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The Evaluation of Earthquake Site Response in the Quebec City Area using Ambient-Noise Measurements

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ABSTRACT

Site effects evaluation from ambient-noise measurements was completed over a deep sediment-filled valley in the lower town of the Greater Quebec City area as part of a seismic microzonation project. Data was collected at 88 sites using long-period (5 sec.) sensors. Three methods of analysis were used for the signal processing: spectral ratio, cross-spectrum spectral ratio and the vertical spectral ratio. The cross-spectrum spectral ratio analysis gave the most realistic results. Two maps of the area were prepared: one showing the fundamental frequency contours and the other the amplification contours from the longitudinal components of the cross-spectrum method..

INTRODUCTION

The most important earthquake to affect Quebec City was the February 28, 1925 event with an estimated magnitude in the range of 7.0 to 7.3. The damage sustained was important and was concentrated mostly in lower town where many buildings were damaged, a shed collapsed in the harbor and a grain elevator showed structural damage. It was reported that the earthquake was barely felt in upper town (Chagnon and Boivin, 1989). The next important event was the Saguenay november 25, 1988 event ($M = 5.9$) which again was barely felt and caused almost no damage in upper town but was strongly felt and resulted in considerable damage, mostly architectural, in lower town. The same pattern was observed in previous historical earthquakes. It should be noted that in 1925 the built-up part of Quebec City covered an area of about 16 km^2 while the Greater Quebec City (including suburbs) now expands over 600 km^2, most of which is in the lower town area. Therefore the damage potential from severe earthquakes is now greater than in the past.

The upper town area is underlain by bedrock which outcrops in many places and which is elsewhere overlain by thin soil deposits about one to three meters in thickness (Cockburn, 1984). The lower town area lies over the breadth (7 km wide) of a deep (over 50 m) sediment-filled valley trending northeast parallel to the St. Lawrence which it joins near Beauport. In order to better understand the factors contributing to the distribution of damage from earthquakes a seismic microzonation mapping project was undertaken in 1982. The usual elements involved in seismic microzonation are slope stability under earthquake loads, soil liquefaction potential and the evaluation of site effects. Up to three versions of

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the microzonation map have been prepared, the first one being published in 1984 (Doré, 1984), the second in 1987 (Chagnon et Doré, 1987) and the third in 1990 (Chagnon et Gilbert, 1990). This last version was modified in view of the distribution of the damage from the november 25,1988 event (Chagnon et Bélanger, 1990). The first versions covered mainly the first two elements, the last one (site effects) being treated cursorily. Beginning in 1991 the systematic evaluation of site effects was undertaken.

This paper presents the results of the evaluation of site effects over the sediment-filled valley using ambient-noise measurements.

DATA COLLECTION

The ambient noise measurements were completed at 88 sites over the sediment-filled valley of the Greater Quebec city area (figure 1) with a bedrock reference site located in upper town at Laval University. The sediment data were collected simultaneously with the bedrock data. Both sites were instrumented with three Kinemetrics SH-1/SV-1 5 seconds sensors and digital portable recording Scintrex/EDA PRS-4 seismometers. The sediment sensors were generally placed on patio-type cement slabs. Each measurement held 60 seconds of ambient noise with a sampling rate of 100 points per second. All the data were recorded during the summers of 1992 and 1993.

ANALYSIS

The data was analyzed with three widely used methods of signal processing. The estimation of the site response was calculated from the spectral ratio, the cross-spectrum spectral ratio and the vertical spectral ratio. The input signals were the reference bedrock site recordings but for the third method the input signals were the vertical recordings at sediment sites.

Power spectrum estimation

For each site, the longitudinal and transverse signals of the sediment and bedrock sites were segmented in 6 parts of 1000 points each. Each was transformed in the Fourier domain by a procedure of discrete Fourier transform (DFT). The power spectrum estimation of each signal was then calculated with these transforms and were smoothed by a simple Hanning window. The result of these operations is the smoothed periodogram. For the cross-spectrum spectral ratio, a cross-spectrum of the input and output signals were performed.

