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HORIZONTAL-TO-VERTICAL COMPONENT RATIOS FOR EARTHQUAKE GROUND MOTIONS RECORDED ON HARD ROCK SITES IN CANADA

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the
degree of Master of Science

Department of Earth Sciences
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Ottawa, Ontario, Canada
March, 2000

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The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of the thesis entitled "Horizontal-to-Vertical Component Ratios For Earthquake Ground Motions Recorded on Hard Rock Sites in Canada", submitted by Jamila A. Siddiqi, in partial fulfillment of the requirements for the degree of Master of Science.

Chairman, Department of Earth Sciences

Thesis Supervisor

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Carleton University,
March, 2000

ABSTRACT

In seismic hazard assessment, site response is one of the most important factors to be determined. In this study, we explore site response for hard rock sites in different parts of Canada. Rock response is an important component of the overall response of any site, and important in the interpretation of seismograms to separate source, path and site effects. The technique used for this purpose was originally proposed by Nakamura (1989) and further extended by Lermo and Chavez-Garcia (1993). According to this method, amplification can be inferred by taking the horizontal-to-vertical component Fourier spectral ratio (H/V) of the site. The hypothesis of this technique is that for a soft layer overlying a half space, the soft layer will amplify the horizontal component of ground motion, while amplification effects on the vertical component are small enough to be neglected.

The H/V method was applied to an earthquake database compiled from the records of 32, three-component, Canadian National Seismograph Network (CNSN) stations. These stations are located on rock outcrops. A total of 61 earthquakes of magnitude 4 – 6 from 1993 – 1996, and 363 earthquakes of magnitude ≥ 2 from 1998 – 1999 were used in this study. Nakamura's method was applied to the strong S-wave part extracted from the seismograms. Assuming the computed H/V ratios to be a measure of site amplification, amplification factors for rock sites in the eastern, middle, and western parts of Canada were determined. The results at frequencies of 1-hz and 5-hz are

compared. For eastern Canada, average amplification at 1-hz is 1.1 and at 5-hz, it is 1.5. For mid-Canada, the average amplification at 1-hz is 1.2 and at 5-hz, it is also 1.2 (this value excludes the mean H/V ratio values for one station to avoid bias due to a high site response). For SW-Canada, amplification at 1-hz is 1.1 and at 5-hz, it is 1.2. For NW-Canada, amplification at 1-hz is 1.1 and at 5-hz, it is 1.5. Thus the average H/V for typical rock sites is 1.1 ± 0.1 at 1-hz, and between 1.2 – 1.5 at 5-hz for the whole country, regardless of geographic location. We generally conclude that the effect of amplification tends to grow with increasing frequency, consistent with what would be expected from a decrease in shear-wave velocity as the seismic waves approach the surface. The mid-Canada sites have the lowest inferred site amplification, consistent with competent hard-rock site conditions with high near-surface shear-wave velocities. The interpretation of the H/V ratio as a measure of site response is consistent with the general geological conditions of the recording sites; the 5-hz H/V ratio appears to be correlated with local geological conditions.

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CHAPTER 1

INTRODUCTION

1.1 SYNOPSIS

In seismology, it is well known that soil deposits amplify ground motion. The amount of amplification depends on several factors such as compaction, age, layer thickness etc. These factors influence the shear-wave velocity, density and damping characteristics of the soil. It is often assumed that hard rock materials do not amplify ground motion. However, the results of previous studies indicate that rock sites may also have significant amplification due to their shear-wave velocity gradient. In this study, we investigate site response associated with hard rock seismograph sites in Canada, as inferred from the ratio of the horizontal-to-vertical component of the Fourier spectrum of ground motions. For this purpose, an earthquake database was compiled based on the seismograph records obtained from the Geological Survey of Canada (GSC). In total, 61 earthquakes of magnitude 4 to 6 from 1993 – 1996 and 363 earthquakes of magnitude ≥ 2 from 1998 – 1999 were analyzed. 32 broadband, three-component Canadian National Seismographic Network (CNSN) seismograph stations recorded these events. The strong S-wave part of the seismograms was windowed from the time series of each component of each record. The Fourier spectrum was calculated, and the ratio of the horizontal to vertical component determined as a function of frequency (H/V). According to Nakamura (1989) and others, the H/V ratio is a

measure of site amplification. The H/V ratios determined by this study were correlated with the general geological conditions of the sites and compared with the findings of previous studies.

1.2 ORGANIZATION OF WORK

The thesis is organized in six chapters. Chapter 1 presents a brief introduction to the work done in the study, an outline of how the work is organized, and an overview of the findings of the study.

Chapter 2 gives the requisite theoretical background of S-waves and Rayleigh waves and their role in the phenomenon of site amplification. An outline of the technique applied in this study is given along with a review of previous studies utilizing this method.

Chapter 3 describes the database used in the study and the data processing procedures. The time series of selected events were processed in a software package (SAC: Seismic Analysis Code) to window the S-wave and a noise sample of the seismograms. These windows were then transformed to the frequency domain by Fast Fourier transform. The values were sampled at 24 frequency values, spaced at interval of 0.1 log frequency units (smoothed within the frequency bins). Data in this form were then used to calculate the horizontal to vertical component ratio (H/V) as a function of frequency.

Chapter 4 presents the computed H/V ratios. The procedure of calculating the ratios is also discussed. The ratios were calculated partly by using spreadsheet software and partly by FORTRAN programs. Once the ratios were obtained, their mean, standard deviation and 90% confidence intervals were also calculated. The results are displayed in graphical form and tabulated in the Appendix.

Chapter 5 discusses the regional geological units and the local surficial materials of Canada with focus on the locations of the seismograph sites. These are presented in the form of tables and maps. H/V ratios were then examined for a possible correlation with the local geology. And, in Chapter 6, we present the conclusions and discuss the H/V results of this study in comparison with those of previous studies.

1.3 FINDINGS OF THE STUDY

The findings of this study suggest that although the H/V ratios are not high for the hard rock sites, they are often significantly greater than unity. This suggests significant site amplification. On average, the highest inferred amplification is a factor of 1.5 at 5-hz, for rock sites in northwestern Canada. The average H/V for typical rock site is 1.1 ± 0.1 at 1-hz and between 1.2 - 1.5 at 5-hz for the whole country. These results are generally consistent with the findings of limited previous studies. A correlation of the computed H/V ratios with the local geology shows that at higher frequencies (5-hz), the H/V is influenced by the local geological conditions.

REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter reviews the literature concerning the response of surficial materials to seismic excitation, focusing on those studies that are based on the use of the horizontal-to-vertical component spectral ratio technique, as proposed by Nakamura (1989). I first outline underlying theory related to seismic waves and the phenomenon of amplification. Then details of Nakamura's technique are given, and alternative site response estimation techniques and their advantages and disadvantages for studying seismic response are explored. However, the main focus of the chapter is on Nakamura's work. Nakamura's technique uses the ratio of the horizontal-to-vertical component of ground motion to calculate the site transfer function; the advantage of this technique is that it is simple to apply, and does not require a "reference" station. I describe how Nakamura's technique has been tested or used in several empirical studies, and discuss the limitations and uses of this technique.

2.2 OVERVIEW OF SEISMIC WAVE PROPAGATION

In considering the amplification of seismic waves by near-surface materials we are concerned with both body waves that travel inside the earth, and surface waves that propagate along the surface of the earth. Body waves include compressional (P-waves) and shear (S-waves), although it is the S-waves that

are of most interest because their amplitudes are generally much higher than P-wave amplitudes. Surface waves include Love waves and Rayleigh waves. At large distances surface waves carry the largest amplitudes. Surface waves arise as a consequence of the free surface of the Earth and are also known as bounded or guided waves. On the other hand, body waves propagate in all directions from the source. (Kulhanek, 1990). The properties of S-waves and Rayleigh waves are of most interest to this study and are outlined below.

2.2.1 SHEAR WAVES

Shear waves (S-waves) are also known as secondary waves because they are the second phase recorded on regional seismograms, after the arrival of the faster P-waves. The particles in the path of S-waves move perpendicular to the direction of wave propagation. S-waves do not pass through liquids because liquids do not transmit shear stress. S-waves travel with a velocity β , given by

$$\beta = (\mu/\rho)^{0.5}, \text{ where}$$

μ = Shear modulus (which is one of the two Lamé's constants; this is the stress- strain ratio for simple shear)

ρ = Density of the medium.

S-wave motion can be resolved into components parallel and perpendicular to the surface of the ground. These are SH and SV waves respectively. S-waves that involve motion in only one plane are known as 'plane polarized' waves.

(Sheriff and Geldart, 1995). Love waves are a special type of shear waves that propagate along the free surface of the Earth.

2.2.2 RAYLEIGH WAVES

Surface waves, including Love and Rayleigh waves, propagate along the free surface of the Earth; the amplitude of surface waves is largest at or near the surface and decreases rapidly with depth. Shallow earthquakes generate large surface waves but for deeper shocks ($h > 100$ km) surface waves become insignificant. This fact helps distinguish shallow from deep shocks. (Kulhanek, 1990)

In Rayleigh waves, sometimes referred to as “ground roll”, the particle motion near the surface is elliptical and retrograde. This means that the particle moves opposite to the direction of propagation at the top of its elliptical path. The particle motion is largely in the vertical plane. Rayleigh waves are low-velocity, low-frequency waves with a broad range of wavelengths. Since the velocity of Rayleigh waves depends on the elastic properties of the medium to a depth of one wavelength, the variability of elastic constants changes the velocity of Rayleigh waves. (Sheriff and Geldart, 1995). It also follows that the velocity varies with frequency (or wavelength). For wavelengths that are very short compared with the layer thickness the propagation speed of Rayleigh waves is about nine-tenths of the shear velocity in the material comprising the surface layer. For very long wavelengths, relative to the thickness of a surficial layer, the

Rayleigh-wave speed is nine-tenths the shear velocity in the substratum material, since the effect of the surface layer is negligible when most of the wave travels in the zone below it. For intermediate wavelengths the velocity falls between these extremes. This variation of velocity with frequency or wavelength is known as 'dispersion'. (Dobrin, 1984); it results in a signal that grows in duration and separates in frequency as distance increases. Rayleigh waves are of particular importance in the formulation of Nakamura's technique, as will be discussed in the next sections.

2.3 OVERVIEW OF SITE AMPLIFICATION

When an earthquake occurs, strain energy is released that spreads through the surrounding crust in the form of seismic waves. During an earthquake, different crustal structures will exhibit different seismic response characteristics. Similarly, a crustal structure may behave differently for different earthquakes, introducing variability in the site response characteristics. The dynamic characteristics of the motion at an observation point on the earth's surface can be written in the frequency domain as follows:

$$\mathbf{O}(\mathbf{f}) = \mathbf{F}(\mathbf{f}) \cdot \mathbf{T}(\mathbf{f}) \cdot \mathbf{S}(\mathbf{f})$$

$\mathbf{O}(\mathbf{f})$ = Observed Fourier spectrum of motion at a point on Earth's surface (as a function of frequency.)

$\mathbf{F}(\mathbf{f})$ = Spectrum of radiation from the focal region, or the source effect.

$\mathbf{T}(\mathbf{f})$ = Transmission characteristics of wave motion propagation through the crustal path, or the path effect.

$S(f)$ = Dynamic characteristics of near surface layers beneath the observation point, or the site effect. (Nakamura, 1989).

It is generally observed that the effect of surface layers, **$S(f)$** , is the most crucial among the three factors influencing the recorded radiations. Therefore, in seismic hazard analysis, site amplification is one of the key factors that determine the amplitude of expected ground motions. Thus it is important to understand why this phenomenon occurs. The amplification of seismic waves may be caused by impedance changes due to a velocity gradient, resonance effects due to a soft layer, and effects due to two-dimensional or three-dimensional geometric effects.

