SITE EFFECT ASSSESSMENT AT SMALL SCALES IN URBAN AREAS: A TOOL FOR PREPAREDNESS AND MITIGATION

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Abstract

Recent destructive earthquakes have clearly shown that near-surface geological and topographical conditions play a major role in the level of ground shaking. In post-disaster reconstruction as in mitigation, information on soft soil response to large earthquakes becomes of prime importance. The mapping of predominant frequency of resonance and amplification of soil permits identification of zones at risk in seismic-prone areas. It can be used as a tool for prevention planning and retrofitting measures and also to define safety zones for reconstruction after a destructive earthquake. In the framework of a seismic risk study of the island of Montreal (Canada), a methodology for seismic zoning in urban areas is validated. It is based on field investigations coupled with numerical modelling.

The field approach is emphasized as a fast and low cost method well adapted for urban areas through pre- and post-disaster surveys. It is based on the well-known "Nakamura's method" (or H/V method) and uses records of ambient noise produced by wind-structure interaction, traffic and other 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 frequency of soft deposits. Extensive use of this method allows the fast and detailed mapping of these frequencies within urban areas. By combining information on ground response and vulnerability, potential damage to buildings and lifelines can be identified.

In the case study of Montreal, different zones with soil profiles typically associated with large amplification factors have been identified and surveyed using the field approach. Preliminary results show a good correlation between thickness and/or the type of soft soil and the fundamental frequency obtained with the H/V method. By identifying the relationship between key soil-profile parameters and estimated fundamental frequencies, it becomes possible to extrapolate the results to parts of the island that are not covered by the field study.

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In conclusion, this method is a fast, economical and useful means of defining the microzonation in urban areas, which is essential for the deployment of seismic instrumentation, land-use planning and seismic mitigation.

Site effects, seismic microzonation, H/V method, urban areas, mitigation

INTRODUCTION

It is now commonly accepted in the earthquake engineering community that soft soils can play a large role in ground motion and must be included in seismic zoning. Well-known examples from San Francisco and Mexico City have been extensively cited to illustrate the role of surface geology on seismic waves. In both cases, soft soils have increased the ground shaking and played a major role in human and economic losses. In San Francisco, during the 1906 and 1989 earthquakes, the intensity level increased by 2 units in areas with unconsolidated sediments. In 1985, during the Guerrero Michoacan earthquake, seismic waves were amplified in the soft clay basin underneath Mexico City some two hundred kilometres from the epicentre. Soft-soil amplification has been noted in the recent destructive earthquakes of Northridge (1994), Kobe (1995), Armenia (1999), Colombia (1999) and Turkey (1999). Consequently, microzonation is an essential step in the formulation of local seismic regulations, land use planning, design criteria, and earthquake hazard reduction programs.

In the following section, important site effects such as local amplification related to sedimentary sites, strong lateral heterogeneity, or surface topography are illustrated. Next, the Ground Ambient Noise (GAN) technique is presented as a means to estimate site effects in an urban environment. Finally, an application of the procedure in the city of Montreal is presented to illustrate the role of recent glacio-lacustrine deposits on seismic response.

SOURCES OF SITE AMPLIFICATION

Effect of unconsolidated layers

Damage due to earthquakes generally decreases as a function of distance from the epicentre. Meanwhile, destructive earthquakes have demonstrated that damage is often more severe over unconsolidated deposits than on firm rock outcrops. Since river valleys are often the site of recent alluvial and glacial deposits and also prime locations for the development of urban areas, local amplification is a major concern in earthquake-prone regions (e.g. San Francisco, Lima, Bogotá, Kobé) but also in moderate seismicity areas where mid-size cities recently developed could be struggle with future damaging events due to the combination of site effects and urban development. Macroseismic surveys of major earthquakes have led to the conclusion that damage on soft deposits corresponds to the local shaking plus 2 degrees on the MM or MSK/EMS scale (in particular cases, an increment of 3 degrees is observed).

