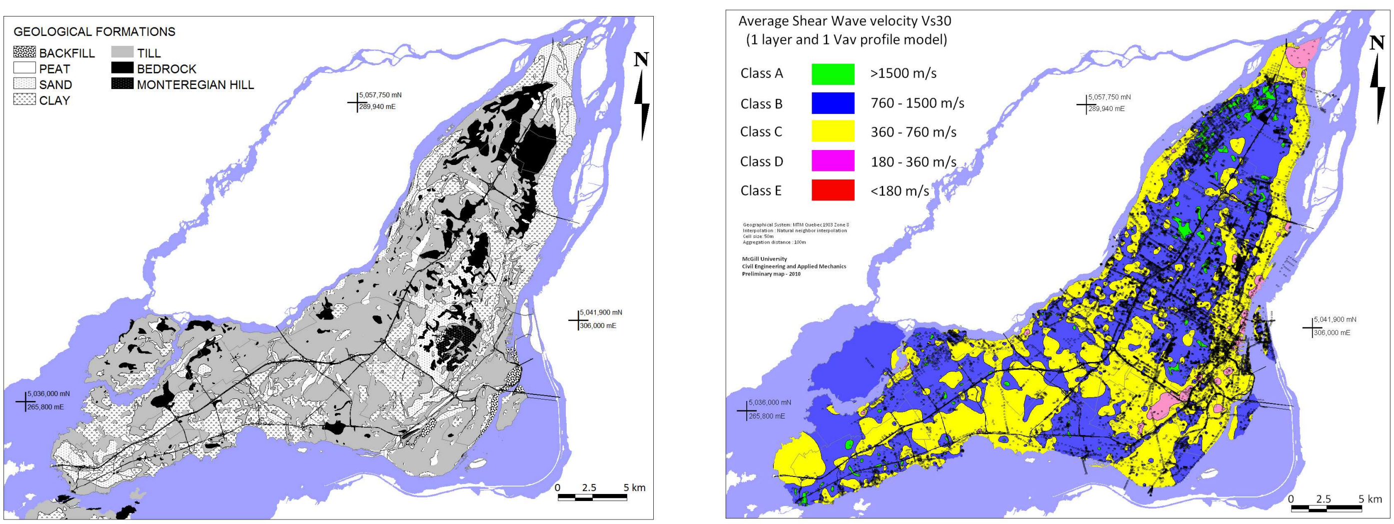
VS30 MODELS

Three models are developed to produce interpolated maps of Vs_{30} using the following averaging formula:

$$Vs_{30} = 30/\Sigma(Z_i/Vs{*}Z_i)+(30-\Sigma Z_i)/\ Vs_{rock} \quad (3)$$

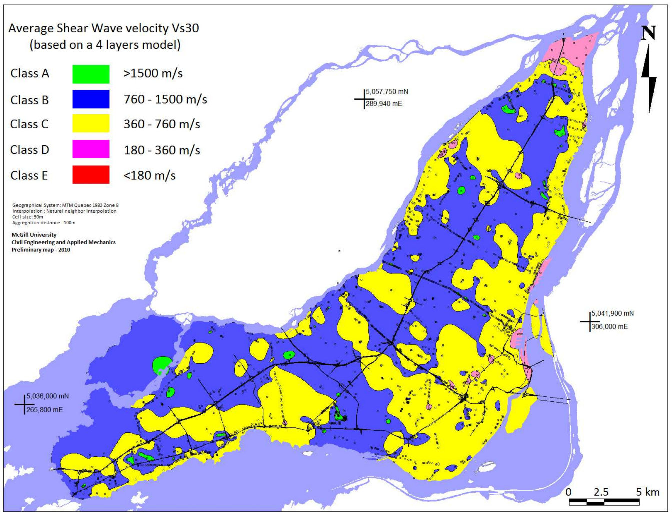
where $\Sigma(Z_i/Vs{*}Z_i) = (Z_{backfill}/Vs_{backfill}) + (Z_{sand}/Vs_{sand}) + (Z_{clay}/Vs_{clay}) +(Z_{till}/Vs_{till})$ and ΣZ_i the total thickness of soft layers (see geological map of Fig.5a).

