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# SEISMIC HAZARD ANALYSIS FOR MONTREAL

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## SUMMARY

The objective of this paper is to describe on-going research on the seismic hazard analysis and vulnerability assessment for the Montreal Urban Community. The first part describes the overall work being performed in developing an inventory of critical lifelines and the estimation of their seismic vulnerability. The second part describes a procedure and the results for a seismic microzonation of site effects that combine both a field approach based on ground-ambient noise analysis and numerical modeling based on one-dimensional SHAKE computations.

## INTRODUCTION

Montreal is the most populated city of the province of Quebec with more than 2.8 millions of inhabitants that live on and in the vicinity of the island. It is the economical capital of the province and an international exchange center. A nationwide seismic risk survey by Adams [1] indicates that Montreal represents 18.76 % of the Canadian risk and ranks second after Vancouver. Montreal is particularly vulnerable to seismic events since a significant portion of its infrastructure is old and deteriorated or has been designed according to standards that predate the development of modern seismic design standards. The case of the City Hall in Montreal-East where the masonry cladding was severely damaged during the magnitude 6 Saguenay earthquake (300km far away) in 1988 is a single but remarkable example of seismic damage. Back-analysis determined that the damage was due both the deteriorated state of the building and local amplification from the thick clay layer at the site (Mitchell et al. [2]). The objectives of the project are to perform a seismic hazard analysis that can be used to develop effective mitigation plans, sensitize emergency agencies to earthquake risks, and provide tools to enhance emergency preparedness. Participants in the project include all major stakeholders in the community, emergency response services (police and fire fighting), public transportation, buildings and maintenance services, water service, gas, electricity and telecommunications utilities, insurance companies, and associations of major building

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owners. This is the first comprehensive seismic hazard analysis for the City of Montreal with the participation of all the major stakeholders for infrastructures. The project can be a showcase for the development of integrated risk management procedures for infrastructures.

The proposed research plan consists of three main components: 1) The development of a digital database of infrastructures and lifelines for Montreal, 2) The calibration and validation of assessment procedures (vulnerability and consequences of failure) for their application to Montreal and 3) A seismic analysis of targeted lifelines in collaboration with major utilities, and the identification of mitigation plans for reducing seismic hazards.

## SEISMIC SETTING

Seismicity around Montreal is controlled by two main active bands within the Western Quebec Seismic Zone (Adams and Basham [3]) that are associated with regional tectonics (Figure 1). One band follows the Ottawa and St. Laurent Rivers and is the location of three major historical earthquakes: a magnitude 5.8 near Montreal in 1732; a magnitude 6.2 near Timiskaming in 1935 and a magnitude 5.6 near Cornwall-Massena in 1944 (Table 1). The seismic activity is related to a normal faulting zone of Cambrian-Palaeozoic age, which may represent a failed rift in the Grenville province. The second band is oriented NW-SE and extends from Montreal to the Baskatong Reservoir (200 km north to Ottawa). Although the relation between epicentres and local tectonics is not clear, Adams and Basham [3] propose that they are due to crust doming and fracturing over a hot spot during the Mesozoic.