Basically, site effects are associated with the phenomenon of the seismic waves travelling into soft soil layers. It is explained firstly by the lower velocity and density between unconsolidated sedimentary layers and the underlying rock (impedance contrast). For conservation of energy, this requires larger amplitudes of the seismic waves in the sediments. Secondly, for a structure composed of sub-horizontal layers, body waves which travel up and down are the chief inputs. However, in 2D and 3D structures (e.g. heterogeneity of sedimentary layer thickness or sedimentary basin depth), surface waves generated by the structure are also trapped. Resonance patterns are created when trapped waves interfere. The shape and frequency content of such waves depends on the geometry and physical properties of the structure. The degree of complexity of predicting a seismic response increases with the complexity of the structure.

Topographic effect

The Influence of surface topography has been noted in several earthquakes reports and demonstrated in instrumental studies (Faccioli, 1991; Finn, 1991); however, there is not enough data to derive a correlation between topography and amplification. Currently, it is not possible to develop a statistical relationship of changes in frequency and amplitude of strong ground motions and topography. However, theoretical and numerical models indicate that seismic waves are amplified at ridges crests or more generally on convex features such as cliffs.

THE USE OF GROUND AMBIENT NOISE (GAN) TECHNIQUE

Estimation techniques for site effects can be divided in two main categories; instrumental, which necessitates records and numerical, which uses soil information (Lacave *et al.*, 1999).

Two main instrumental techniques are widely used:

- By simultaneously comparing records from a fixed station on rock and a mobile station. It can control the time-variable aspects of ambient noise, but requires a carefully assessed “real” rock site.
- By comparing earthquakes records at a rock site and several stations on soil. Although it seems to be the most accurate means to assess the soil response, it requires a seismic station at each investigated site and time to record seismic events if and when they occur. Thus the equipment and logistics become a limitation in zones where seismicity is moderate.

The numerical approach requires a good knowledge of the local structure responsible for site effects. Both geometric and mechanical properties have to accurately model the seismic response of soil. A more complex model requires more precision.

Considering the limitations of each method, the GAN method represents a convenient and inexpensive means of investigation. It is based on a theory and hypotheses developed by Nakamura (1989). He demonstrates that the ratio between horizontal and vertical ambient noise records is related to the fundamental frequency of the soil beneath the site and hence to the amplification factor. The theory and hypotheses are not unanimously accepted by the scientific community but comparisons with other techniques have proven the validity and efficiency of the method (Lermo and Chavez-Garcia, 1994).

Nakamura (1989) developed the technique by formulating three main hypotheses:

1. Ambient noise is generated by reflection and refraction of shear waves within superficial soil layers and by surface waves.
2. Local superficial sources of noise do not affect ambient noise at the bottom of the unconsolidated structure.
3. Soft soil layers do not amplify the vertical component of ambient noise.

Ambient noise is composed of Rayleigh-type surface waves generated by wind-structure interactions, traffic and other urban activities (Lermo and Chavez-Garcia, 1994). Transfer functions S_E and A_S which are respectively the intrinsic site effect and the single Rayleigh wave effect could be defined as:

$$S_E = \frac{H_S}{H_B} \qquad A_S = \frac{V_S}{V_B}$$

Where H and V the spectra for the horizontal and vertical components respectively of the ambient noise records at the surface (S) or at the basement (B). Site effect that do not include source contribution are defined by S_M as :