For each model, a natural weighted neighborhood interpolation procedure with an aggregation distance of 100m is used to calculate values on a regular grid with a resolution of 50m. The interpolation is not performed on Vs_{30} but rather on values given for the 5 classes of soils of the NBCC2005; 1 for soil class A, 2 for class B, 3 for class C, 4 for class D and 5 for class E. This procedure tends to smooth the transition between the different soil classes and better fits contours of the surface geology (Rosset et al., 2011). The first model considers the borehole dataset (more than 26600 sites) to interpolate the depth to the top of the rock and uses Equation (1) to estimate V_{av} of glacial and post glacial sediments (backfill, sand, clay and till) while Vs_{rock} is set at 2344 m/s. The second model is based on the detailed stratigraphic information from 2413 boreholes where the thickness of backfill, river sand, Leda clay and till is available. V_{s30} is then calculated using Equation 3. V_s for sand and clay are calculated with the equations shown in Fig. 3 and values of 155m/s and 565 m/s are specifid for backfill and till respectively. The third model is derived from the F_0HVSR data at 2520 sites to calculate V_{s30} using Equation 2. Maps of Figures 5b, 5c and 5d show the resulting microzonation maps obtained for the three models.

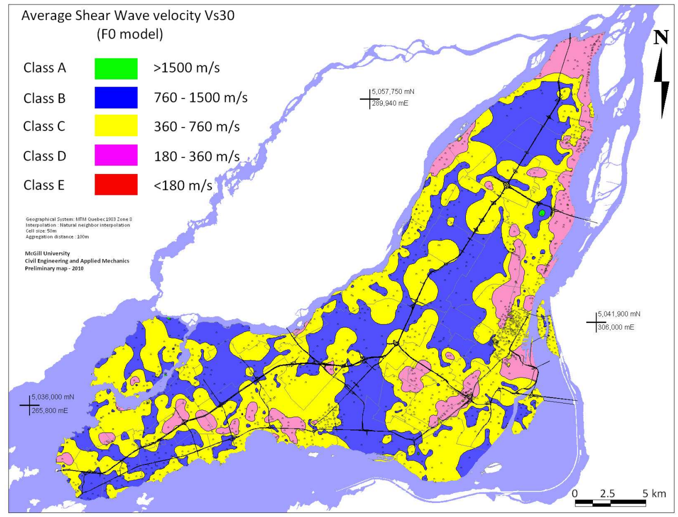


(a) (b)

Fig. 5. Geological map and models of soil classes' microzonation for Montreal. (a) Geological map (b) the model considers a single layer of glacial and post-glacial sediments overlying the bedrock. Black dots locate the sites. Soil classes are the ones used in NBCC2005 (from Rosset et al., 2011).



(c)



(d)

Fig. 5 continued. Geological map and models of soil classes' microzonation for Montreal. (c) the model includes 4 layers of glacial and post-glacial sediments and the bedrock (d) the model uses the relation between Vs30 and F0HVSR. Black dots locate the sites. Soil classes are the ones used in NBCC2005 (from Rosset et al., 2011).

DISCUSSION

Microzonation maps of Figures 1, 2 and 5 were derived using different sets of data and are obtained by using well-established analytical and experimental methods. Significant differences can be noticed in the location of the boundaries between the different soil classes. The map of Fig. 2 is derived from the 1D site response analyses of Fig.1 and HVSR predominant frequencies. Zones with higher expected amplification correspond to the zones where Leda clay is present. Amplification factors are smaller in the eastern tip of the island where the clay layers are thicker and can be partly explained by the presence of a sand layer above the clay. In general, the boundaries between soil classes are consistent with surface geological data.

The microzonation maps of Figures 5b and 5c are mainly based on borehole information and field measurements of V_s. The last map of Fig.5d combines V_s and F_{0HVSR} data. The map based on a 1 layer model (Fig. 5b) shows boundaries that are similar to those between the different soil units on surface geology maps (Fig. 5a) because it is produced by incorporating data from more than 26600 sites that provide depth to bedrock. In this map, soil class D is only identified at the eastern part of the island and in a central part where a peat deposit is present. Soil classes C and B are predominant within the island. The density of sites used in the interpolation is much lower for the map derived using the 4 layers model (Fig. 5c) but exhibits similar features of those from the map based on the 1 layer model. The spatial extent of the soil class D is larger in the eastern part of the island and is attributed to a more precise model for clay layer, while the spatial extent of the soil class D is smaller in the central part because the influence of the peat layer is reduced. Finally, the model based on the relation between Vs_{30} and F_0HVSR (Fig. 5d) is the one that shows the largest spatial extent for soil class D. This result is consistent with the Vs_{30} values calculated at the sites where Vs measurements were performed. The similarity of the boundaries for clay and oil class D is relatively good if we consider the density of sites located in soft soil zones and the fewer sites in zones for glacial sediments and bedrock. Finally, the HVSR method seems to be an efficient means of estimating Vs_{30} using Equation 2 because F_0HVSR is highly correlated with the thickness of the soft layers and the predominant frequency of the site response.