2.3.1 EFFECTS OF IMPEDANCE CHANGES

Consider two horizontal layers, where the velocity of underlying layer 2 is greater than the velocity of surficial layer 1. As a seismic wave travels towards the surface from layer 2 to layer 1, the energy **E** per unit area carried by a wave of single wavelength is given by:

$$E = 2 \pi^2 \rho V f A^2, \text{ where:}$$

ρ = density, V = velocity, f = frequency, A = amplitude.

Assuming that all or nearly all energy is transmitted, then the energy in layer 1 must be equal to that in layer 2. By equating the expressions for energy in the layers, we see that:

$$A_1/A_2 = (\rho_2 V_2 / \rho_1 V_1)^{0.5}, \text{ where:}$$

A_1 is the wave amplitude in layer 1, A_2 is the wave amplitude in layer 2, etc.

In this relation, the product of density and velocity (ρV) is known as acoustic impedance. If $\rho_2 V_2 > \rho_1 V_1$, the height of the wave will be amplified in layer 1, relative to its incoming amplitude from layer 2. (Atkinson, 1999)

2.3.2 RESONANCE EFFECTS

Resonance effects are caused by a discontinuity in the medium properties, which leads to trapped waves with multiple reflections within the layer. When the reflected waves have constructive interference, the phenomenon of resonance occurs. Resonance effects depend on the thickness and elastic properties of the trapping layer. The phase shift required for resonance (assuming a 180° phase shift at the boundary) is given by:

$$f_n = (2n - 1) V / 4H.$$

Where $n = 1, 2, \dots$ V = velocity of S-wave, H = thickness of the layer.

For $n = 1$, the fundamental resonance frequency is obtained:

$$f_1 = V / 4H.$$

If the above equation is re-arranged to obtain an expression for thickness, we see that:

$$H = V / 4f$$

Since the wavelength, $\lambda = V / f$, the above expression can be rewritten to produce the well known "quarter-wavelength rule":

$$H = \lambda / 4$$

Hence, the frequency of the resonant peak can be used to find the thickness of the layer (if the velocity is known). The resonant amplification is given by the ratio

of acoustic impedance in the first and the second layer: $\rho_2 V_2 / \rho_1 V_1$. Note that the amplification due to resonance is greater than that due to a simple impedance effect. (Atkinson, 1999)

2.3.3 HARD ROCK SITE EFFECTS

It is well known that soil sites can strongly influence seismic signals, while it is often believed that hard rock sites have negligible site effects. However, rock sites may also amplify incoming waves, due to either impedance or topographic effects. Tucker et al (1984) conducted a study, which showed that there are significant topographic rock site effects. Basement rock outcrops on a ridge can amplify motions by a factor of eight over a narrow frequency band. Rock sites on topographic features affect frequencies inversely proportional to the dimension of the feature. Geli et al (1988) surveyed the effect of topography on seismic motion. They conclude that amplification is greater on hilltops with respect to the base. This phenomenon occurs at frequencies corresponding to wavelengths equal to the mountain width. The sides of the hills experience complex amplification and de-amplification patterns particularly in the upper parts of the hill. Thus for rock sites, topographic amplification effects may be significant. There may also be rock amplification due to near-surface weathering, as this results in acoustic impedance differences.

2.4 TECHNIQUES FOR ESTIMATING DYNAMIC SITE CHARACTERISTICS

In order to explore the dynamic excitation characteristics of near-surface materials, various estimation techniques have been used. Borehole methods and micro-tremor methods are commonly applied. A brief description is given below.

Borehole Methods: Borehole methods have been used to measure directly the ground motion amplitudes at the surface versus those at depth. This method can be very accurate and is very expensive because drillholes must be made, often to large depths (tens of meters), and borehole seismometers must be placed in the boreholes. Hence, borehole methods are used only for special studies where a significant budget is available.

Micro-tremor Methods: Micro-tremors are small tremors of short period caused by: (i) natural sources (e.g. storms and seas), and (ii) artificial sources. Waves from sea sources are long period tremors (2-3 seconds), while those from artificial sources are usually short period motions. (0.05 to 1 second) (Nakamura, 1989).

The method of using micro-tremor measurements to determine site response is very useful because it is simple and economical. The micro-tremors can be analyzed to obtain site amplification using either a "reference site" technique or "Nakamura's technique". The "reference site" technique involves making recordings on both a soil site of interest, and a nearby "reference" rock outcrop. Amplification is then obtained as the ratio of the soil to the reference rock motion.

The problem with this method is the identification of a common wave train for the two stations. (Lermo & Chavez-Garcia, 1994). In this approach, the effect of the particular source of micro-tremors should be minimized and the measurements should be taken during a relatively quiet time like midnight to avoid background micro-tremor levels. These constraints remove the advantage of taking the measurements readily. (Nakamura, 1989)

Nakamura (1989) proposed a new micro-tremor method for amplification studies, which avoids the constraints of the reference site approach. The dynamic characteristics of surface layers are estimated by measuring solely the micro-tremor at the surface of the soil layer. A stable estimation of predominant frequency and amplification factor can be made regardless of the excitation source. Nakamura's method is based on the resemblance of the transfer function for the horizontal motion of surface layers to the spectral ratio of the horizontal-to-vertical component motion. The advantage of Nakamura's technique is that it works well even in the presence of artificial tremors and is not affected by micro-tremor noise. There is no need for a reference site.

2.5 NAKAMURA'S TECHNIQUE

Nakamura made micro-tremor observations for two sites continuously for thirty hours. His observations at one of the sites, Kamonomiya, showed that the dominant vibration frequency of the surface layers was about 1.5-hz as observed during quiet time periods. For the other observation site, Tabata, he found that 2

to 3-hz and 4 to 8-hz frequencies were dominant. However, it was determined that a train induced the 4-hz tremors. This source caused a considerable change in the micro-tremor observations, especially in the vertical component. Frequencies of 2 to 3-hz prevailed at Tabata during quiet time spans. Hence, fluctuations in the prevailing observed frequency of micro-tremors may be caused by a strong effect of artificial tremors in the surrounding areas. Artificial tremor sources have mostly prevailing vertical motions as they induce Rayleigh waves. Rayleigh waves may therefore be treated as noise in micro-tremor surveys.

Nakamura's concept of using micro-tremor observations to determine the response characteristics of surficial materials is based on the following assumptions:

- Micro-tremors consist of various wave motions.
- The ratio of the horizontal component to the vertical component spectrum of earthquake motions ($= A_H / A_V$) is related to soil conditions.
- A_H / A_V is close to 1 for hard rock (having high shear wave velocity).
- Horizontal and vertical tremor motions are similar to each other as input at the base of the surficial layer and are amplified by soft surface layers on hard substrate.

Based on these assumptions, Nakamura (1989) develops a new transfer function estimation method to determine the horizontal-component amplification of

surface layers. The transfer function S_T of surface layers, for horizontal motions, is generally defined as

$$S_T = S_{HS} / S_{HB} , \text{ Where}$$

S_{HS} = Horizontal tremor spectrum on the surface. S_{HS} is readily affected by surface waves. Since artificial noise sources mostly propagate as Rayleigh waves, S_{HS} of micro-tremors may possibly be affected by Rayleigh waves.

S_{HB} = Horizontal tremor spectrum incident at the substrate (base of surficial layer)

The effect of surface layer on vertical tremors, E_s , can be written:

$$E_s = S_{VS} / S_{VB}$$

Here, E_s primarily represents the contribution of Rayleigh waves to the vertical tremor motions, as there is generally no significant amplification of motion in the vertical component by low-velocity layers near the surface (because the refraction of the rays towards the vertical reduces the vertical-component shear amplitudes, counterbalancing the impedance amplification effects). If there is no Rayleigh wave contribution, then, $E_s = 1$. If $E_s > 1$, it indicates a significant Rayleigh wave effect. Assuming that the relative effect of Rayleigh waves (at the surface versus at the base) is equal on vertical and horizontal components, a more reliable transfer function for the horizontal motions, that removes the spurious Rayleigh waves contributions from artificial sources, can be written as:

$$S_{TT} = S_T / E_s = (S_{HS} / S_{HB}) \cdot (S_{VB} / S_{VS}) = R_s / R_B$$

$$\text{Here } R_s = S_{HS} / S_{VS}$$

$$\text{And } R_B = S_{HB} / S_{VB}$$

Nakamura obtains R_s by dividing the horizontal tremor spectrum, measured at the surface, S_{HS} , by the vertical spectrum S_{VS} , also measured at the surface.

Theoretically and experimentally

$$S_{HB} \approx S_{VB} \text{ so } R_B \approx 1 \quad \text{and thus}$$

$$S_{TT} \approx R_s = S_{HS} / S_{VS}$$

This relation implies that the transfer function of surface layer may be estimated from surface measurements of the tremors only, at a single station. Put simply, the vertical tremor on the surface retains the characteristics of the horizontal tremor input at the base of the substrate, and hence substitutes for the latter.

Nakamura's method includes a correction through R_s to eliminate the effects of Rayleigh wave contributions. However, results show that the accuracy of the amplification estimates is reduced when there exists a noise tremor whose frequency matches the prevailing frequency in the estimated transfer function. (Nakamura, 1989)

2.5.1 VERIFICATION OF THE METHOD

Nakamura verified the micro-tremor site response results at the two observation points at Kamonomiya and Tabata. At Kamonomiya, he computed the transfer function S_{TT} from seismic observations using the reference site technique, and compared the results with the average of $R_s = S_{HS} / S_{VS}$. His results showed that R_s is similar to S_{TT} in terms of the peak frequency, amplification and shape. At Tabata, S_{TT} and R_s were estimated from simultaneous observations of micro-

tremors on the surface and at a point 25 meters below the surface, over a 24-hour period. The ratio of the surface-to-downhole observations was used to compute S_{TT} , while R_s was computed from the surface observations only. The values of S_{TT} and R_s were shown to be roughly similar. Nakamura also compared R_s and S_T at Mexico City using the recordings of strong earthquake motions to compute S_T using the reference site approach. R_s was then obtained by micro-tremor observations. He found that the maximum amplification of peak ground velocity due to the soil layer could be estimated by using the maximum acceleration ratio of horizontal and vertical tremors on the surface, although there was considerable variability. In all cases, however, R_s and S_T were highly correlated with each other, implying that R_s is a good estimator of the transfer function.

2.6 GENERAL APPLICATION OF NAKAMURA'S TECHNIQUE TO S-WAVE AMPLIFICATION

Nakamura's technique was developed for micro-tremor studies of site amplification. Lermo and Chavez-Garcia (1993) extended this technique for the strong S-wave part of earthquake seismograms. To explain why Nakamura's technique should be applicable to the S-waves, Lermo and Chavez-Garcia (1993) follow two lines of argument. They observe that in Mexico City, the amplification factors due to a thin soft layer are very high (amplification of a factor of 50 was observed in the 1985 Michoacan earthquake). For the vertical component however, the amplification factors are small enough to be neglected

and this is invariant to the soil condition and the magnitude of the earthquake. Therefore, the vertical component can be used as an estimate of the ground motion incident to the surficial layer. Their second argument is based on numerical modelling. In this model, they assume that site effects are caused by a single layer over half space, and the excitation is due to plane S-waves. The parameters of this model are incidence angle and the mechanical properties of the layers. They compute the theoretical transfer functions of the model and observe that for the horizontal component, the amplitude of the resonant peak varies (by a factor larger than 2) as a function of incidence angle. For the vertical component, this variation is small and is less than a factor of 2. They also computed the transfer function of the model using Nakamura's method. They found that for all angles of incidence, resonance frequencies were identified well by Nakamura's ratio. For incidence angles of 50° and greater, the resonance frequency and also the amplification values at the first resonance frequency agreed well with the standard spectral ratios. (Lermo and Chavez-Garcia, 1993).

In another study by Lachet and Bard, (1994), the authors notice that the H/V ratio is a stable site characteristic for body waves. This result is verified by experiments done by researchers such as Lermo and Chavez-Garcia. Therefore, the H/V ratio can be used as an estimate of site amplification for weak or strong motion recordings.