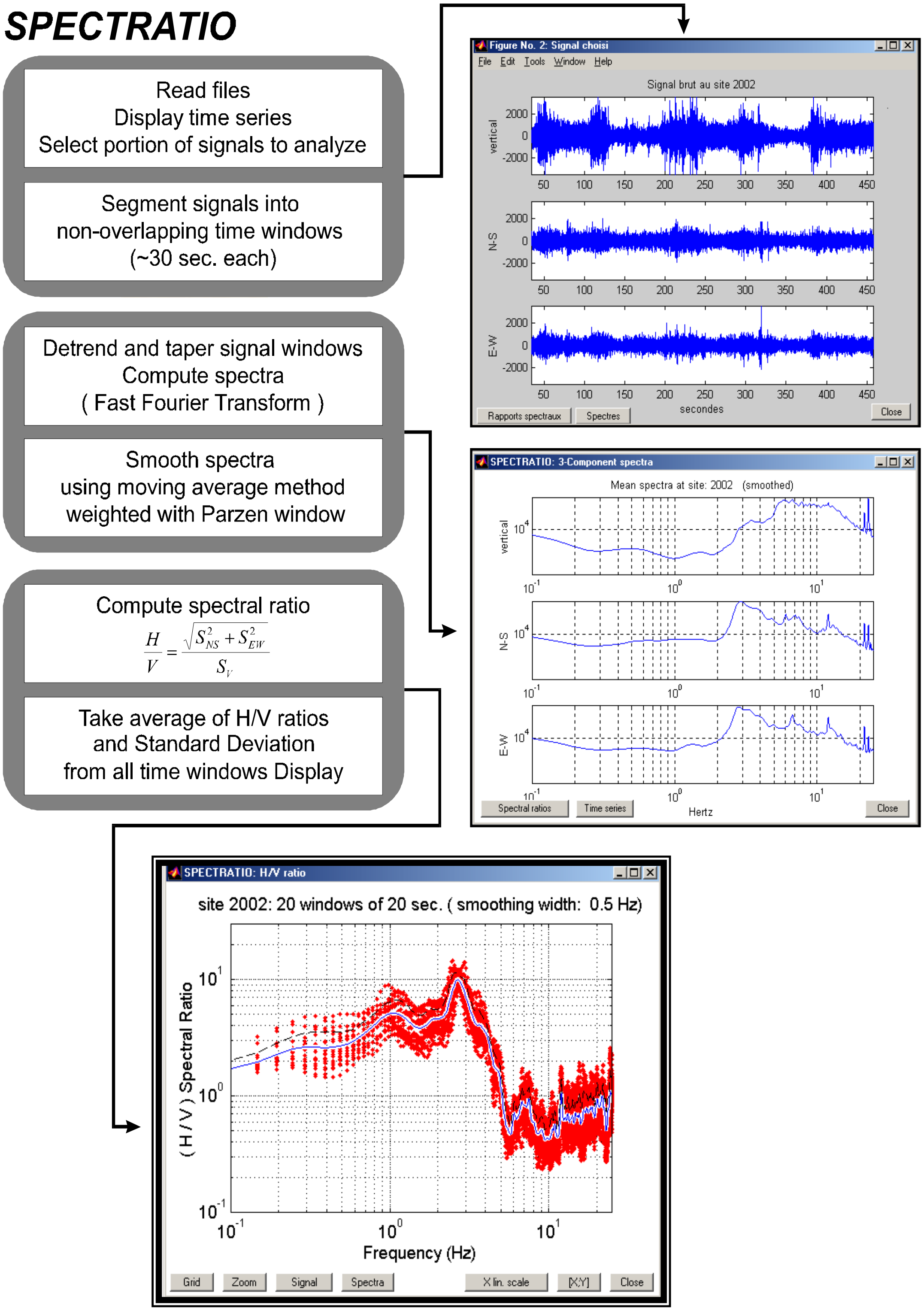
$$S_M = \frac{S_E}{A_S} \quad \Leftrightarrow \quad S_M = \frac{H_S}{V_S}\frac{V_B}{H_B}$$

Nakamura (1989) and Theodulidis *et al.* (1996) demonstrate that the spectra of the vertical (V_B) and horizontal (H_B) components are equivalent at the base of the structure.

$$\text{if} \quad \frac{H_B}{V_B} \cong 1 \quad \text{then} \qquad S_M = \frac{H_S}{V_S}$$

Finally, site effects S_M can be expressed as the spectral ratio of the horizontal and vertical components of ambient noise at the surface.