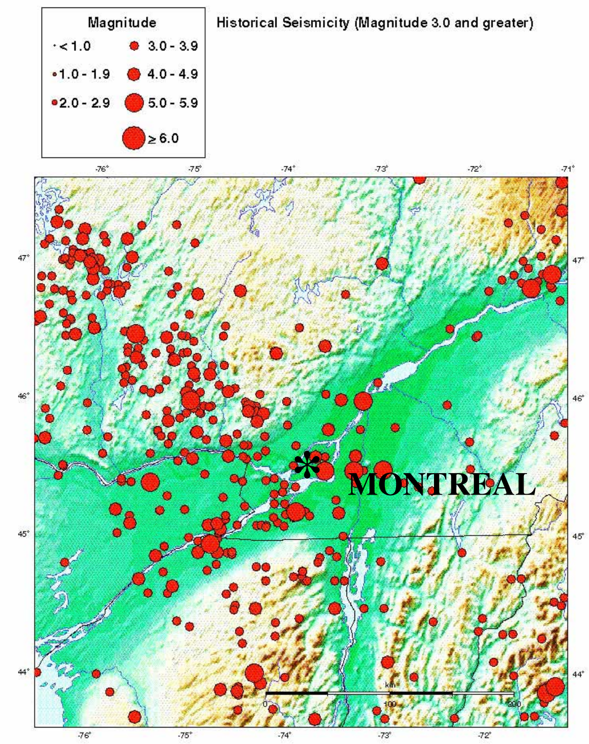


**Figure 1: Historical seismicity around Montreal. (Halchuk [13])**

The current edition of the National Building Code of Canada (NBCC [4]) indicates that Montreal can expect horizontal PGA of 0.16g for a probability of non-exceedence of 10% in 50 years. Seismic hazard maps being prepared for the next NBCC (2005) will incorporate new information and will use lower-probability hazards, 2% in 50 years (Adams and Atkinson [5]; Adams et al., [6]).

**Table 1 : Major historical earthquakes felt in Montreal. (Halchuck [13]).**

| Date | Latitude North | Longitude West | Magnitude $M_L$ | Epicentral distance (km) | Estimated MMI | Estimated PGA (g) |
|---|---|---|---|---|---|---|
| 1732/09/16 | 45.5 | 73.6 | 5.8 | 0 | VIII | 0.241 |
| 1816/09/09 | 45.5 | 73.6 | 5.7 | 0 | VIII | 0.212 |
| 1816/09/16 | 45.5 | 73.6 | 5.0 | 0 | VI | 0.085 |
| 1893/11/27 | 45.5 | 73.3 | 5.7 | 23 | VI | 0.091 |
| 1897/03/23 | 45.5 | 73.6 | 5.0 | 0 | VI | 0.085 |

## INFRASTRUCTURES AND LIFELINES

The development of a digital database in a Geographical Information System (GIS) is essential to process all the information required to perform a vulnerability analysis of lifelines and main typical buildings. The database integrates the most recent elements for the regional seismic hazard , the local effects of recent deposits given by the microzoning information, and the location and characteristics of infrastructure and lifelines.

The Emergency Preparedness Centre of the Montreal Urban Community compiled a database of emergency buildings and infrastructure within the community and has made it available for the project. Similarly, participating utilities have digital databases of their respective facilities and are contributing their information to the project.

To date, several projects have been completed. New seismic screening procedures for buildings (Leung [7]) and bridges (Liu [8]) have been developed and applied to a sample of representative structures. A representative sample of buildings important to public health and safety were selected for a detailed screening inspection. One team of inspectors focused on structural components while the second team focused on functional and operational components within the facilities. The objective was to demonstrate the process of seismic screening to participating municipalities, evaluate the time and personnel required for each inspection, and to identify typical deficiencies. This exercise demonstrated the need to better integrate seismic screening procedures for structures and functional and operational components, that the effect of deterioration of existing structures is not considered in sufficient detail in the screening procedure, and that a map of local soil conditions, which play a critical role in the amplification of ground motions, was lacking. Potential damage assessment to buidlings have not yet been performed. The analysis procedures based on available damage functions need to be validated and calibrated for the Montreal area. For this purpose, detailed non-linear analyses of individual typical buildings and infrastructure have been performed (Lamya [9], Lim [10]). Non-emergency buildings have initially not been included in the study but will be the subject of future studies.

Lifelines considered in the project are: 1) Bridges and overpasses, 2) Water supply, 3) Waste water collection systems (and treatment), 4) Electricity network, 5) Natural gas network and 6) Telecommunications. Currently, a project is underway for mapping the liquefaction potential across the island of Montreal. This study will also be used in assessing the vulnerability of numerous underground facilities such as water supply and gas networks. Bridges and overpasses are vulnerable elements of the transportation network, and several of these are being evaluated through a detailed structural analysis (De la Puente [11]). Some utilities in Montreal have performed vulnerability analyses for individual components of their networks and these will be incorporated into the global analysis of the vulnerability of lifelines. Currently, this data is being compiled and analysed in order to develop overall vulnerability analyses for the entire network and to convert these to fragility curves (Jengirdar [12]). The proposed research plan is to first perform the vulnerability analysis for each component of the lifelines independently and then determine the joint probability of multiple simultaneous failures. Sequence of events and cascading failures are important in the identification of critical infrastructures and the development of effective mitigation plans.