2.7 USES OF H/V TECHNIQUE

Since Nakamura originally proposed the technique, several investigators have applied this technique to estimate amplification based on the H/V ratio, using earthquake databases in different parts of the world. An overview of pertinent results is given here:

- For cities with different geological and tectonic settings, the site response estimates obtained with the H/V method were compared with standard spectral ratio techniques based on a reference rock site, and found to be very similar. (Lermo & Chavez-Garcia, 1993).
- If site effects are caused by simple geology, it is possible to estimate the dominant period and local amplification factor using records at only one station, based on H/V. The method gives a good estimate of the frequency and amplitude of the first resonant mode, though the higher modes do not appear. (Lermo & Chavez-Garcia, 1993).
- The method is useful for site effect evaluation in urban areas. Knowledge of the resonance frequency of the soil is an effective tool in determining the kinds of buildings most susceptible to damage. (Lachet & Bard, 1994)
- Micro-tremor measurements can complement other site effect studies. For example, in regions of low seismicity, site amplifications can be spatially interpolated with micro-tremor data. (Lermo & Chavez-Garcia, 1994). In one study by Duval et al (1995), H/V curves were spatially interpolated to obtain maps of spectral site effect. The results were in accordance with the

geological data. Also, the highest computed amplifications coincided with areas known to experience strong site effects during earthquakes.

- Since micro-tremor measurements are simple and inexpensive to obtain, they can be used in microzonation techniques, especially in urban areas. (Teves-Costa et al, 1995). An example of this is the study undertaken by Bour et al (1998) in which H/V spectral ratios were used to establish maps to characterize the site amplifications for the Rhone Delta region (France). Resonance frequency maps and maps of amplification level were used for the seismic microzonation for the whole region.
- Field and Jacob (1995) observe the H/V method of assessing site response is very useful for hazard assessment in regions that lack adequate reference sites.

2.8 COMPARISON WITH OTHER TECHNIQUES:

In this section, Nakamura's (1989) technique will be compared to the other widely used techniques to estimate the site response. Broadly, these include the popular spectral ratio technique (based on a reference rock site), and numerical simulation techniques.

The spectral ratio technique is among the widely used techniques for the estimation of site effects in regions of moderate to high seismicity. It consists of recording several earthquakes in an array of stations. One station serves as the reference station and is located on hard rock, away from the source of site

effects. The S-wave signal from earthquakes is used to estimate the site effects of soil stations relative to the reference station. Lermo and Chavez-Garcia (1993) have compared the results of Nakamura's technique with the results obtained using the spectral ratio technique. For the spectral ratio technique, they observe that the technique has some important limitations to it. For example, the nearby reference station may not record all of the events recorded by the soft soil (due to lower signal amplitudes). This introduces the constraint of long periods of observation, so that sufficient events are recorded simultaneously on both sites. In some areas, it might be difficult or impossible to find a nearby reference station on rock. Also, in the case of spectral ratio technique, the reference station is located on a rock site, which might itself have a significant site response. In Nakamura's technique, by contrast, we do not need a reference station, thereby eliminating many of these limitations.

In a study by Field and Jacob (1995), the modified H/V technique (as proposed by Lermo and Chavez-Garcia, 1993) was applied to the shear-wave part of the aftershock records of the California 1989 Loma Prieta earthquake. From the H/V ratio technique, they were able to reproduce fundamental and higher mode resonant peaks for the sites under study. They found, however, that the amplitudes obtained using the H/V ratio technique were underpredicted as compared to the spectral ratio estimates. In the case of the study by Lermo & Chavez Garcia (1993), they were able to reveal only the fundamental resonant frequency. Unlike the results of Field and Jacob (1995), the H/V amplification

estimate at the fundamental frequency was in good agreement with the amplification obtained from the spectral ratio method. Finally, Lermo & Chavez-Garcia found less variability among the H/V ratios compared to spectral ratios. By contrast, Field and Jacob found the uncertainty level to be the same for the two techniques. A study by Bonilla et al (1997) finds that H/V ratio technique obtains the same predominant peaks as the direct spectral ratio method, but the amplification level obtained is different for the two techniques.

Nakamura's technique has also been compared with the results of numerical simulation techniques and theoretical models. For example, Tavez-Costa et al (1996) made a comparison with 2D theoretical results for a vertically incident SV-wave. Fourier transform functions for different points on the basin under study were obtained. Comparing the theoretical H/V ratios and the Fourier transfer functions, three out of five stations show agreement between the dominant frequency and the resonance frequency. For the other two stations, the authors concluded that they might not have been properly modelled by the synthetic data.

Bour et al (1998) compared the results of their study, which utilised Nakamura's technique, to the solutions of one-dimensional numerical simulation models of site response (based on a popular engineering program called SHAKE91). The simulation model computes the response of horizontally layered soils under seismic excitation, assuming equivalent linear soil behaviour. Using geotechnical and drilling data, they constructed models of the soil columns for several

industrial sites. Then these soil columns were used to calculate transfer function using the program SHAKE91. A comparison of results reveals good overall agreement between the transfer functions obtained by the two methodologies. However, the amplification suggested by the H/V ratio is higher than that obtained by numerical modelling.

2.9 STABILITY TESTS

Tavez-Costa et al (1996) examined time variant characteristics of the micro-tremor amplitudes and the stability of H/V spectral ratios over repeated observations. In their study, micro-tremors were continuously recorded at a rock site. Their results show that the predominant frequency of the ratio remains stable over repeated observations despite the amplitude fluctuations presented for each component. The authors also applied this technique to thick and thin alluvial deposits and compared the results with numerical simulations. Their results indicate that the observed predominant frequency is, as expected, based on the thickness of the alluvium deposits, for thin alluvium deposits. For thick alluvial deposits, one deposit showed predominant frequencies that agreed with theoretical results. For another thick basin, however, the H/V ratios did not present a peak so clearly. The authors concluded that the reason for this could be that the impedance contrast was not so strong. Overall, the evaluated predominant frequencies correlated well with the depths of alluvial deposits.

Theodulidis et al (1996) checked the stability of the H/V spectral ratio at different depths in the Garner Valley Downhole array in Southern California. They found that the stability of these ratios at each individual depth (as deduced from the standard deviation values) was remarkable. However, their shape drastically changed from the surface to a depth of 220 meters, indicating the influence of depth and site geology. They compared the mean spectral ratio of surface to deep sites with the mean H/V ratio on the surface. Their study found a similarity in the shape of spectral ratio and H/V ratio curves for frequencies below 10-hz and above 13-hz. However, H/V ratio exhibits a simpler shape than the actual spectral ratio of surface to deep motions. Theodulidis et al. (1996) also compared experimental to synthetic ground motion data for the ratio of surface to deep motions. The H/V spectral ratios of the experimental data showed 2 – 4 times lower amplitude than the corresponding synthetic ones. This could be because in the synthetic data, scattered waves are absent. Also, for the H/V spectral ratio, the amplitudes are lower for the experimental data implying an enrichment of the vertical component due to the presence of scattered waves. The authors also concluded that the focal mechanism radiation pattern seriously affects the theoretical H/V ratio amplitude, but the shape of the H/V ratio curve remains the same for different focal mechanisms. Variations in the regional quality factor (Q) do not change the shape and amplitude of H/V ratio.

Duval et al (1995) investigated the stability of the H/V ratios, using a micro-tremor data set obtained for Niceport, France. They found that H/V ratios inferred from

recorded micro-tremor spectra were stable, even between day and night, in comparison to the source spectra (which varied greatly). At sediment sites, H/V ratios from micro-tremors form peaks centred at a well-defined frequency. They also studied velocimeter-recording data at 10-meter distance spacing. For velocimeters placed in the same geological conditions, H/V results were the same.

2.10 SITE AMPLIFICATION MAPS

Duval et al (1995) produced amplification maps for the region of Nice, France, based on micro-tremor observations. Recordings were obtained at a 50-meter spacing for four days and nights. Data were processed and the values interpreted for each site to obtain an H/V ratio curve in the frequency domain. From these curves, the maximum amplitude and its frequency were determined for each site. These values were interpolated in space to produce site amplification maps. The maps identified two zones where maximum amplification values were high. These were the areas at the middle of the alluvial basin, and on part of a limestone hill. The maximum amplification in the middle of the basin occurred at a frequency between 0.5 – 2.0-hz. At higher frequencies, the maximum leaves the deepest part of the fill to reach the edges of the valley. Hence, by using the H/V ratios, their spatial interpretations give valuable indication about the distribution of the amplification peak. Bour et al (1998) performed microzonation using Nakamura's method in the plain near Rhone Delta in Southern France. In the Rhone Delta, there are several critical

installations in proximity to active faults. H/V ratios were calculated from recordings of background noise for a grid of sites. With these results, Bour et al (1998) produced maps to characterize amplification effects of the region. These included a resonance frequency map and maps of amplification amplitudes as a function of frequency range, leading to a seismic microzonation for the region.

2.11 INFLUENCE OF DIFFERENT PARAMETERS ON H/V RATIO

Lachet and Bard (1994) studied the influence of different parameters on the H/V ratio. They carried out synthetic waveform calculations for fifteen soil profiles. Noise was simulated as the signal produced at a single site by a set of superficial sources distributed all around with random amplitude and time delay. Three types of relations were explored. They included (i) variations in source characteristics (ii) influence of geological structure and (iii) varying incidence angles. A brief description of the results of Lachet & Bard (1994) is given below:

VARIATION OF SOURCE CHARACTERISTICS: Experiments were performed using two different source types. The H/V ratios obtained for different source excitations all exhibit a peak whose position is constant regardless of the source type and source function. This means that for randomly distributed surface sources, the H/V peak position is independent of the source characteristics. Other calculations made for different geological structures with various sources confirm the result.

INFLUENCE OF GEOLOGICAL STRUCTURE: Synthetic waveforms were generated for geological structures in three different regions: Ashigara Valley, Turkey Flat and coastal site in SE France. The general shape of the H/V ratios obtained in these cases indicates that they present a clear peak at varying frequency. Results obtained for different sites show a strong influence of geological structures on the H/V peak position. The resonance frequency as calculated for vertically incident S-waves agrees well with the calculated H/V peak frequency.

SV-WAVES WITH VARYING INCIDENCE ANGLE: A 1-D Program was used to compute the surface response to SV waves with incidence angle varying from 5° to 89° . The results show that the H/V ratios exhibit rather stable peaks, the first of which corresponds to the fundamental resonance frequency. Theodulidis et al (1996) also found that the H/V ratio due to incident P and SV plane waves exhibit stable resonant peaks at various frequencies, whose positions are almost independent of the incidence angle, although their absolute amplitudes vary significantly with incident angle.

2.12 LIMITATIONS OF NAKAMURA'S TECHNIQUE

Although Nakamura's technique has been successfully used as described above, this section discusses the limitations of the technique and the possible solutions to them.

1. THEORETICAL ASPECTS NEED FURTHER TESTING:

Gutierrez and Singh (1992) argue that while in some cases the micro-tremor results agree reasonably well with those obtained during earthquakes, this is not

always the case. For example in Imperial Valley, California, site effects observed from strong motion data were not satisfactorily reproduced from the analysis of micro-tremor recordings. The origin and propagation of micro-tremors and their reliability in shedding light on site effects still remain doubtful. They argue that a general acceptance of the technique would require extensive testing against amplification results obtained from earthquake records, which is a difficult proposition in areas of low seismicity. In a recent study by Bour et al (1998), the authors have pointed out that the physical phenomena underlying the method are only partially understood.