In summary, it implies that an estimate of the soil response at a site can be obtained by recording ambient noise with a single 3-components seismometer. Field experience has shown that 15 minutes of records per site are long enough to record stable results in various urban environments. User-friendly software has been developed to process sets of records (Gonzenbach, 1997; Rosset, 2002) as illustrated in Figure 1.



SPECTRATIO

Read files
Display time series
Select portion of signals to analyze

Segment signals into
non-overlapping time windows
(~30 sec. each)

Detrend and taper signal windows
Compute spectra
(Fast Fourier Transform)

Smooth spectra
using moving average method
weighted with Parzen window

Compute spectral ratio

$$\frac{H}{V} = \frac{\sqrt{S_{NS}^2 + S_{EW}^2}}{S_V}$$

Take average of H/V ratios
and Standard Deviation
from all time windows Display

Figure 1: Procedure for calculating the H/V ratio from records of ground ambient noise.

Left - Stages of the spectral analysis from ambient noise records to calculated H/V ratio.
Right – Processing software developed in Matlab© environment. From top to bottom, recorded signal, Fourier Spectra of the selected portion of signal and spectral ratio based on the segmented signal.

MICROZONATION IN MONTREAL: THE CASE OF MONTREAL-EST

The urban area of Montreal is the second city of Canada in terms of population and economic activity. Montreal is vulnerable to seismic events since most of its infrastructures predate the development of modern seismic design standards and are often in a deteriorated state. One of the objectives of the current research is to develop seismic hazard mitigation plans. A key component of this plan is to identify zones where soft soil deposits could amplify ground shaking in the event of a major earthquake (M>5.5) (Adams *et al.*, 2002; Chouinard *et al.*, 2001). To date, hundreds of sites have been investigated that cover the various typical soil profiles throughout the island of Montreal.

Geological context

The geological basement of Montreal is igneous and metamorphic rocks of the Precambrian Canadian Shield covered by Ordovician sedimentary rock (Trenton limestone and Utica shale). The basement was faulted during the opening of the proto-Atlantic Ocean about 550 million years ago, and during up-doming and volcanism due to the passage of a hot spot 110 to 90 million years ago; both events weakened the Canadian Shield and seem to be controlling the local earthquakes (Adams and Basham, 1991). The island of Montreal was repeatedly glaciated during the Quaternary, depositing during the Wisconsin, in chronological order, the Malone Till, Middle Till complex and Fort Covington Till. The land was depressed after the ice retreated, and was covered by silt- and clay-sized deposits (Leda Clay) from the Champlain Sea and by coarser sediments from the Saint-Lawrence River before the land emerged; these comprise the surficial deposits important for the microzonation.

Soft soils that play a major role in site effects are marine clays and silts, river sands, and in particular cases, till. Marine clays vary considerably in type from massive to silty depending on its depositional history. Its extent is variable throughout the island and the thickness ranges from one to tens of meters. Fluvial sand and gravel deposits occur widely over the Montreal Island. The thickness of deposits is again quite variable but remains below 10 m. Till deposits are composed of boulders, gravel, sand and silt in varying proportions. A detailed description of the different glacial and sedimentary episodes is provided by Prest and Hode-Keyser (1977).

Seismic hazard context

Seismicity around Montreal seems to be controlled by two main active bands within the Western Quebec Seismic Zone (Adams and Basham, 1991). One band which follows the Ottawa and St. Lawrence rivers and was the site of three major historical earthquakes; namely a magnitude 6 near Montreal in 1732; a magnitude 6.2 near Timiskaming in 1935 and a magnitude 5.6 near Cornwall-Massena in 1944. These earthquakes correlate with a zone of normal faulting of Cambrian-Paleozoic age which may represent a failed rift. The second band is oriented NW-SE and extends from Montreal to Baskatong Reservoir (200 km north to Ottawa). Although the relation between epicentres and local tectonics is not clear, Adams and Basham proposed they were due to crust doming and fracturing over a hot spot. From the first seismic zoning maps in the National Building Code of Canada (NBCC) in 1950, Montreal has been recognized as being in a zone of moderate seismic hazard. The current (1985) maps in the NBCC indicate Montreal can expect peak horizontal ground acceleration of 0.16g for a probability of non-exceedence of 10% in 50 years. Seismic hazard maps being prepared for the next (2003) NBCC will incorporate new information and will used to base designs on lower-probability hazards (Adams *et al.*, 1999; Adams and Atkinson, 2002).