## ESTIMATION OF THE SEISMIC SITE RESPONSE

The Montreal Urban Community (MUC) is located on an island bordered southward and eastward by the St. Lawrence River and westward by the Des Prairies River (Figure 2). Many geological episodes during the Cambrian to Late Quaternary have shaped its landscape. A failed rift is at the origin of the limestone and shale basement and an up-doming over a hot-spot fashioned the hill of Mont-Royal. Alternating periods of glaciations and melting shaped and deposited considerable quantities of soft material later altered by the emergence of the Champlain Sea and giving clay and sand layers. Finally, the influences of the St. Lawrence River and its secondary channels have deposited fine and coarse materials on the banks. A comprehensive review of glacial and sedimentary episodes is provided by Prest and Hode-Keyser [14] (Figure 2). The map of surface deposits shows clay deposits at the periphery of the island to the south, east, and west and sand deposits in the south central area and at both tips of the island. The land-use map of Montreal indicate that some strategic areas of the city are within soft soil zones, in particular, the downtown area and the Port of Montreal (Figure 3).

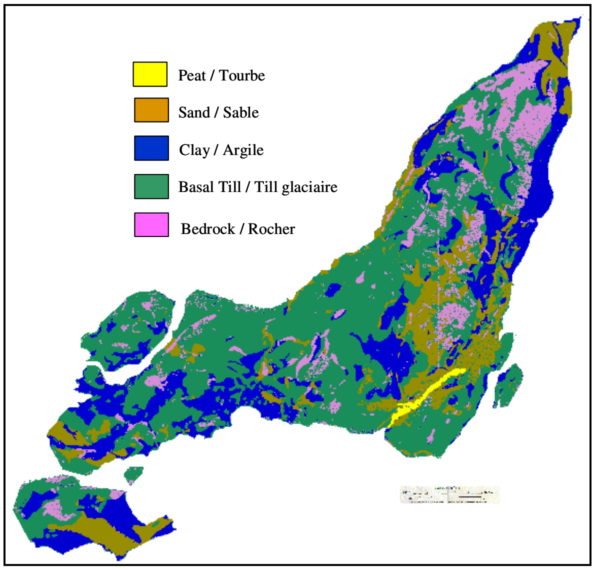


**Figure 2: Simplified geological map of surface quaternary deposits (adapted from Prest and Hode-Keyser [14]).**

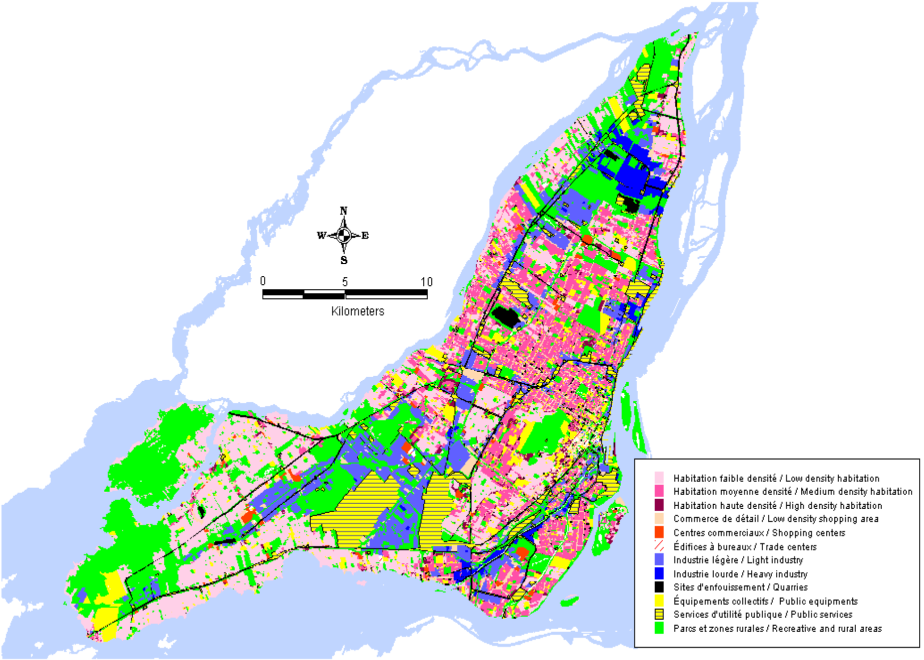


**Figure 3: Land-use for the Montreal Urban Community.**

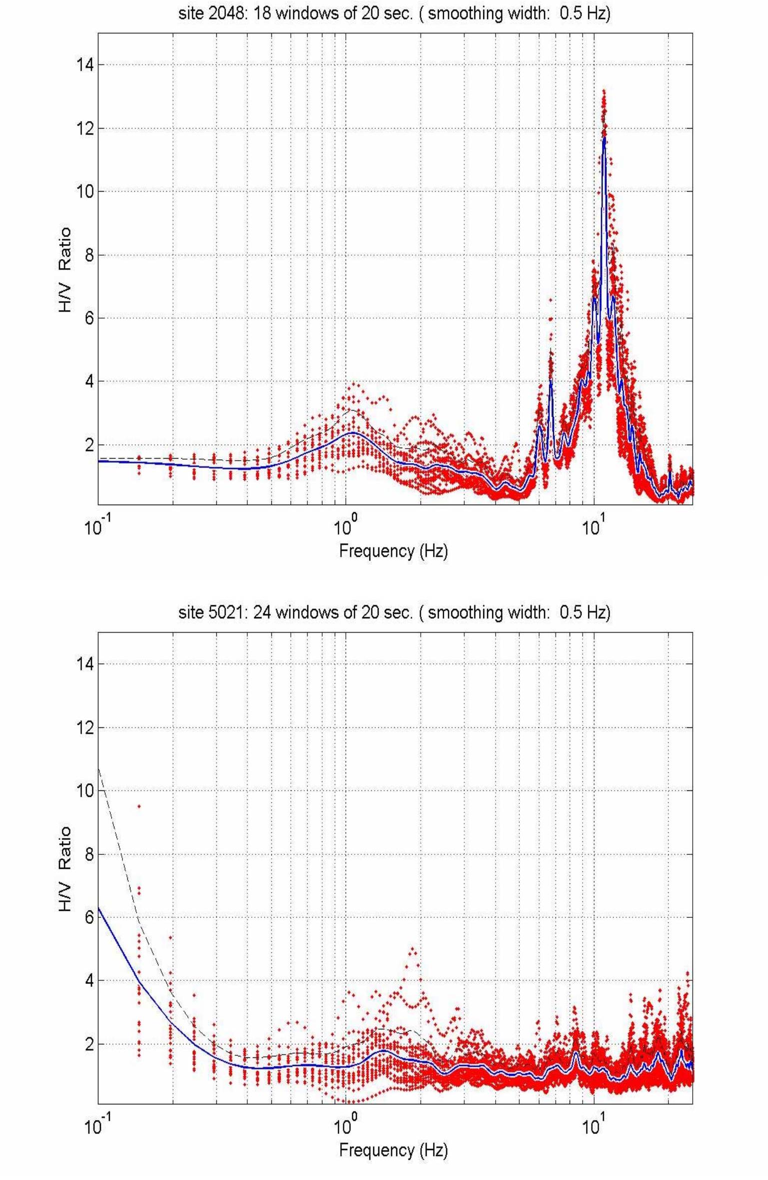
A seismic microzonation of the Island of Montreal was initiated in 2001 in collaboration with the Geological Survey of Canada (Rosset et al. [15] [16] and is still in progress (Madriz [17]). A protocol, comprising field investigations coupled with numerical modelling was developed (Rosset [18]; De la Puente and Rosset [11]). The field approach is based on the well-known H/V spectral method (Nakamura [19]) and uses records of ambient noise produced by wind-structure interaction, traffic and man-made vibrations. It has been demonstrated that the spectral ratio between the horizontal and vertical components of such records gives a good estimate of the fundamental period of soft deposits (Bard [20]). The numerical approach is based on a one dimensional equivalent linear seismic response analysis using SHAKE91 (Idriss and Sun [21]). It provides a good estimate of the modes of resonance and amplification factor of soil deposits when appropriate soils properties and input rock motions are available. Input ground motions on firm rock are selected from a set of real and synthetic earthquake records in order to cover a wide range of excitation's periods. Different seismic scenarios are proposed that deal with the lack of knowledge in the source mechanism of earthquakes around the MUC.

## Empirical Approach : The H/V Method

The empirical or H/V method developed by Nakamura [19] relates the spectral ratio between horizontal and vertical ambient noise records to the fundamental frequency and amplification factor for a soil deposit.