2. H/V RATIOS SHOW ONLY THE FUNDAMENTAL RESONANCE:

Tavez-Costa et al (1996) observe that when applied to micro-tremor recordings for sedimentary sites with large impedance contrast with the underlying bedrock, the H/V ratios exhibit a single peak, indicating only the fundamental frequency and not the harmonics, or the whole frequency range over which the sedimentary site amplifies motion. The amplitude of this peak does not seem well correlated with the actual amplification of the S-wave amplitude. Lachet and Bard (1994) observed that the peak in the H/V ratio for micro-tremors might be related to the polarisation curve of Rayleigh waves. These waves are polarized in both horizontal and vertical directions. To test this, polarisation curves were computed for a half space model, and for real sites. These curves were compared with H/V ratios calculated from a noise simulation. The results suggest that the H/V peak position in the noise simulation corresponds to the first peak in the polarisation

curves. This implies that the shape of the H/V ratio from micro-tremor studies is widely controlled by the fundamental Rayleigh wave.

3. AMPLITUDE OF THE H/V PEAK IS NOT A RELIABLE ESTIMATE OF ACTUAL AMPLIFICATION:

Some researchers have observed that the amplitude of the H/V peak does not correlate well with actual amplification. (e.g, Lachet and Bard (1994)). Nakamura's technique suggests that it is possible to estimate the amplification of seismic motion due to resonance of surface layers simply from the maximum spectral amplitude of the H/V ratio. Lachet and Bard test this hypothesis by comparing the amplitude (A_n) of the H/V peaks obtained from noise simulations with the maximum amplitude of the transfer function for vertically incident S-waves (A_s). However, in the simulation results, they obtained a poor agreement between the H/V peak amplitude and the amplification for theoretical vertical S-waves. Lachet and Bard (1994) further test the influence of Poisson's ratio on the amplitude of the H/V ratio. Their results show significant variations as a function of V_p/V_s ratio (which is related to Poisson's ratio).

Lachet and Bard (1994) also explore the possibility that results may be influenced by the relative location of source and receivers. Therefore, they investigated parameters like structure thickness, maximum source-receiver distance and source depth, that might influence the excitation of surface waves. Their results show that the greater is the source-receiver distance, the bigger is the Rayleigh wave contribution, and thus the higher is the H/V peak amplitude.

H/V ratios obtained for varying source depths show that the H/V peak amplitude remains nearly constant for different source depths. These results indicate that the H/V peak amplitude cannot be used in a straightforward way for amplitude studies since it shows considerable variability with respect to parameters such as Poisson ratio in sedimentary structure and source-receiver distance.

Lermo and Chavez-Garcia (1994) have further tested the validity of Nakamura's technique by examining two observations. According to them, if the Nakamura technique is valid, then we should observe the following:

- i) The ellipticity computed at the surface (horizontal-to-vertical motion ratio) should bear some resemblance to the one-dimensional transfer function for vertical S-wave incidence.
- ii) The ellipticity at the interface between the sediments and substratum should be close to unity.

They examined data from two strong motion stations in Mexico City where reliable geotechnical information is available. The results for the first test show that the frequency of occurrence of the highest amplification peak of the 1D transfer function is in very good agreement with the ellipticity at surface, although there was a significant difference in amplitude.

They tested second assumption by comparing S-wave transfer function at surface and the ellipticity for different modes of Rayleigh waves at the base of stratigraphy. The sites chosen for this test had reliable information of P- and S-

wave velocities from boreholes. They observed ellipticity of near one at the fundamental resonant frequency of the stratigraphy, which is in agreement with the second assumption. However, for higher modes of Rayleigh waves, this assumption does not hold.

Castro et al (1997) test the following two hypotheses of Nakamura's Technique:

- i) The vertical component of ground motion should not be significantly amplified.
- ii) The spectral amplitude of the vertical and horizontal components at the base of the sediments should be approximately equal.

They used a data set of accelerograms from 10 earthquakes with magnitude between 4.7 and 6.6. Accelerograph stations located on different geologic conditions in the region of Friuli, Italy (including rock sites) recorded the ground motions. Regression results indicate that low vertical amplification factors were obtained for most of the stations (both rock and soil). This implies that the vertical component of S-wave arrival is approximately free of site amplification effects (within a factor of 2). However, when the signal is contaminated by surface waves, the variability in apparent vertical amplification effects increases. Regarding the validity of the second assumption, the authors suggest that it still needs further testing. Since the borehole method allows a direct determination of the seismic response, the authors propose that data should be obtained from well-instrumented boreholes, and used to test the validity of second assumption.

2.13 SUMMARY OF REVIEWED ARTICLES

AUTHORS OF STUDY	FOCUS OF STUDY	DATA SET AND FINDINGS OF THE STUDY
1 Lermo & Chavez-Garcia, 1993	To show that it is possible to estimate the empirical transfer function without a reference station	Data set: consists of S-wave part of earthquake events. It has 6 earthquake events from 1985 – 1990 for Mexico city, 12 events in 1991 for Oaxaca, and 8 events from 1989 – 1990 for Acapulco. Results of study strongly suggest that site effects can be evaluated using spectral ratio from one station. The results hold good where amplification is caused by simple geology. There is a good agreement between results from Nakamura's ratio and those obtained from standard spectral ratio technique
2 Lermo & Chavez-Garcia, 1994	To review the applicability of micro-tremor measurements in evaluating site response of soft soils. To evaluate three techniques using micro tremor measurements	Data set is the same as used in the 1993 study of Lermo and Chavez-Garcia for the three cities of Mexico. Results show that micro tremor measurements allow for determination of the dominant period of amplification with good reliability in the range 0.3 to 5-hz. The three techniques compared were: direct computation of amplitude spectra, computation of spectral ratios relative to a firm soil reference station, computation of spectral ratios between horizontal component relative to vertical components of motion. Findings of study show that best results were obtained by the third (Nakamura's) technique, which also provided a rough estimate of amplification.
3 Lachet & Bard, 1994	To investigate the characteristics of H/V ratio and its sensitivity to various parameters	Data set: consists of synthetic calculations for 15 soil profiles. Results of the study indicate that for noise-simulated data, the position of the peak is independent of the source excitation function. Ratios for SV waves show several peaks whose position is independent of incidence angle. The peak position is influenced by the geological structure. Shape of H/V ratio is controlled by the polarization curve of fundamental Rayleigh waves. The ratio is a reliable indication of the resonance frequency of a horizontally layered structure. The amplitude of H/V peak is sensitive to velocity contrast, Poisson's ratio, and source-receiver distance.

AUTHORS OF STUDY	FOCUS OF STUDY	DATA SET AND FINDINGS OF THE STUDY
4 Field and Jacob, 1995	To compare and test site response estimation techniques.	Data set: 1989 Loma Prieta earthquake aftershock data collected in Oakland, California. Results: The results for the non-reference site-response estimation techniques reveal frequency dependence of site response at sediment sites. (For bedrock sites, the response is flat and near unity.) The authors observe that revelation of frequency dependent character of site response by the non-reference site methods is promising for site-specific hazard assessments in regions lacking adequate reference sites
5 Duval et al, 1995	To check the stability of results obtained by H/V ratio. To map the site effects by spatial interpolation of H/V curves	Data set: consists of micro tremor recordings in Nice (France). Results: The study establishes the stability of H/V method. The interpolation of H/V curves is very close to the expected results. The frequency accuracy is remarkable. For civil engineering purposes, maps of spectral site effects can be obtained. By increasing the density of measurements, the spatial definition can reach the precision of a building scale.
6 Tevez-Costa et al, 1996	To characterize the seismic behaviour of alluvium layers in the study area using micro tremor measurements.	Data set: is comprised of two sets of micro-tremor measurements in the town of Lisbon. Results: The study confirms the fact that micro tremor recordings give reliable information about seismic behaviour of thin alluvium layers. H/V ratio gives a good estimate of the resonant frequency for the surface soft layers. The evaluated predominant frequencies correlated well with the depths of the alluvial deposits.
7 Theodulidis et al, 1996	To check the use of H/V ratio technique as an indicator of site effects and to check the stability of the results	Data set: consists of 110, three-component accelerograms recorded at five different depths in Southern California. The magnitude range is $3.0 \leq M_s \leq 4.6$. Results of the study show that by computing the mean of the data set obtained at different depths, the results are quite stable. This is confirmed by a low standard deviation from the mean. There is a remarkable difference in amplitude between the observed H/V ratio and spectral ratio. This point needs further research. The focal mechanism radiation pattern does seriously affect the ratio amplitude. The influence of quality factor is negligible on the shape and amplitude of the ratio.

AUTHORS OF STUDY	FOCUS OF STUDY	DATA SET AND FINDINGS OF THE STUDY
8 Bonilla et al, 1997	To find the variability of site effect estimation using S-wave, Coda, and H/V methods.	<p>Data set: consists of aftershocks of 1994 M 6.7 Northridge, California earthquake. A total of 38 aftershocks from M 3.0 to 5.1 were used.</p> <p>Results: Findings regarding the comparison of H/V ratio method and the direct spectral ratio method suggest that H/V ratio method extracts the same predominant peaks as the direct spectral ratio. However, the amplification levels from the two methods are different.</p>
9 Castro et al, 1997	To test the hypothesis involved in determining the response of soils using H/V spectral ratio technique.	<p>Data set: contains accelerograms from 10 earthquakes with magnitudes between 4.7 and 6.6 for Friuli, Italy.</p> <p>Results: The study examined two assumptions of the H/V method. (i) The vertical component of ground motion should be free of amplification. (ii) The spectral amplitudes of the vertical and horizontal components at the base should be the same. Test of the first assumption shows that low amplifications were obtained for the vertical component of S-wave arrival. However, when S-waves are contaminated by surface waves, the results are more uncertain. Conclusions could not be reached for second assumption as it needs further testing using borehole data</p>
10 Bour et al, 1998	To identify and map zones of homogeneous seismic response using Nakamura's technique.	<p>Data set: consists of 137 measurement points over a region of 60 km² in Rhone Delta (South of France) during 1995 and 1996.</p> <p>Results: The study shows that H/V ratio approach provides a simple means of determining the predominant frequency of a soil site. In comparison with a numerical modeling technique, the results obtained from the two methods are similar for formations less than 10 m thick and the harmonics of fundamental resonance frequency are missing from the H/V ratio spectral ratios. The findings also suggest that Nakamura's technique is a useful tool for establishing a seismic microzonation of the whole studied region. Also, the data obtained for the technique gives reliable information on the seismic behaviour of thin, gently dipping surficial layers.</p>

DATABASE AND PROCESSING

3.1 INTRODUCTION

This chapter describes how the earthquake database was compiled and processed. The data set consists of time series of earthquakes of magnitude 4 to 6 from 1993 – 1996, plus events of $M \geq 2$ from 1998 - 1999. The choice of data set was based on data availability. The list of events for 1993 – 1996 was prepared (in 1997) by downloading the event attributes from the Internet site of the Geological Survey of Canada (www.seismo.nrcan.gc.ca). From this list, events from magnitude 4 – 6 were chosen according to certain criteria discussed in the next sections. Time series data of these chosen events were obtained from the Geological Survey of Canada (GSC) and converted to SAC (Seismic Analysis Code, Lawrence Livermore National Laboratory) format using the scripts provided by the GSC. These data were processed using the SAC software package [www-ep.es.lnl.gov/tvp/sac_manual]. Two time windows of the data were selected. One was the noise window, preceding the earthquake, and the other was the signal window, containing the strong part of the S-wave motion. The time series in these windows were Fourier transformed and smoothed over log frequency increments of 0.1 units. The output files gave the values of the Fourier velocity spectrum sampled at 0.1 log frequency units (smoothed within the log frequency bins), covering the frequency range from 0.1

to 20-hz. The 1998 - 1999 data (magnitude 2 and over) were downloaded from the GSC using the autodrm (Automatic Data Request Manager) facility [ftp.seismo.nrcan.gc.ca], Fourier transformed, and tabulated in the same format. The autodrm facility allows download of waveforms within a time period of about two weeks following the event (thus these events were readily obtainable).