The use of the power spectrum estimation is better than a standard FFT routine for ambient noise analysis. Due to the random fluctuations in such signals, the Fourier analysis method cannot be applied. A statistical approach such as the power spectrum estimation has been adopted in this project to cope with the average characteristics of these random signals. The autocorrelation function used implicitely in the power spectrum estimation is an appropriate statistical average for characterizing random signals (Proakis, 1988).

Spectral ratio

To perform spectral ratios, the power spectrum estimation of each longitudinal and transverse segment of sediment site are divided by the power spectrum estimation of each equivalent segment of bedrock site. The 6 transfer functions obtained for each site are averaged for each longitudinal and transverse components. Numerically, the procedure may be represented by this equation:

$$|\bar{H}[f]|^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{|Y_i[f]|^2}{|X_i[f]|^2}\right] = \frac{\bar{S}_{yy}}{\bar{S}_{xx}}$$

Cross-spectrum spectral ratio

To perform cross-spectrum spectral ratios, the cross-spectrum estimation of each longitudinal and transverse segment of sediment site are divided by the power spectrum estimation of each equivalent segment of bedrock site. The 6 transfer functions obtained for each site are averaged for each longitudinal and transverse components. Numerically, this procedure may be represented by this equation:

$$|\bar{H}[f]| = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{|Y_i^*[f]\,X_i[f]|}{|X_i[f]|^2}\right] = \frac{\bar{S}_{xy}}{\bar{S}_{xx}}$$

Vertical spectral ratio

To perform vertical spectral ratios, the power spectrum estimation of each longitudinal and transverse segment of sediment site are divided by the power spectrum estimation of each equivalent vertical segment of sediment site. The 6 transfer functions obtained for each site are averaged for each longitudinal and transverse components. Numerically, this procedure may be represented by this equation:

$$|\bar{H}[f]|^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{|Y_i[f]|^2}{|Y_{V_i}[f]|^2}\right] = \frac{\bar{S}_{yy}}{\bar{S}_{yy_v}}$$

Coherency

The coherency has also been calculated for each determination. The coherency indicates the degree of linearity in the transformation of the input signal to the output signal. It also indicates the validity of the peak response of the sediments. If the coherency of a peak response is weak, this peak is probably not due to a resonance in the sediments and if the coherency of a peak response is strong, this peak is probably due to a resonance in the sediments. The coherency is represented by this equation:

$$|\bar{C}_{xy}[k]|^2 = \frac{|\bar{S}_{xy}[k]|^2}{\bar{S}_x[k]\,\bar{S}_y[k]} \qquad \textit{With} \qquad 0 \le |\bar{C}_{xy}[k]|^2 \le 1$$

RESULTS AND DISCUSSION

Following the analysis, the fundamental resonant frequency and the amplitude of this frequency (i.e. amplification factor) were identified for each longitudinal and transverse components and for each method of signal processing. Then, maps of isofrequency and isoamplitude were established for the region of the sediment filled valley of Quebec. Only the isofrequency and the isoamplitude maps of the longitudinal cross-spectrum method are presented here (figure 1 and 2).

Spectral ratio

The fundamental resonant frequency of longitudinal and transverse components vary from 1.5 Hz to 25.8 Hz. We observe low fundamental frequencies over the deep sediments (center of the valley near the St-Charles river) with an increase in fundamental frequency on both sides of this zone. This relation is consistent with a model of site amplification shown in Reiter (1990). The amplification factors vary from 2.6 to 210.8. The amplification seems to be abnormally strong. The largest amplifications are within the sediment-filled valley.

The spectral resolution of the results is 0.6 Hz. The bias of the results is strongly controlled by the signal to noise ratio. When the inverse of this ratio is weak, the estimation is less biased. In spite of the urban noise, the signal to noise ratio seems to be moderate in the data collected. Therefore, the results are not very biased and show a strong variance. The variance is proportional to the power of 4 of the transfer function. This explains the large range of the amplification factor. The variance of the results remains important even if it has been reduced significantly by the averaging procedure in the signal processing. The variance is reduced by a factor 1/N where N is the number of segments in the signal processing. We also conclude that the data are contaminated by noise because of the average coherency obtained (0.4). However, the coherency is strongly linear over the range of 0 to 50 Hz and this is consistent with the low level of sollicitation from the ambient noise in the sediments.