Over 1000 sites were investigated using ambient noise records of 7-10 mn at a sampling rate of 100Hz. The 24 bit digitizer ORION from Nanometrics Ltd. was coupled to the Guralp velocimeter CMG-40T. Surveys were performed during the night to avoid disturbing noises in the vicinity of the sensor that was leveled directly on the asphalt most of the time. Sites on rock basement typically have a flat signature with an inflexion point at low frequencies, while sites on soft soils exhibit well-defined peaks (Figure 4).

Difficulties in the recording and treatment of ambient noise records were mainly encountered in downtown Montreal due to parasitic noise up to 10Hz or no clearly identified polarization peak. The presence of numerous underground structures and of high-rise buildings and 2) the complexity of the layering are two explanations (i.e. inhomogeneous velocity profile with depth, 2D and 3D effects).



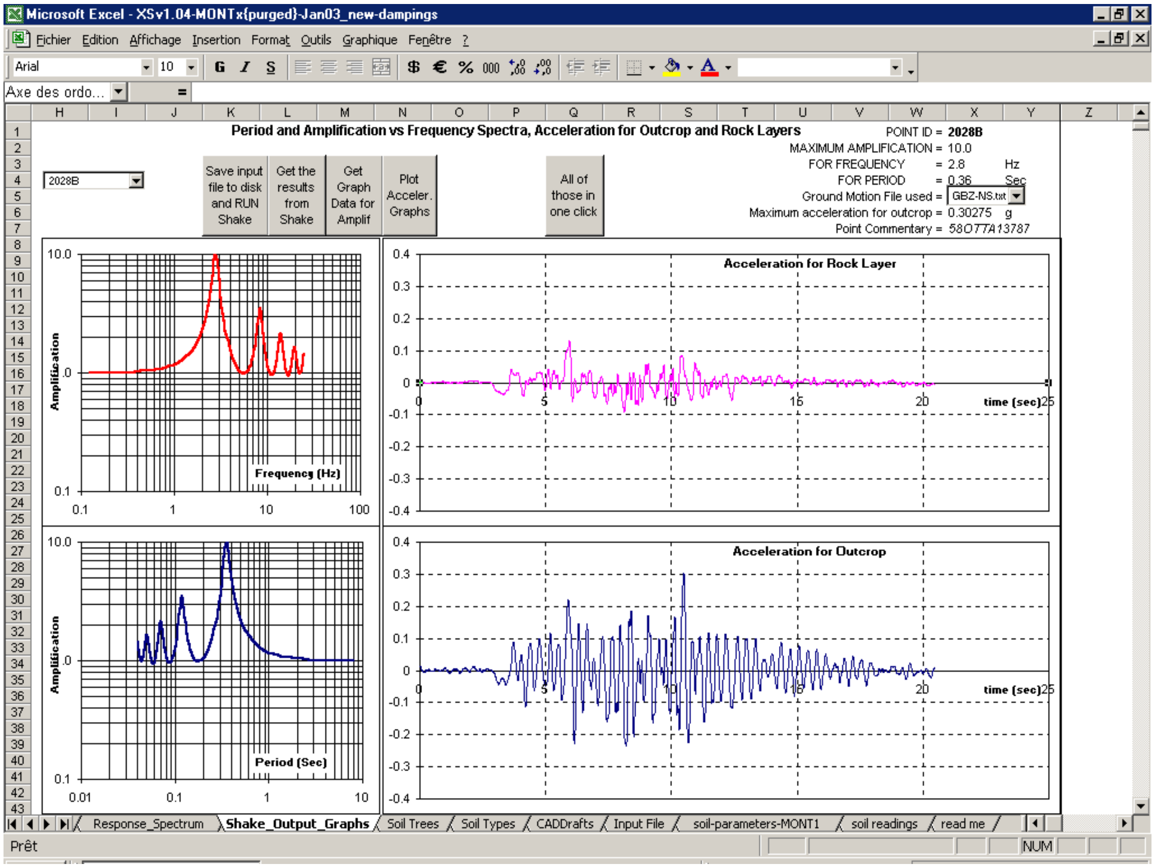
(a)

(c)