3.2 RECORDING STATIONS

As the first step of data collection, the information was organized in the form of two lists. One describes the recording stations and the other describes the earthquake events that were analyzed. The list of recording stations was obtained from the GSC [www.seismo.nrcan.gc.ca]. From this list, three-component broadband recording stations were chosen, because they recorded all the three components over a broad frequency range. Table 3.1 shows selected stations. Tables 3.2 and 3.3 (next sections) show the analyzed events.

(Note: Location of events and stations are also shown on Fig. 5.1)

Table 3.1 List of recording stations.

NET-WORK	STATION	LATITUDE	LONGITUDE	ELEV (KM)	NAME	INSTALLATION DATE	INSTRUMENT TYPE
CNSN	A11	47.243	-70.198	0.061	ST-ROCH-DES-AULNAIES	19941019	S-13
CNSN	A16	47.471	-70.006	0.015	RIVIERE OUELLE, QUE	19941019	S-13
CNSN	A21	47.704	-69.690	0.046	ST-ANDRE, QUE	19941019	S-13
CNSN	A54	47.457	-70.412	0.381	MISERE, QUE	19941019	S-13
CNSN	A61	47.693	-70.090	0.358	SAINT MATHILDE, QUE	19941019	S-13
CNSN	A64	47.826	-69.892	0.137	SAINT-SIMEON, QUE	19941019	S-13
CNSN	BBB	52.185	-128.113	0.014	BELLA BELLA, B.C	19931029	CMG-3E
CNSN	DAWY	64.065	-139.391	0.808	DAWSON, Y.T	19940311	CMG-3E
CNSN	DLBC	58.437	-130.027	0.978	DEASE LAKE, Y.T	19940928	CMG-3E
CNSN	DRLN	49.256	-57.504	0.238	DEER LAKE, NFLD	19931214	STS-1V
CNSN	EDM	53.222	-113.350	0.730	EDMONTON, ALTA.	19920603	CMG-3E
CNSN	FCC	58.762	-94.087	0.039	FORT CHURCHILL, MAN.	19920603	CMG-3E
CNSN	FRB	63.747	-68.547	0.018	IQALUIT, N.W.T	19920603	STS-1V
CNSN	GAC	45.703	-75.478	0.062	GLEN ALMOND, QUE.	19920603	STS-1
CNSN	INK	68.307	-133.520	0.040	INUVIK, N.W.T	19920603	CMG-3E

Table 3.1 continued....

NET- WORK	STA- TION	LATI- TUDE	LONGI- TUDE	ELEV (KM)	NAME	INSTALL- ATION DATE	INSTRU- MENT TYPE
CNSN	LMN	45.852	-64.806	0.363	CALEDONIA MTN., N.B	19930726	CMG-3E
CNSN	LMQ	47.548	-70.327	0.419	LA MALBAIE, QUE.	N.A	STS-1V
CNSN	MBC	76.242	-119.360	0.015	MOULD BAY, N.W.T	19920603	CMG-3E
CNSN	MOBC	53.197	-131.898	0.675	MORSBEY, B.C	19960226	CMG-3E
CNSN	PGC	48.650	-123.451	0.005	SIDNEY, B.C	19931105	CMG-3E
CNSN	PMB	50.519	-123.076	0.400	PEMBERTON MEADOW, B.C	19931112	CMG-3E
CNSN	PNT	49.317	-119.617	0.550	PENTICTON, B.C	19930203	CMG-3E
CNSN	RES	74.687	-94.900	0.015	RESOLUTE, N.W.T	19920603	CMG-3E
CNSN	SADO	44.769	-79.142	0.243	SADOWA, ONT.	19940720	CMG-3E
CNSN	SCH	54.818	-66.783	0.518	SCHEFFERVILLE, QUE.	19940327	CMG-3E
CNSN	ULM	50.250	-95.875	0.281	LAC DU BONNET, MAN.	19941207	CMG-3E
CNSN	WALA	49.059	-113.911	1.400	WATERTON LAKE, ALB.	19920603	CMG-3E
CNSN	WHY	60.660	-134.881	1.292	WHITEHORSE, YT	19930827	CMG-3E
CNSN	YKW1	62.493	-114.509	0.205	YELLOWKNIFE, N.W.T	19940920	STS-1V
CNSN	YKW2	62.425	-114.605	0.180	YELLOWKNIFE, N.W.T	19940920	STS-1V
CNSN	YKW3	62.561	-114.616	0.200	YELLOWKNIFE, N.W.T	19940920	STS-1V
CNSN	YKW4	62.492	-114.742	0.200	YELLOWKNIFE, N.W.T	19940920	STS-1V

3.3 PROCESSING FOR EVENTS FROM 1993 - 1996

The events from 1993 – 1996 were obtained from the archives of the GSC.

These data were augmented by recent events that were downloaded from the GSC using their autodrm facility (as described in the next section).

3.3.1 DATA SELECTION

For the GSC earthquake catalogue of 1993 – 1996, events with the following attributes were selected:

- (i) Magnitude ≥ 4 (Based on catalogued magnitude value)
- (ii) The event was recorded by at least three stations within the following distance range:
 - < 500 km for $M \geq 4$

- <800 km for $M \geq 4.5$
- <1000 km for $M \geq 5$

These constraints were established to ensure good signal strength. Under these criteria the signal to noise ratio is generally very high (much greater than 2). Using these constraints, the following events were chosen (Table 3.2)

Table 3.2: List of selected events from 1993 – 1996.

NO.	DATE	LONGITUDE	LATITUDE	MAGNITUDE	DEPTH (KM)
1	19930129.0705001	-128.546	49.309	4.30	10.0
2	19930313.1759001	-129.216	48.960	4.10	10.0
3	19930325.1334001	-122.607	45.035	5.60	20.6
4	19930529.0529002	-130.335	50.531	4.10	10.0
5	19930627.1636001	-139.370	60.150	4.40	10.0
6	19930803.0920002	-130.763	51.238	4.54	10.0
7	19930803.1303001	-130.666	51.303	5.20	10.0
8	19931022.1310003	-129.005	48.737	4.60	10.0
9	19931202.2030003	-133.709	64.988	4.74	10.0
10	19931222.1701003	-129.327	48.172	4.30	10.0
11	19940103.0126005	-127.018	49.643	5.70	23.6
12	19940116.0149003	-76.047	40.330	4.60	5.0
13	19940202.1209003	-140.099	61.015	4.23	0.0
14	19940212.0704003	-128.962	49.278	5.40	10.0
15	19940220.0737003	-129.176	47.483	4.20	10.0
16	19940220.1520003	-129.078	47.399	4.40	10.0
17	19940412.2114003	-130.268	50.387	4.17	10.0
18	19940427.0030004	-129.109	48.686	4.40	10.0
19	19940714.1241001	-66.600	47.000	4.10	5.0
20	19940715.0502003	-130.310	50.394	4.20	10.0
21	19940821.1305003	-130.397	50.406	4.40	10.0
22	19940925.0053005	-69.961	47.752	4.30	12.2
23	19941003.1310002	-124.931	62.678	4.00	10.0
24	19941006.1747002	-135.743	66.969	4.00	10.0
25	19950129.0311003	-122.365	47.388	5.10	17.2
26	19950301.1607005	-135.108	65.911	4.90	10.0
27	19950612.1723009	-138.404	60.952	5.10	5.0
28	19950724.0607002	-138.963	65.015	4.70	5.0
29	19951015.0129003	-128.587	48.842	4.29	10.0
30	19951112.1304001	-129.179	48.838	4.30	10.0
31	19951121.1230004	-140.932	60.101	4.51	10.0
32	19960103.1312004	-130.392	49.484	4.80	10.0
33	19960128.1130003	-129.276	48.945	4.20	10.0

Table 3.2 continued....

NO.	DATE	LONGITUDE	LATITUDE	MAGNITUDE	DEPTH (KM)
34	19960208.0619003	-131.297	63.353	4.73	0.0
35	19960310.2112001	-130.436	50.573	4.31	10.0
36	19960311.1120001	-131.617	63.449	4.13	0.0
37	19960314.1042014	-74.396	45.925	4.36	18.0
38	19960316.2318001	-130.331	50.471	4.40	10.0
39	19960318.0801003	-127.306	49.689	4.91	38.4
40	19960503.0404007	-121.876	47.760	5.50	4.1
41	19960714.1530001	-131.262	63.325	4.00	0.0
42	19960721.2038006	-137.577	64.371	5.00	0.0
43	19960816.0341004	-130.738	51.074	4.50	10.0
44	19960823.0533004	-132.330	70.347	4.70	35.0
45	19960825.0049002	-144.753	67.115	4.30	0.0
46	19961006.2043010	-128.250	48.792	4.50	10.0
47	19961006.2310003	-128.114	48.809	4.00	10.0
48	19961007.0204008	-128.157	48.815	4.20	10.0
49	19961007.0620004	-128.200	48.854	4.00	10.0
50	19961007.1018009	-128.259	48.944	4.30	10.0
51	19961007.1836009	-128.113	48.919	4.60	10.0
52	19961008.0503004	-128.361	48.779	4.30	10.0
53	19961009.0712006	-129.962	49.492	5.70	10.0
54	19961013.1133007	-128.163	48.899	4.20	10.0
55	19961014.2303007	-128.203	48.841	4.60	10.0
56	19961014.2342007	-128.228	48.835	4.30	10.0
57	19961016.0433008	-137.053	64.129	4.90	0.0
58	19961026.2005005	-130.011	63.946	4.70	0.0
59	19961121.0124002	-128.795	49.586	4.40	10.0
60	19961121.0125002	-128.786	49.579	4.30	10.0
61	19961127.2238002	-133.623	64.927	4.00	0.0

Note: Depths of 0 and 10 km are generally fixed, when the focal depth cannot be determined by data.

3.3.2 DATA COLLECTION

The data were obtained from GSC, with the help of Bill Shannon. They are stored at GSC in optical disks in two compressed data formats referred to as SEED and CA formats. Each event was individually extracted from the optical disks and copied in the workstation at GSC. It was later transferred by DAT tapes to the Carleton University Seismology laboratory for further processing.

3.3.3 DATA PROCESSING

The data were processed with the aim of obtaining the Fourier spectra of the S-wave and noise windows. The S-window contains the strongest part of the shaking. The noise window is a pre-event sample. Windowing was done using the SAC2000 software [www-ep.es.llnl.gov/tvp/sac-manual]. Therefore, the first step was to convert the data to SAC format. Data from 1993 till about mid June 1995 were in SEED format. After that till the end of 1996, they were archived in CA format. The scripts to do the format conversions were obtained from GSC. These data conversion procedures are discussed in the following paragraphs:

SEED data were converted to SAC using the RDSEED utility program, which extracts data for the specified start and end times of the event and the Julian day of the event (since SAC only accepts Julian days).

Data after mid June 1995 were archived by the GSC in CA format. Conversion from CA to SAC format was a two-step procedure; data were first converted from CA format to SEED format, then from SEED to SAC.

Most of the steps of data conversion were iterative in nature. Therefore, several macros (command files) were created within SAC to speed up the work. For example, to extract the desired data window, two macros were created with the names of NOISE and SIGNAL. These macros were used to select the noise and signal windows, take their Fourier Transform, write the transformed files in

alphanumeric format and then move them to their proper sub-directories.

Basically, the macro reads the time series files specified by the user. After that, it shows the plots for all three components of the station. From these plots, I would choose the start and end times of the noise window. The ending time of this window should be just before the arrival of the Primary wave. The window length is about 30 – 40 seconds on average. (This length is later normalized to the length of the signal window). The start and end times will be approximately the same for each component. These values are then used in the "cut" command of the macro, to select the portion of the data between the two times. Then the selected time series is Fourier transformed by FFT and written in alphanumeric format. The macro creates a directory called NOISE. It also gives a listing of all the created files and moves selected files to the NOISE directory.

The SIGNAL macro runs exactly the same way to facilitate the creation of the SIGNAL directory. The idea is to create a well-organized directory structure of signal and noise windows for all events.