Results

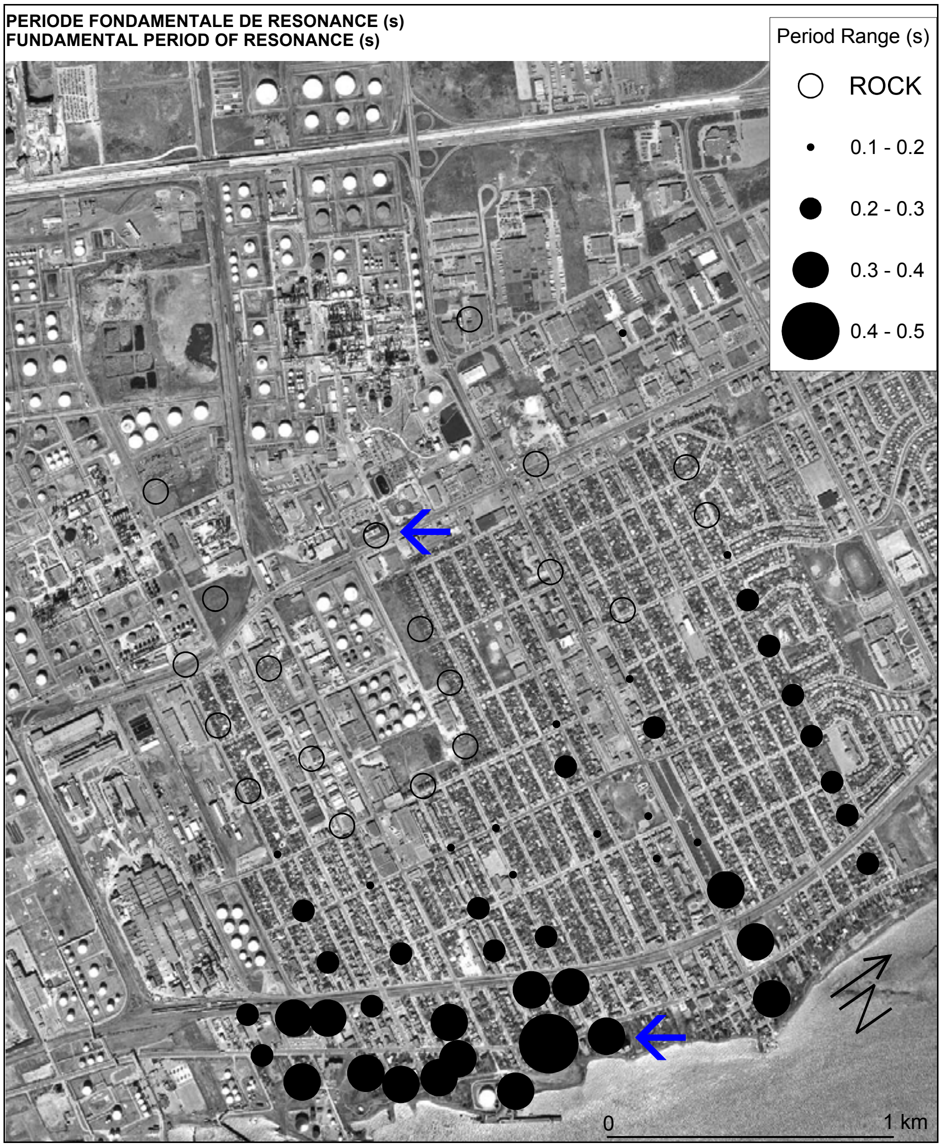
The GAN method for the estimation of site amplification is illustrated for one of the zones investigated. It is located at the eastern end of the island in the district of Montreal-East. The district of Montreal-East is both a residential and industrial district with several oil refineries and port facilitites. During the 1988 Saguenay earthquake (Ms=5.9), the City Hall was heavily damaged by the ground motion although it was 300 km from the epicentre; soil amplification has been identified as one of the causes (Mitchell *et al.*, 1990). A zone of four square kilometres has been analysed using records at 70 sites over a three days period (Figure 2). The zone has a rock basement overlain by a clay layer that increases in thickness going east. In a few locations, boreholes also indicate the presence of basal till and sand lenses. Figure 2 shows the location of the 70 sites and their spectral response. Two typical records on rock and soil sites are presented.