**Figure 4: Visual estimation of the quality of the spectral shape: (a) grade A spectra, the peak is well identified and the bias around the mean is small (b) grade C spectra, the main peak is mask by secondary ones and the bias is important (c) typical response for rock site, a flat spectra showing any particular peak.**

## Analytical Approach: 1d Modelling

The computer program for earthquake response analysis SHAKE91® was chosen (Idriss and Sun [21]; Schnabel et al. [22]) to complete the information given by the empirical approach (i.e. mainly for the amplification factor) (Figure 5). The software considers horizontally layered sites that can be characterized with data from a single borehole. The 1D numerical analysis is performed for a sample of input ground motions to consider the uncertainty on seismicity. Five different events are used for the dynamic analysis with SHAKE91 that correspond to strong ground motions in intra-plate regions mainly strike-slip and thrust movements They correspond to three different predominant periods of strong motion: low, intermediate and high. The Saguenay earthquake of 1988, The Kocaeli and Duzce earthquakes of 1999 (Turkey), The Imperial Valley (1940) and Loma Prieta (1989) earthquakes. A "broadband" scenario based on synthetic signals provided for Montreal by Atkinson and Beresnev [23] was also included in the sample. They are scaled to a PGA value of 0.16g in order to be consistent with the value given in the National Building Code of Canada (NBCC [4]) for Montreal (Rosset et al. [17]).



Period and Amplification vs Frequency Spectra, Acceleration for Outcrop and Rock Layers

2028B

POINT ID = 2028B
MAXIMUM AMPLIFICATION = 10.0
FOR FREQUENCY = 2.8 Hz
FOR PERIOD = 0.36 Sec
Ground Motion File used = GBZ-NS.txt
Maximum acceleration for outcrop = 0.30275 g
Point Commentary = 58O77A13787

**Figure 5: Modes of resonance and time histories as displayed with the Excel-Shake tool. (De la Puente and Rosset [11]).**

*Geological and geotechnical database for recent deposits in Montreal*

A detailed compilation of more than 600 boreholes was used to define a layers structure for 313 sites. Some of them correspond to sites investigated with the empirical approach. Information on thickness of soil layers is obtained from boreholes (Public Works service of the MUC), geological profiles (Jacques [24]; Jacques [25]) and geological maps (Prest and Hode-Keyser [14]). The quality and level of detail in the description of borings are very variable. Geological profiles can be used to infer layer thickness at specific sites, but accuracy is limited to the scale of the profile (often 1:200). Most profiles were derived from the same borings database used for the project. Geological and quaternary thickness maps (scaled at 1:50000) are used to validate or duplicate information on bedrock depth and to extrapolate in some cases when information from borings is incomplete. The unit weight of a layer of soil is an important parameter for the analytical studies. An average unit weight for each layer is based on studies in similar quaternary context of deposition (Benjumea et al. [26]; Decroix [27]; Prest and Hode-Keyser [14]). There are no readily available data related to S-wave velocities for soft soil layers on the island. Simple or 3-pod well locking geophone array borehole measurements in similar formations in Ontario are used for sand (Sharpe [28]) and clay (Nixon [29]). Seismic refraction tests in a deep basin of the Ottawa River are used for tills and bedrock formations (Benjumea et al. [26]). Values for other formations have been chosen based on general engineering practice. Calculations made with these values should be considered as current best estimates and should be updated as local data on S-wave velocities become available. Initial damping is fixed to 5 % for soft layers and 1% for rock basement. They correspond to initial values used by engineers when no specific information is available. Laboratory tests to derive dynamic stress-strain relationships for quaternary deposits in Montreal are non-existent. Few were performed on clay (Cao et al. [30]) in a quite similar zone near the Saguenay area. Other curves are proposed by Seed and Sun [31] for peat and by Seed and Idriss [32] for basal tills. Damping curves are based on Idriss [33] since no specific information is available at the current time for the Montreal area.