3.3.4 THE OUTPUT

The alphanumeric Fourier transformed data were used to obtain summary files of the signal and noise values. This was done using a simple FORTRAN program provided by Atkinson (Carleton University), which smoothes the log amplitudes over specified logarithmically-spaced frequency bins. This program summarized the output of each seismogram in the form of records of two lines

each. The first line gives the event and component name, azimuth, distance and start and stop times of the window. The second line gives 24 values of smoothed Fourier velocity spectrum, sampled in 0.1 log frequency units, beginning at $\log f = -1$ (i.e. frequency = 0.1-hz to 20.0 -hz). The spectrum values are given in log units. They were not corrected for instrument response, as it is the ratio of horizontal to vertical components that is of interest. Division of H/V automatically removes instrument response, as it is the same for both horizontal and vertical components.

3.4 PROCESSING FOR EVENTS FROM 1998 - 1999

The data from May 1998 to July 1999 were collected from the GSC using their autodrm facility. This facility provides online access to data for events within the last 15 days. (Note: The autodrm capabilities are rapidly improving and will soon provide data over a much longer period). The processing of these data was done by Eleanor Sonley (Carleton student). These data had fewer constraints regarding distance between the event and the recording stations. (Due to greater ease of the data extraction process, we were less restrictive over selected records.) For each record, the portion of the spectrum for which signal to noise ratio was 2 or more was chosen. Events of $M \geq 2$ were considered. From these data, H/V ratios were calculated using a FORTRAN program. A list of the recent events is shown in Table 3.3.

Table 3.3: List of events from May 1998 to July 1999

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
1	980518.153920	45.18	-74.00	3.0	18.0g
2	980520.043814	62.01	-124.10	3.6	0.0g
3	980521.020529	57.83	-60.94	4.0	18.0g
4	980531.110225	48.71	-128.65	3.7	0.1g
5	980603.095940	82.92	-178.50	4.6	18.0g
6	980609.003413	81.13	-89.63	5.3	5.0g
7	980610.031016	58.31	-133.54	3.0	5.0g
8	980610.171950	58.22	-133.63	3.1	5.0g
9	980611.025556	58.38	-133.49	3.2	5.0g
10	980611.113720	61.16	-60.54	3.5	18.0g
11	980611.160015	58.31	-133.54	3.0	5.0g
12	980611.185426	51.14	-124.89	2.5	5.0g
13	980612.202435	48.89	-129.03	4.2	10.0g
14	980613.195023	53.52	-117.57	2.8	5.0g
15	980614.011240	48.15	-128.90	2.7	1.0g
16	980614.084856	53.09	-79.90	2.6	18.0g
17	980614.180420	53.14	-132.58	2.9	20.0g
18	980615.085102	59.68	-75.94	3.6	0.0g
19	980616.194955	61.47	-78.89	3.1	18.0g
20	980617.200654	45.95	-74.90	2.8	18.0g
21	980625.021551	52.77	-34.67	5.1	18.0g
22	980625.031751	52.73	-35.73	4.4	18.0g
23	980625.225154	49.99	130.24	4.5	10.0g
24	980629.121155	59.42	-73.98	3.1	18.0g
25	980702.003132	48.83	-125.60	2.7	33.4g
26	980702.052436	58.04	-136.79	2.6	0.0g
27	980702.083326	71.69	-135.32	3.0	35.0g
28	980702.132916	67.97	-143.81	3.1	20.0g
29	980707.233019	48.83	-129.56	3.2	10.0g
30	980709.011716	60.67	43.65	4.1	18.0g
31	980709.015213	44.80	-73.74	2.5	18.0g
32	980710.030500	50.55	-130.33	3.7	0.1g
33	980713.000000	49.36	-66.14	3.1	1.8g
34	980714.010535	48.73	-129.14	4.3	10.0g
35	980714.014949	48.77	-129.01	3.7	10.0g
36	980714.044017	50.57	-130.43	2.5	10.0g
37	980714.150501	72.78	-74.04	3.3	18.0g
38	980715.003016	47.52	-129.20	3.5	10.0g
39	980715.070804	47.02	-66.61	4.0	5.0g
40	980716.134653	50.03	-130.23	2.6	10.0g
41	980720.122700	62.26	-58.00	2.8	0.0g
42	980721.004804	54.99	-134.00	2.7	20.0g
43	980721.030612	57.74	-142.73	3.1	10.0g
44	980723.055332	57.73	-142.38	2.9	10.0g
45	980724.075620	72.02	-74.74	2.8	18.0g
46	980726.102030	59.34	-136.42	3.6	10.0g
47	980728.113848	59.22	-137.86	4.7	10.0g
48	980729.033202	48.39	-104.77	3.5	0.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
49	980730.022259	46.35	-76.15	2.7	18.0g
50	980730.085722	46.17	-71.22	4.4	18.0g
51	980730.102931	46.19	-74.69	2.5	18.0g
52	980730.113826	76.03	-118.88	3.4	18.0g
53	980730.165319	62.49	-125.09	3.2	5.0g
54	980731.074028	51.34	-130.78	4.0	10.0g
55	980731.074042	72.32	-74.70	3.8	18.0g
56	980731.081801	51.34	-130.80	3.6	10.0g
57	980803.072520	71.85	-133.30	3.9	35.0g
58	980806.024300	52.13	-131.64	4.4	20.0g
59	980806.180519	49.00	-129.11	3.1	10.0g
60	980806.181118	48.88	-129.22	4.1	10.0g
61	980806.181723	48.88	-129.35	4.5	10.0g
62	980808.082310	49.05	-68.33	2.9	18.0g
63	980811.192824	60.00	-140.00	3.2	1.0g
64	980812.061029	61.80	-65.99	0.3	18.0g
65	980813.113832	51.71	-116.05	3.6	0.0g
66	980813.113833	51.81	-115.75	3.8	18.0g
67	980814.185135	60.08	-73.60	3.2	18.0g
68	980816.131205	50.94	-130.79	3.1	10.0g
69	980816.131942	49.01	-128.14	2.6	10.0g
70	980818.080754	53.93	-131.78	3.4	3.5
71	980819.043905	50.37	-130.35	4.3	0.0g
72	980819.050456	50.36	-130.24	2.5	10.0g
73	980824.192733	43.87	-75.76	3.1	18.0g
74	980827.025435	57.76	-136.61	3.9	5.0g
75	980830.113333	50.91	-130.66	6.0	10.0g
76	980901.091942	49.14	-127.77	4.0	10.0g
77	980901.120203	50.91	-130.65	3.0	10.0g
78	980901.145200	50.69	-130.54	3.1	10.0g
79	980901.161803	50.74	-130.56	3.6	10.0g
80	980901.181249	50.73	-130.58	4.6	10.0g
81	980901.235602	60.84	-140.34	2.9	5.0g
82	980905.051905	44.20	-68.71	2.5	18.0g
83	980906.075002	60.16	-73.38	3.5	18.0g
84	980906.151601	60.18	-73.38	3.1	18.0g
85	980907.144004	59.55	-136.24	3.2	0.0g
86	980908.191305	40.07	-52.53	4.0	18.0g
87	980909.144804	4.16	-133.94	4.6	20.0g
88	980910.232926	50.96	-130.33	2.8	10.0g
89	980911.083206	50.04	-130.64	2.6	10.0g
90	980911.213611	51.04	-130.52	2.6	10.0g
91	980912.081654	56.55	-134.42	2.6	10.0g
92	980913.005513	58.85	-136.78	2.6	5.0g
93	980913.032843	58.29	-136.85	3.2	0.0g
94	980913.062334	46.86	-76.95	2.7	18.0g
95	980913.170412	56.33	-136.11	3.7	10.0g
96	980914.022147	59.01	-135.74	3.3	10.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
97	980915.190654	60.95	-138.54	3.0	10.0g
98	980916.074915	45.48	-67.27	2.5	18.0g
99	980917.203200	59.12	-135.19	2.8	10.0g
100	980918.213005	49.06	-67.59	3.6	18.0g
101	980919.142528	49.96	-130.25	4.7	10.0g
102	980920.084924	49.95	-130.25	2.8	10.0g
103	980920.122400	49.90	-130.28	2.9	10.0g
104	980921.132100	62.45	-125.05	3.0	0.0g
105	980921.213122	50.93	-130.60	2.8	10.0g
106	980924.000053	49.89	-130.26	3.0	10.0g
107	980924.120642	48.90	-128.14	2.8	10.0g
108	980924.181559	46.50	-76.31	2.8	18.0g
109	980925.195255	41.57	-80.35	5.4	5.0g
110	980927.081802	46.47	-76.21	2.7	18.0g
111	980929.010341	45.88	-75.35	2.8	18.0g
112	980929.074252	50.02	-130.09	3.1	10.0g
113	980930.111522	48.90	-129.13	3.7	10.0g
114	980930.133446	51.10	-130.75	2.7	10.0g
115	980930.162627	66.82	-93.22	4.4	18.0g
116	981002.023243	48.81	-129.37	2.9	10.0g
117	981003.205636	62.17	-124.43	3.2	0.0g
118	981004.113138	59.05	-136.46	4.2	10.0g
119	981005.092250	45.14	-75.52	2.5	18.0g
120	981005.095947	58.13	-127.07	3.0	10.0g
121	981005.100408	58.18	-127.09	3.1	10.0g
122	981005.113049	52.62	-131.94	2.6	20.0g
123	981005.124511	61.97	-124.18	2.9	0.0g
124	981006.132054	60.22	-140.75	2.5	10.0g
125	981006.070453	65.39	-135.94	2.6	0.0g
126	981006.064238	65.40	-135.93	2.8	0.0g
127	981008.181340	46.39	-74.01	2.5	18.0g
128	981009.160051	59.43	-144.01	3.2	20.0g
129	981010.081090	59.58	-135.67	2.5	0.0g
130	981010.213538	59.17	-137.22	3.2	0.0g
131	981010.204513	60.59	-141.22	2.9	10.0g
132	981010.000656	60.09	-140.66	2.8	5.0g
133	981013.072833	39.47	-52.84	4.1	18.0g
134	981014.013622	60.70	-43.94	5.3	18.0g
135	981014.084619	61.57	-73.50	2.5	18.0g
136	981015.112930	50.62	-130.52	3.3	10.0g
137	981016.161255	48.89	-128.73	3.1	10.0g
138	981016.212033	58.39	-136.87	2.8	0.0g
139	981018.150817	50.49	-130.26	2.9	10.0g
140	981019.211650	59.97	-140.71	2.7	0.0g
141	981019.020416	60.06	-140.73	2.8	10.0g
142	981019.050332	59.83	-139.63	3.6	10.0g
143	981020.010612	59.96	-140.61	3.7	0.0g
144	981020.110424	59.38	-135.28	2.8	10.0g