Cross-spectrum spectral ratio

The fundamental resonant frequency of longitudinal and transverse components varies from 1.7 Hz to 28.7 Hz. These results are similar to those obtained with the spectral ratio. The relation identified in the spectral ratio concerning the evolution of the fundamental resonant frequency with the depth of the sediments (figure 1) is also observed. The amplification factor varies from 2.9 to 39.6. The amplification seems to be realistic. The largest amplifications are over the sediment-filled valley.

The spectral resolution of the results is also 0.6 Hz. In this case, the bias of the results is still controlled by the signal to noise ratio. The signal to noise ratio is also moderate indicating little bias in the results. The variance is the least of all for the three methods. The variance is proportional to the power of two of the transfer function. This explains why the amplification factor is more realistic compared with the previous method. The variance of the results has also been reduced significantly by the averaging procedure used in the signal processing. The average coherency obtained (0.4) indicates local noise contamination of the results. However, the coherency is also strongly linear over the range of 0 to 50 Hz for this method.

Vertical spectral ratio

The fundamental resonant frequency of longitudinal and transverse components varies from 1.1 Hz to 29.8 Hz. Generally, the fundamental resonant frequencies identified by this method are lower than those from the other methods by 0.5 to 2.5 Hz. This method generally gives different resonant frequencies than the other methods. The relation between the level of the fundamental resonant frequency and the depth of the sediments is also respected with this method. The amplification factor varies from 1.3 to 313.8. The amplification range is abnormally large. The zone near the center of the sediment-filled valley shows the largest amplification.

The spectral resolution of the results is 0.6 Hz. The bias and the variance are very difficult to identify using the method developed by Nakamura (1989) and Lermo and Chavez-Garcia (1993). In these results, the urban noise seems to severely affect the vertical component and, also, the signal to noise ratio is weak. The results are probably biased. Their variance is strong and this is confirmed by the large range of the amplification factor. Even if the variance of the results has been reduced by the averaging procedure in the signal processing, it remains the highest for the three methods. The results are also contaminated by noise as indicated by the average coherency obtained (0.35). However, the coherency is not linear over the range of 0 to 50 Hz and this indicates that the transformation between the input signal and the output signal is not linear. This is abnormal for the low level of sollicitation of the sediments from the ambient noise.

CONCLUSIONS

The frequencies determined by the spectral ratio and the cross-spectrum ratio methods are similar and are the most significative. The vertical spectral ratio identifies different resonances than those obtained by both the other methods. The amplification factors of the cross-spectrum spectral ratio are considered to be the most realistic. Those of the spectral ratio are significant but they have a higher variance than the spectral ratio. The amplification factors from the vertical spectral ratio method are overly high. The coherency of the spectral ratio and the cross-spectrum spectral ratio shows a linear transformation between the input and the output signals while the coherency of the vertical spectral ratio does not. However, the coherencies are weak for all the methods and this reflects the presence of urban noise. In this project, we have measured the site response of the sediment-filled valley of the urban area of Quebec city from ambient noise measurements. Other recent experiments tend to confirm the validity of ambient noise measurements in the characterization of site response (Akamatsu et al., 1991; Dravinski et Ding, 1993; Field et al., 1990; Gutierrez et Singh, 1992; Hough et al., 1992; Kameda et al., 1991; Lermo et Chavez-Garcia, 1992 et 1993; Okada et al., 1991). We consider that the absolute values calculated from the measurements, both in terms of frequency and amplification, are realistic. The regional approach used also provides a relative view of the values over the mapped area.