The methodology used to assess site effects associated with quaternary deposits gives promising results for several reasons:

1) Field measurements are a fast and low cost means to obtain an estimate of the fundamental mode of resonance of a site as 1D modelling is well-adapted in zones with detailed geotechnical data to estimate both fundamental mode of resonance and amplification factor. The good relationship between empirical and analytical frequency of resonance in clayey and marly zones favors the use of the field approach to provide this parameter as much as possible
2) The ambient noise analysis is able to give a good estimate of the predominant mode of resonance of a site in zones where the unconsolidated soil layers are mainly clay deposited during the Champlain sea episodes and marl from the late St Laurent River deposits (Figure 6). A relationship between the site's response and the thickness of soft layers is proposed (Rosset et al. [18]). In areas with multiple episodes of river deposits, the analysis of ambient noise records is more complicated. A preliminary interpolated map of predominant frequencies is proposed in Figure 7.
3) The estimation of amplification factor for different seismic scenarios shows that we could expect values up than 3 in zones with a 10-15m clay layer. Unconsolidated river deposits also have amplification factors of 3 corresponding to zones with many lifelines. A first investigation of landfill areas (e.g. the port of Montreal) shows that more detailed analyses should be performed, especially relative to liquefaction hazards.
4) The development of tools to analyse ambient noise records (Rosset, 2002) and to perform SHAKE computations for several sites and seismic scenarios (De la Puente and Rosset, 2002) allows quick updates of the microzonation maps as soon as new information becomes available.

## ON-GOING AND FUTURE RESEARCH

In conjunction with the on-going microzonation, studies on liquefaction potential have been initiated. In addition, experience gained in the microzonation of the experience may be used to expand the study and cover the Island of Laval as well as urban areas on the south and north shore of Montreal. Specific projects have also been initiated with various utilities to analyse the component and system reliability of lifelines.