Table 3.3 continued

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
145	981021.074451	47.56	-70.28	2.6	9.8
146	981022.205422	58.29	-133.56	2.9	5.0g
147	981022.094335	49.34	-66.88	4.1	18.0g
148	981022.175218	58.19	-133.59	3.3	5.0g
149	981023.153350	56.34	-117.02	2.6	0.0g
150	981023.220113	58.24	-133.56	3.3	5.0g
151	981023.070223	45.71	-73.82	2.5	18.0g
152	981024.171010	48.64	-129.22	2.5	10.0g
153	981027.235653	58.58	-137.64	2.6	5.0g
154	981027.182335	58.26	-133.61	3.2	5.0g
155	981027.194300	58.22	-133.56	3.4	5.0g
156	981029.121853	60.13	-141.14	3.1	0.0g
157	981031.183044	60.21	-140.96	4.4	5.0g
158	981031.192444	60.12	-141.01	4.0	10.0g
159	981031.182521	60.15	-141.01	4.3	5.0g
160	981102.043905	65.81	-90.53	3.2	18.0g
161	981105.013317	49.06	-67.89	2.5	18.0g
162	981106.150123	62.25	-142.92	2.8	0.0g
163	981107.205124	50.52	-130.40	3.0	10.0g
164	981107.205340	50.57	-130.33	2.5	10.0g
165	981108.212208	60.81	-43.93	4.5	18.0g
166	981108.041540	48.13	-119.30	2.6	10.0g
167	981109.203452	59.52	-136.58	3.2	0.0g
168	981109.193217	59.40	-139.11	4.0	5.0g
169	981110.013246	59.42	-139.15	4.3	5.0g
170	981111.214541	57.29	-136.74	2.5	10.0g
171	981111.115942	48.49	-103.99	3.5	10.0g
172	981112.034130	61.36	-129.65	2.6	5.0g
173	981112.063823	48.15	-119.29	2.8	10.0g
174	981117.152643	50.43	-130.18	2.8	10.0g
175	981117.174606	51.21	-131.28	2.5	10.0g
176	981119.084315	62.62	-125.38	3.1	0.0g
177	981120.031525	70.60	-137.50	3.9	35.0g
178	981121.032833	74.44	-70.39	3.1	18.0g
179	981123.070916	79.94	-90.84	3.6	18.0g
180	981123.082549	79.97	-91.95	3.1	18.0g
181	981123.123620	79.83	-90.22	3.2	18.0g
182	981124.184207	51.01	-130.29	2.5	10.0g
183	981124.215527	64.18	-140.57	2.8	5.0g
184	981124.135047	50.47	-130.34	3.1	10.0g
185	981125.025507	41.10	-82.63	3.2	5.0g
186	981126.142231	60.85	-138.01	2.7	10.0g
187	981128.163851	45.78	-77.00	2.5	18.0g
188	981128.221125	61.04	-59.04	4.1	18.0g
189	981201.050220	46.59	-74.29	2.6	18.0g
190	981203.041248	58.69	-136.71	3.1	5.0g
191	981205.015450	53.94	-131.79	2.6	10.0
192	981206.021255	60.41	-59.42	3.1	18.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
193	981207.133708	52.68	-79.83	3.3	18.0g
194	981209.024018	63.94	-138.22	2.5	0.0g
195	981210.132632	61.68	-127.18	2.9	10.0g
196	981210.071512	59.22	-136.45	4.0	10.0g
197	981211.203307	51.83	-131.40	2.5	10.0g
198	981211.211131	73.04	-89.78	3.5	18.0g
199	981212.234601	60.90	-138.06	2.6	0.0g
200	981213.140808	58.52	-142.25	3.6	10.0g
201	981214.133845	48.84	-127.95	2.6	10.0g
202	981215.041708	63.40	-131.56	3.1	5.0g
203	981216.055403	55.28	135.04	4.5	10.0g
204	981217.130337	60.20	-137.67	2.5	0.0g
205	981218.174141	62.07	-124.09	3.1	5.0g
206	981218.002257	62.40	-141.86	2.7	10.0g
207	981218.093323	55.28	-134.66	2.7	0.0g
208	981222.170435	79.93	-91.04	4.4	18.0g
209	981222.011747	48.00	-115.24	4.6	10.0g
210	981225.133026	43.83	-77.91	3.6	18.0g
211	981227.215159	74.30	-70.29	4.2	18.0g
212	981229.231504	47.03	-66.55	3.0	5.0g
213	990101.092810	79.86	-110.24	5.3	18.0g
214	990101.110103	48.48	-128.75	3.4	10.0g
215	990104.224117	59.09	-136.50	4.2	10.0g
216	990106.220313	77.43	-104.86	3.1	18.0g
217	990110.105216	42.87	-71.00	3.1	2.0g
218	990110.152044	42.86	-70.96	3.0	2.0g
219	990114.104736	72.96	-113.62	3.2	18.0g
220	990116.203059	64.65	-134.73	3.5	0.0g
221	990116.161234	61.98	-133.57	3.6	0.0g
222	990117.044904	59.94	-137.41	3.2	0.0g
223	990118.073529	77.47	-105.04	2.6	18.0g
224	990119.150917	66.25	-135.22	2.6	10.0g
225	990119.062320	45.44	-74.53	3.0	18.0g
226	990121.235055	49.24	-123.63	3.0	3.9
227	990121.053824	59.47	-138.93	2.8	10.0g
228	990122.042725	49.13	-67.09	3.5	18.0g
229	990123.202500	60.49	-139.51	2.5	5.0g
230	990124.122007	49.89	-130.21	3.4	10.0g
231	990124.121541	49.81	-130.20	2.6	10.0g
232	990125.092757	48.85	-123.43	2.6	3.0
233	990125.201228	42.79	-77.82	2.7	5.0g
234	990125.060855	59.98	-137.43	3.3	0.0g
235	990126.081428	45.92	-74.85	2.9	18.0g
236	990127.015719	42.31	-82.31	2.5	5.0g
237	990127.013807	42.33	-82.30	2.6	5.0g
238	990129.061033	60.12	-141.11	2.7	10.0g
239	990131.110557	48.26	-118.68	2.5	15.0g
240	990201.222205	49.26	-80.94	3.4	18.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
241	990203.231659	60.11	-140.23	2.5	0.0g
242	990203.224832	49.74	-66.98	2.5	18.0g
243	990204.213620	49.81	-130.21	2.7	10.0g
244	990206.221127	50.56	-130.35	2.7	10.0g
245	990207.130754	59.22	-138.49	2.5	10.0g
246	990207.095658	48.97	-129.87	2.5	10.0g
247	990207.004009	50.17	-129.62	3.1	10.0g
248	990211.144912	51.15	-125.83	2.7	5.0g
249	990214.133414	65.29	-88.18	3.0	18.0g
250	990215.160428	44.46	-56.22	3.6	18.0g
251	990216.210223	58.45	-142.78	4.2	10.0g
252	990217.075826	65.40	-144.26	3.2	10.0g
253	990219.170220	50.56	-130.38	2.9	10.0g
254	990220.201638	57.19	-136.31	3.8	0.0g
255	990220.075942	48.26	-113.32	2.5	10.0g
256	990221.033323	60.26	-140.99	3.2	10.0g
257	990221.173411	70.92	-64.44	4.1	18.0g
258	990221.211718	76.70	-106.60	3.7	18.0g
259	990223.111233	47.61	-65.99	2.7	5.0g
260	990223.151239	65.00	-138.81	2.6	0.0g
261	990223.180409	77.87	-19.54	3.8	18.0g
262	990223.011036	48.02	-70.67	2.7	18.0g
263	990225.204209	50.23	-130.26	3.0	10.0g
264	990226.033844	44.62	-69.67	3.8	18.0g
265	990228.141026	47.92	-124.38	2.5	0.0g
266	990301.211925	64.82	-139.49	2.5	5.0g
267	990302.050609	50.55	-130.20	2.6	10.0g
268	990302.071110	76.54	-91.62	4.0	18.0g
269	990303.152631	67.69	-93.52	3.2	18.0g
270	990306.014541	64.86	-134.09	2.8	0.0g
271	990306.103340	49.03	-128.73	3.2	10.0g
272	990307.034215	53.39	-131.47	3.8	9.6
273	990308.113804	46.04	-74.99	2.8	18.0g
274	990309.120704	44.77	-73.83	3.0	10.0g
275	990315.143235	45.89	-74.38	2.8	18.0g
276	990316.173311	49.61	-66.31	2.6	18.0g
277	990316.150415	49.62	-66.34	2.6	18.0g
278	990316.125048	49.61	-66.32	5.1	18.0g
279	990317.175059	65.42	-134.24	3.4	0.0g
280	990317.052700	62.34	-124.16	3.5	0.0g
281	990317.085537	49.62	-66.32	2.5	18.0g
282	990317.142655	49.61	-66.29	2.5	18.0g
283	990318.060003	50.57	-130.31	2.9	10.0g
284	990319.130127	47.40	-129.20	2.6	10.0g
285	990321.223054	61.60	-140.88	3.4	0.0g
286	990322.060311	49.62	-66.38	2.5	18.0g
287	990323.015334	66.72	-135.51	3.7	20.0g
288	990325.140608	45.96	-74.86	3.0	18.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
289	990330.155136	49.63	-66.39	2.7	18.0g
290	990330.133014	59.81	-72.94	3.3	18.0g
291	990401.051139	59.69	-137.45	3.0	10.0g
292	990401.013523	57.97	-138.87	2.7	0.0g
293	990402.063959	59.17	-137.33	4.0	0.0g
294	990402.005705	50.87	-129.82	2.5	10.0g
295	990402.134051	59.63	-138.67	2.8	10.0g
296	990402.072549	59.19	-137.27	2.7	0.0g
297	990403.172922	48.36	-123.26	3.3	45.0
298	990403.094458	58.76	-137.42	2.8	0.0g
299	990403.215007	72.88	-90.95	3.1	18.0g
300	990406.180632	62.32	-71.16	3.6	18.0g
301	990410.095713	56.82	-51.55	3.5	18.0g
302	990411.000537	48.21	-122.86	2.7	30.2g
303	990414.002833	67.49	-64.26	3.1	18.0g
304	990414.164635	68.18	-66.82	3.2	18.0g
305	990418.202100	47.44	-70.47	2.5	9.2
306	990422.235641	72.39	-92.72	2.5	18.0g
307	990422.005641	48.70	-128.98	3.4	10.0g
308	990422.055538	50.52	-130.38	2.8	10.0g
309	990422.095324	52.32	-119.32	2.8	10.0g
310	990422.073016	50.53	-130.30	2.5	10.0g
311	990424.070907	60.17	-137.54	3.3	0.0g
312	990425.092133	60.12	-141.04	2.7	5.0g
313	990428.005347	62.58	-65.99	3.3	18.0g
314	990429.210945	48.19	-121.33	2.5	1.0
315	990429.044107	60.26	-141.57	2.9	5.0g
316	990429.190430	58.10	-143.20	3.3	10.0g
317	990430.080256	62.02	-124.07	3.5	0.0g
318	990501.012131	61.59	-140.94	3.8	0.0g
319	990503.180848	58.03	-139.00	2.9	0.0g
320	990504.050304	60.24	-140.92	2.7	10.0g
321	990504.174058	61.94	-135.72	2.8	10.0g
322	990505.174714	64.95	-125.17	3.0	0.0g
323	990506.181814	49.51	-129.42	2.9	10.0g
324	990512.082739	63.33	-64.47	2.7	18.0g
325	990512.050715	76.69	-107.04	3.3	18.0g
326	990512.160329	76.60	-106.99	3.0	18.0g
327	990515.032134	46.98	-79.07	3.0	18.0g
328	990516.050427	62.14	-71.98	3.1	18.0g
329	990518.204629	59.95	-140.63	3.2	5.0g
330	990518.063612	63.87	-128.65	3.2	0.0g
331	990518.174009	69.74	-129.99	3.1	0.0g
332	990521.110051	47.94	-124.37	2.5	27.6g
333	990524.052235	60.04	-139.33	4.4	0.0g
334	990525.162808	47.00	-66.60	2.7	5.0g
335	990526.115130	60.90	-66.08	2.5	18.0g
336	990530.093042	47.11	-76.37	2.9	18.0g

Table 3.3 continued....