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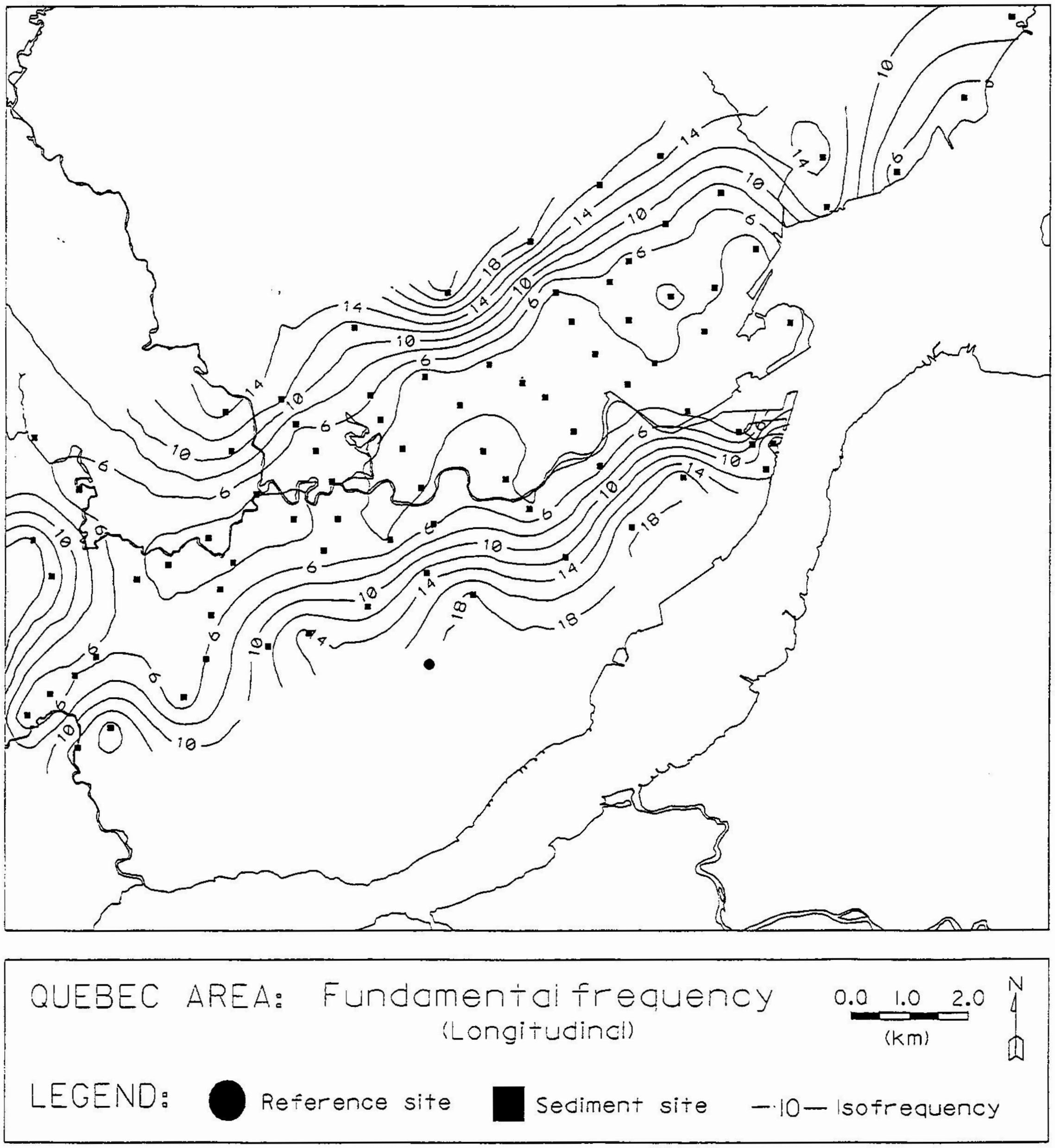
QUEBEC AREA: Fundamental frequency
(Longitudinal)
0.0 1.0 2.0
(km)
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LEGEND:
Reference site
Sediment site
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6
10
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Figure 1