Interpolation procedures are crucial when producing microzonation maps. Different interpolation methods were investigated and the natural weighted neighborhood method gives the best results when compared to the surface geology boundaries. Rosset et al. (2011) propose to combine the different models described above and to adjust the boundaries of the microzonation using geological information. Combination of 1D calculations and HVSR methods influences the amplification factors in the eastern part of the island where the soft soil layer is the thickest. The influence of multi-layering of different soil types reduces the level of amplification predicted with 1D calculations, an effect that is not captured in the Vs_{30} mapping. Amplification factors differ in magnitude as a function of the method. Maximum amplifications obtained with 1D calculation are around 4 for frequencies 2-7Hz and a maximum PGA of 0.16g in zones where soil class D are found. These values are larger than the NBCC (2005) recommended amplification factor of 2.4 for soil class D. In this sense, Vs_{30} is not necessarily the best parameter to assess site response when a high velocity gradient is found between the soft soil and bedrock as is prevalent in the Montreal area.

REFERENCES

Adams, J., and S. Halchuk [2003]. “Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada”, Geological Survey of Canada Open File 4459.

Chouinard, L.E., and P. Rosset [2007]. “Seismic site effects and seismic risk in the Montreal urban area. The influence of marine clays”, Proceedings of the Ninth Canadian conference on earthquake engineering, Ottawa, Ontario, Canada, pp 26–29.

Chouinard, L.E., and P. Rosset [2011]. “On the use of ambient noise technique for microzonation purposes: the case of Montreal”, to be published in a book series. Geological Survey of Canada.

Finn, W.D. L. and A. Wightman [2003]. “Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada”, Can. J. Civ. Eng., Vol. 30, pp. 272–278.

Hunter, J. A., Benjumea, B., Harris, J. B., Miller, R. D., Pullan, S. E., Burns, R. A. and R. L. Good [2002]. “Surface and downhole shear wave seismic methods for thick soil site investigations”, Soil Dynamics and Earthquake Engineering, Vol. 22, pp. 931-941.

Lamontagne, M. [2008]. “Earthquakes in eastern Canada: a threat that can be mitigated”, Proceedings of the 4th Canadian conference on geohazards : from causes to management, Locat, J (éd.); Perret, D (éd.); Turmel, D (éd.); Demers, D (éd.); Leroueil, S (éd.). pp. 13-24.

Leblanc, G. [1981]. "A closer look at the September 1732, Montreal earthquake", Canadian Journal of Earth Sciences, Vol. 18; No. 3, pp.539-550.

Mitchell, D., Tinawi, R., and T. Law [1990]. “Damage caused by the November 25, 1988 Saguenay earthquake”, Can. J. of Civil Eng. Vol. 17, No. 3, pp 338-365.

Park, C. B., and R.D. Miller [2008]. “Roadside passive multichannel analysis of surface waves (MASW)”, Journal of Environmental & Engineering Geophysics (EEGS), Vol. 13, No. 1, pp. 1-11.

Pugin, A. J-M., Pullan, S. E. and J.A. Hunter [2008]. “SV-wave and P-wave high resolution seismic reflection using vertical impacting and vibrating sources”, Proceedings of SAGEEP’08 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Philadelphia, PA, April 6-10, 2008, 10p.

Rosset, P. and L.E. Chouinard [2009]. “Characterization of site effects in Montreal, Canada”, Natural Hazards, Vol. 48, pp. 295-308.

Rosset, P., Bour, M., and L.E. Chouinard [2011]. “Vs30 maps for Montreal. Variability of the contours”, to be submitted.