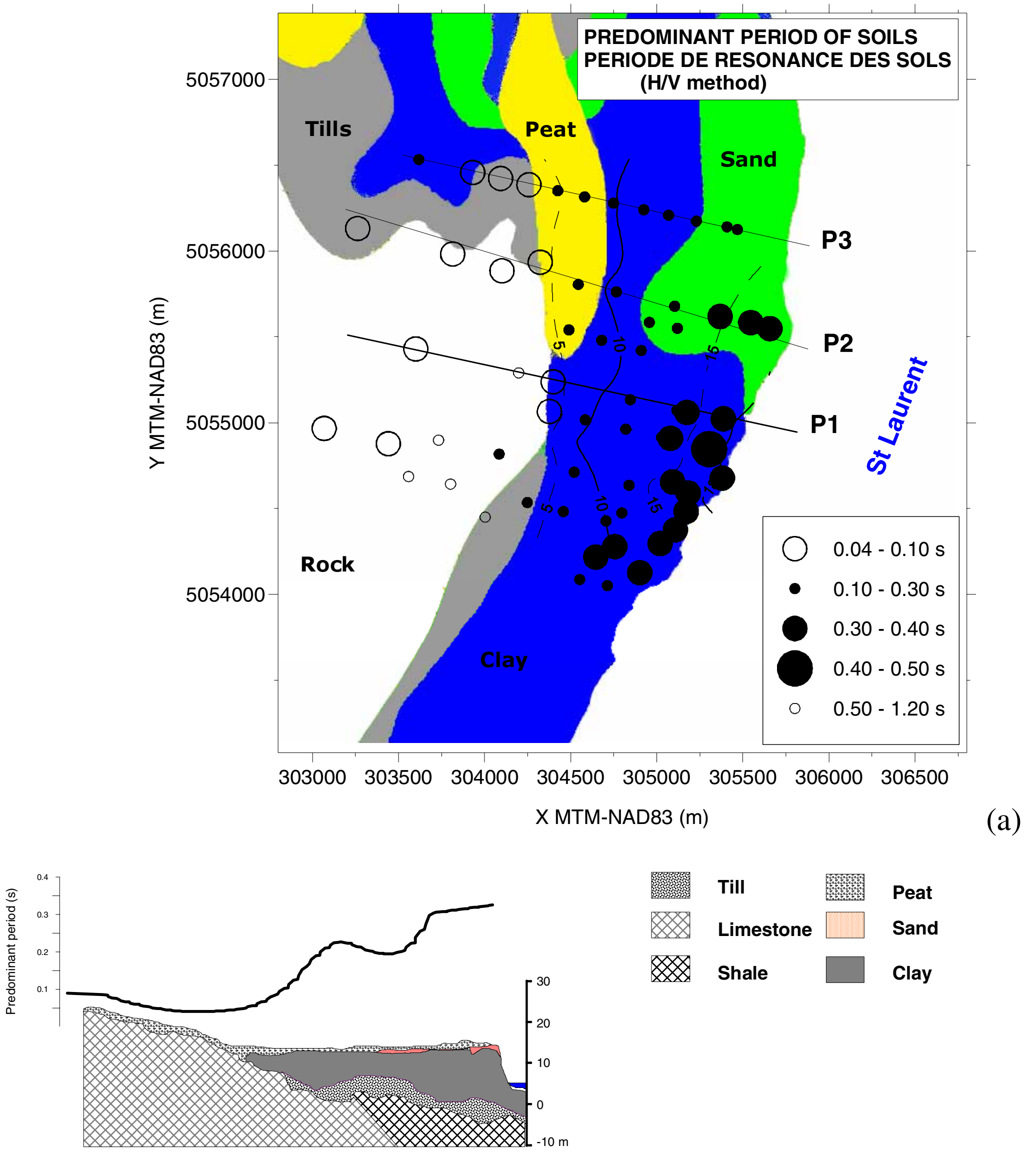


**Figure 6: Example of site's response zonation in terms of predominant period of resonance for a zone in the northern part of the island of Montreal. (a) Ranked predominant period of resonance for the 64 investigated sites. Surface geology and depth of the bedrock are indicated (from Prest and Hode-Keyser [14]). The track of the three geological profiles P1, P2 and P3 are also mentioned. (b) The values of predominant period of resonance are interpolated along the three profiles marked. Obtained curves are confronted to geological profile P2(from Jacques [24]).**

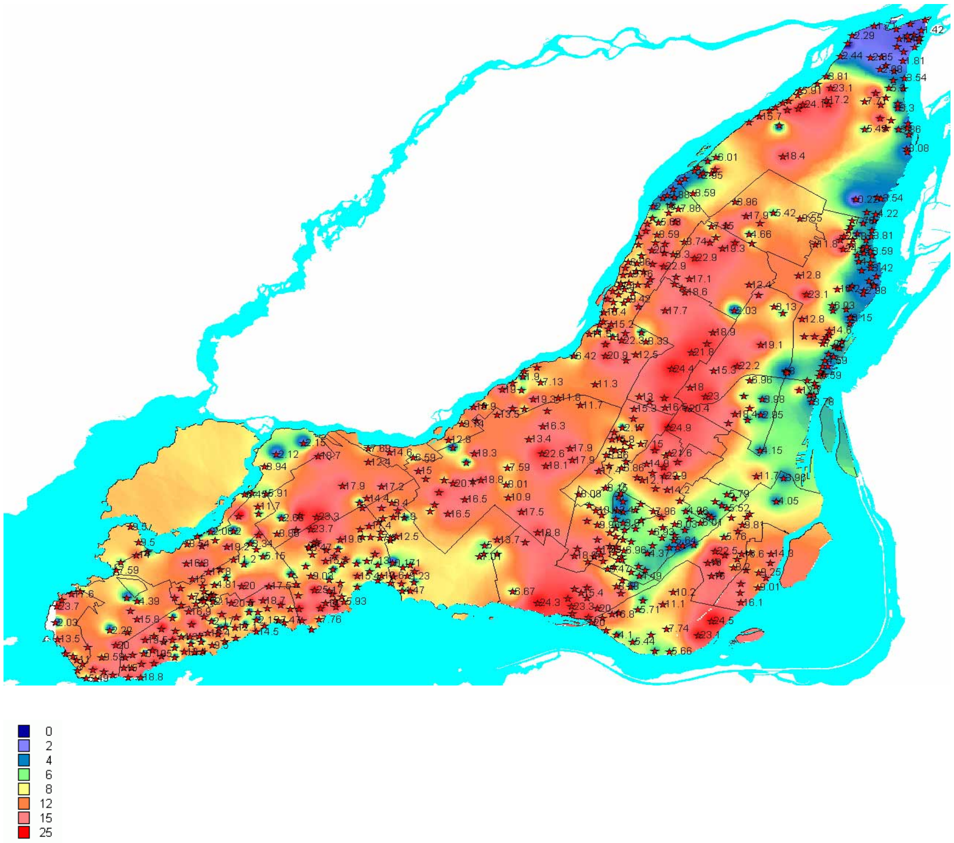


**Figure 7: Interpolated map of the fundamental frequency of resonance obtained with the ambient noise records analysis.**

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