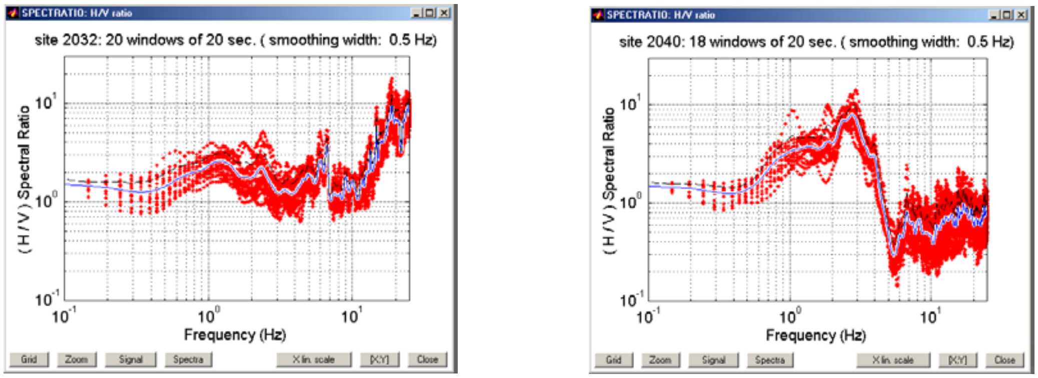
After processing of each record to obtain the fundamental frequency, a map was produced to show its spatial variation (Figure 3). Rock sites have a flat response curve, while soft soil sites exhibit a peak of maximum amplitude defining their fundamental frequency or period. The limit between rock (i.e. limestone of Trenton) and soft sediments (i.e. marine clay) can be clearly inferred from the change in the spectral shape of records for the various sites.

Geological map and soil profiles were available to validate instrumental results (Prest and Hode-Keyser, 1977; Jacques, 1985). The thicker the clay layer is, the higher is the predominant period of soil which reach 0.3 s near the St. Lawrence

River. The presence of sand lenses is detected by a decrease in the fundamental period.

Calculated peak amplitude does not present a clear correlation with type or thickness of soils (Figure 4). Values range from 1 to 19 with half of them between 8-12. Presently, no clear relation exits between the H/V peak amplitude and the site amplification factor though, it is suggested to use the H/V ratio as a "lower bound estimate" to the weak motion amplification (Bard, 1999).