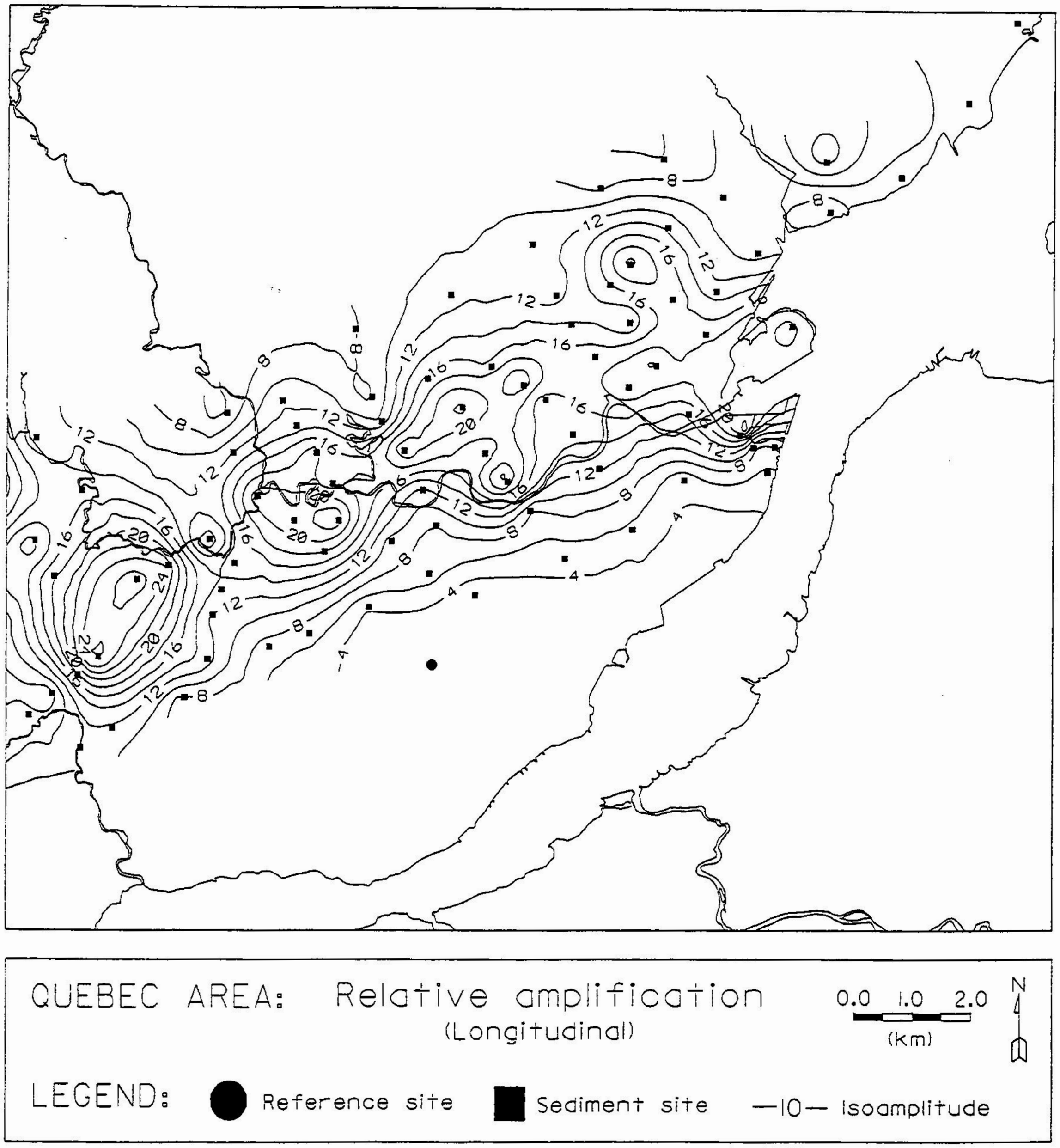
QUEBEC AREA: Relative amplification
(Longitudinal)
0.0 1.0 2.0
(km)
N
LEGEND:
Reference site
Sediment site
—10— Isoamplitude

Figure 2