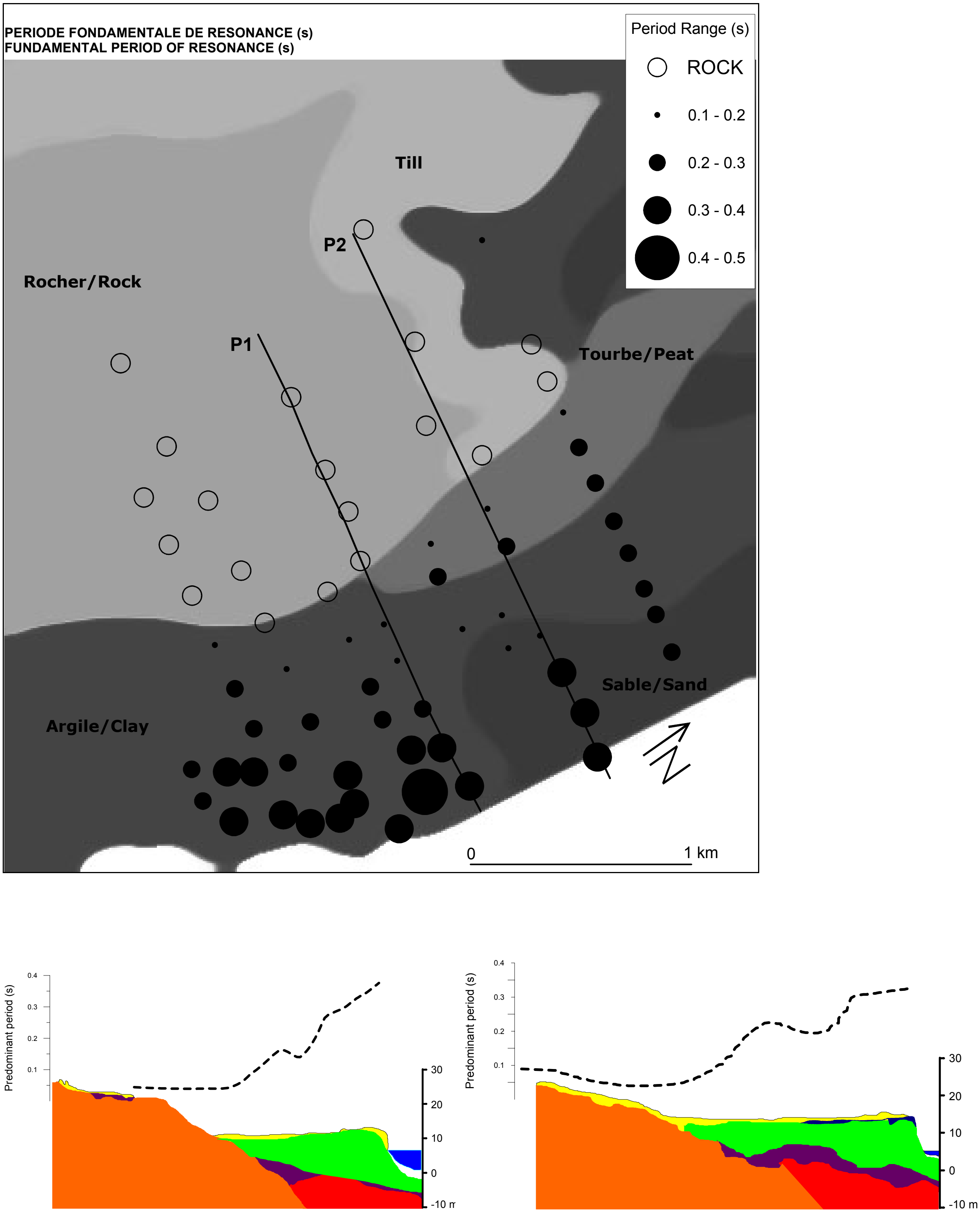




Site on rock (open circle)

Site on soft soil (fill circle)

Figure 2: Fundamental period of resonance for one zone investigated with GAN technique (Montreal-Est). Bottom: Spectral ratio for rock (open circle) and soil (fill circle) sites pointed by arrow on the aerial photography (Courtesy of the Montreal City Council)



Profile P1

Profile P2

Figure 3: Geology and fundamental period of resonance for one zone surveyed with GAN technique (District of Montreal-East). Bottom: Interpolated GAN profiles

compared with geological profiles P1-P2 . Limestone (orange), Shale (red), Basal Till (purple), Clay (green), Sand (blue) and Peat (yellow).

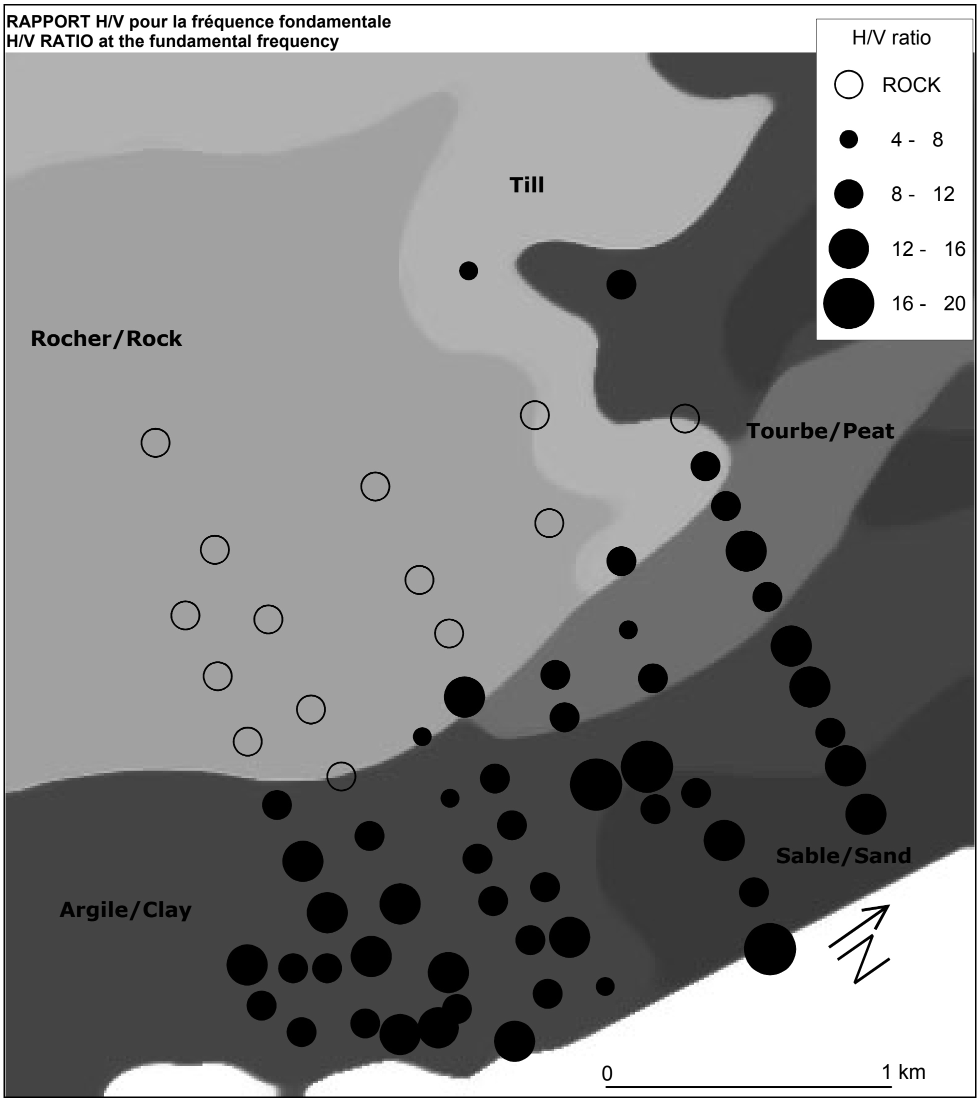


Figure 4: Geology and H/V peak amplitude at the fundamental period. The maximum amplitude of the H/V ratio is a first estimate of the spectral amplification for a given period and does not reflect the amplification factor of the ground motion.

CONCLUSION

The Ground Ambient Noise technique is recognized as a fast and inexpensive way to estimate the fundamental frequency of resonance of soil sites and perhaps the lower value of spectral amplification in cases of seismic ground motion. It is well adapted in urban environments for local seismic microzonation. It provides information on the seismic response of soft soils and can be used for seismic mitigation and earthquake planning. Results of an analysis performed in Montreal indicate that GAN analysis is able to identify and quantify soft soil site response to seismic waves.

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