No.	DATE	LATITUDE	LONGITUDE	MAGNITUDE	DEPTH (KM)
337	990530.143359	46.55	-78.39	2.6	18.0g
338	990601.175910	59.43	-138.76	2.6	0.0g
339	990601.152237	58.18	-138.38	3.4	0.0g
340	990603.032139	64.59	-131.08	3.1	0.0g
341	990607.065218	63.81	-131.37	2.9	15.0g
342	990609.013501	47.70	-69.89	2.8	11.2g
343	990612.071303	69.94	-85.34	3.4	18.0g
344	990618.231908	46.47	-75.11	3.5	18.0g
345	990619.092943	47.72	-128.95	3.7	10.0g
346	990620.195503	52.60	-132.14	3.2	0.0g
347	990620.215944	73.91	-72.92	3.4	18.0g
348	990621.072607	47.42	-128.94	3.1	10.0g
349	990621.081348	72.91	-74.54	3.2	18.0g
350	990623.200646	50.12	-71.22	2.5	18.0g
351	990624.113621	62.13	-140.45	2.5	5.0g
352	990628.102118	48.83	-129.29	4.6	10.0g
353	990701.112909	73.86	-94.79	3.2	18.0g
354	990702.114529	49.23	-129.43	5.7	10.0g
355	990703.014354	47.10	-123.50	5.5	0.0m
356	990705.033458	49.43	-129.41	3.5	10.0g
357	990707.063728	49.63	-66.41	2.7	18.0g
358	990708.202353	58.56	-137.31	2.6	0.0g
359	990709.063329	49.20	-129.38	2.7	10.0g
360	990710.075149	64.22	-140.66	3.5	0.0g
361	990710.154025	67.00	-136.19	3.1	0.0g
362	990710.230523	49.41	-129.30	2.8	10.0g
363	990714.111147	46.59	-75.39	2.9	18.0g

Note: A 'g' beside the depth indicates it was fixed by the analyst.

CHAPTER 4

H/V RATIO RESULTS

4.1 INTRODUCTION

The results obtained from the processed data are presented in this chapter. In the first few sections of the chapter, the procedure for calculating the H/V ratios is discussed. Data from 1993 – 1996 were mainly manipulated in spreadsheet software. Data from 1998 – 1999 were processed using FORTRAN programs written for this purpose. Once these H/V ratio values were obtained, some basic statistics were calculated. These included average H/V, standard deviation, and the 90% confidence interval on the mean. These are shown graphically for each station in the last section of the chapter.

4.2 H/V RATIO CALCULATION

For the 1993 - 1996 data, there were two files for each event; one giving the signal spectrum and one giving the noise spectrum. These were used to calculate signal to noise ratio. Signal spectra for which the S/N ratio was greater than 2 over the frequency band of interest were used in the results. For 1998 - 1999 data, the events were also processed to obtain the values of signal spectra at frequencies for which signal/noise ratio was greater than 2. Then from these data, the H/V ratios were calculated. A detailed description of how the ratios were calculated for the 1993 - 1996 data and for the 1998 - 1999 data follows:

4.2.1 RATIO CALCULATION FOR 1993 - 1996 DATA

For the 1993 - 1996 data, the output of the data processing was two files providing the noise and signal spectra for each station for each event. The H/V ratios are calculated for the frequencies with signal/noise ratio greater than 2. To find the signal/noise ratio, the noise spectrum was normalized to the same window length as the signal window. This was done by squaring the noise spectral amplitudes (to ensure energy conservation at each frequency), and then multiplying by the ratio of length of the signal window to the length of the noise window. The final normalized noise spectrum was obtained by taking the square root. This procedure was performed in a spreadsheet program. (Due to the bulk of the data, several template files were created with embedded links. The files for each station of each event were created by changing the source of the links in the template file and re-saving the file with the associated naming convention). The second set of template files was used to calculate the H/V ratios using the output of the above step. These too were modified in the same way and the H/V ratio files were saved according to the chosen naming convention. At this point of processing, the minimum S/N ratio criterion was not applied. Rather, the values of this ratio were also incorporated in the H/V ratio files, and this information was later checked in a FORTRAN program.

The noise and signal files were used in the spreadsheet program EXCEL to calculate the normalized noise spectrum. These files were used jointly to

calculate the normalized noise spectrum and the signal to noise ratio. The H/V ratio was then calculated in EXCEL (by creating template files; the links in these files were connected to the output files created in the previous step). Since the values of the signal were in log units, we took the difference between the horizontal and the vertical components to obtain the log of the H/V ratio. We used the resulting value only if the S/N ratio was greater than 2. An example template is provided in table 4.1.

Table 4.1 Calculation of H/V Ratio.

Freq.	H/V Ratio (log)		Signal starts here (log units)			S/N RATIO (anti-log values)		
	H1/V	H2/V	H1	H2	V	H1	H2	V
					9302swala .bhz			
-1.00	-0.26	0.10	5.45	5.81	5.71	2.57	2.40	3.09
-0.90	-0.33	-0.11	5.74	5.96	6.07	2.00	1.86	2.09
-0.80	-0.23	-0.10	5.93	6.06	6.16	1.38	1.17	0.81
-0.70	-0.40	-0.13	5.84	6.11	6.24	0.95	0.87	1.00
-0.60	-0.23	-0.12	5.65	5.76	5.88	1.00	0.87	0.71
-0.50	-0.17	-0.14	5.40	5.43	5.57	1.12	0.89	1.05
-0.40	-0.14	-0.01	5.10	5.23	5.24	1.15	0.95	1.07
-0.30	-0.09	0.20	4.96	5.25	5.05	2.04	2.09	2.04
-0.20	-0.18	0.05	4.70	4.93	4.88	2.82	1.41	2.04
-0.10	-0.15	0.10	4.49	4.74	4.64	3.24	1.20	1.86
-0.00	-0.10	0.09	4.36	4.55	4.46	3.63	1.00	1.74
0.10	0.01	0.16	4.24	4.39	4.23	3.72	0.87	1.38
0.20	-0.09	0.22	3.97	4.28	4.06	2.45	0.85	1.20
0.30	-0.06	0.31	3.80	4.17	3.86	2.24	0.83	0.98
0.40	-0.02	0.35	3.68	4.05	3.70	2.00	0.81	0.83
0.50	-0.04	0.36	3.54	3.94	3.58	1.66	0.78	0.78
0.60	-0.11	0.41	3.30	3.82	3.41	1.26	0.74	0.68
0.70	-0.11	0.38	3.24	3.73	3.35	1.15	0.74	0.69
0.80	-0.12	0.32	3.22	3.66	3.34	1.17	0.78	0.81
0.90	-0.09	0.39	3.08	3.56	3.17	1.20	0.78	0.71
1.00	-0.10	0.34	3.05	3.49	3.15	1.15	0.78	0.78
1.10	-0.06	0.29	3.13	3.48	3.19	1.29	0.85	0.93
1.20	0.03	0.28	3.18	3.43	3.15	1.66	0.87	1.00
1.30	-0.11	0.40	2.83	3.34	2.94	1.23	0.76	0.72

Using the template of table 4.1, H/V ratios were calculated for all of the data and stored in different files.

4.2.2 RATIO CALCULATION FOR 1998-1999 DATA

The data from 1998-1999 were manipulated through several FORTRAN programs. The Fourier spectra were summarized using the program "stonbat.for" by Atkinson, Carleton University. This produced the output spectral values in log units, with signal/noise ratio > 2, for 24 frequency bins ($\log f = -1, -0.9, -0.8, \dots, 1.3$). Once these were obtained for all the data, the values were input to a second program to calculate the H/V ratios. The data were saved in different files for different months. These files were later combined to one file for further calculations of mean, standard deviation and 90% confidence interval of the data for different stations.

4.3 CALCULATION OF MEAN H/V

The final output to be obtained from the data is the mean, standard deviation, and 90% confidence interval of the mean for all of the stations. Since the data were in two blocks, one from 1993-1996 and the other from 1998 – 1999, they had to be combined so that the results could be obtained for the whole data set. Four FORTRAN programs accomplished these tasks. In the first program, the data from 1993 – 1996 relating to a particular station (e.g WALA) were selected. In the second step, data from 1998 – 1999 for that station (WALA) were read and merged with the 1993 – 1996 data to form a combined data set. In the third

step, the means for the combined data sets were calculated. In the fourth step, the final statistics, like mean H/V, including its standard deviation, and the 90% confidence interval about the mean were calculated.

4.4 H/V RESULTS

Mean H/V ratios are plotted for each station in figures 4.1 – 4.3. On the same graph, the standard deviation of observations, and the 90% confidence limits about the mean are also shown. These values are tabulated in the appendix.

Figure 4.1: Mean H/V ratios, Standard Deviation, 90% confidence Interval for Eastern Stations

Figure 4.2: Mean H/V Ratios, Standard Deviation, 90% Confidence interval for Mid-Canada

Figure 4.3: Mean H/V Ratios, Standard Deviation, 90% Confidence Interval for SW-Canada

Figure 4.4: Mean H/V Ratios, Standard Deviation, 90% Confidence Interval for NW-Canada

Chapter 5

CORRELATION OF H/V RATIOS WITH GEOLOGY

5.1 INTRODUCTION

This chapter discusses possible correlation of the H/V results obtained in this study with general geological conditions. The geology is discussed on two scales: (i) regional scale geological units, and (ii) local surficial materials. These sections are presented in the form of tables and maps. The maps for surficial materials were produced by modifying the digital release of 'Surficial Materials of Canada: Map 1880 A' (Dr. R.J. Fulton, 1995) in a GIS software package (Arcview 3.0). The H/V results of this study are then compared with reference to the general geology and are presented in tables 5.3 – 5.8.

5.2 GENERAL GEOLOGY

5.2.1 MAIN GEOLOGICAL REGIONS

Canada is comprised of several major geological units: a shield region, four platform regions, three orogens, and three continental shelves. (Geology and Canada, GSC, 1990). These regions are shown in Fig. 5.1 and narrated in table 5.1:

Fig 5.1: Main Geological regions of Canada.
Scanned from: Geology and Canada, GSC, 1990.

Table-5.1 The Four Main Geological Units of Canada

GEOLOGICAL UNIT	LOCATION	ROCKS AND STRUCTURE
1. CANADIAN SHIELD	Underlies about half the total area of the country.	<ul style="list-style-type: none"> • Rocks of Precambrian ages exposed or covered only by overburden. • Shield fairly stable since the end of Precambrian time, except for: • Uplifting in late Tertiary time, changes in elevation after the glaciation of the Pleistocene period, faulting along the southern border and near Boothia Peninsula at different times after the end of the Precambrian.
2. PLATFORMS		
• Interior Platform	Mainland of Canada between Canadian Shield and Cordillera.	<ul style="list-style-type: none"> • Undisturbed or gently flexed sedimentary strata overlie a basement of Precambrian rocks.
• Arctic Platform	Arctic platform underlies most of the Arctic Islands.	<ul style="list-style-type: none"> • Contains flat strata, mainly Ordovician and Silurian limestone, dolomite, and shaly dolomite. • Strata of Cambrian, Devonian, and Tertiary ages are also present locally.
• St. Lawrence Platform	The St. Lawrence Platform is the southern part of the Shield from Lake Huron to Quebec City, except for a small area of the Shield called the Frontenac Axis.	<ul style="list-style-type: none"> • Areas towards southwest and northeast of the Axis are underlain by gently dipping beds of limestone, dolomite, sandstone, and shale of Cambrian, Ordovician, Silurian, Devonian, and Mississippian ages.
• Hudson Platform	Hudson platform underlies most of Hudson Bay and Hudson Bay Lowland between Churchill and Moosonee.	<ul style="list-style-type: none"> • The platform is underlain by Ordovician, Silurian, and Devonian strata of limestone and dolomite. • Large deposits of gypsum in the Devonian succession and lignite deposits occur in Mesozoic beds.

Table 5.1 Continued.....

GEOLOGICAL UNIT	LOCATION	ROCKS AND STRUCTURE
3. OROGENS		
<ul style="list-style-type: none"> Appalachian Orogen 	<p>The Appalachian Orogen includes the part of Quebec lying south of the St. Lawrence River and east of a line between Lake Champlain and Quebec City, and all of New Brunswick, Nova Scotia, Prince Edward Island, and the Island of Newfoundland.</p>	<ul style="list-style-type: none"> A great fault separates Appalachian Orogen and St. Lawrence Platform. The fault forms a sweeping curve to the south shore of the lower St. Lawrence as a result of thrusts that occurred during the Ordovician and Devonian periods.
<ul style="list-style-type: none"> Cordilleran Orogen Western Cordillera Eastern Cordillera 	<p>The Canadian Cordillera is part of a wide belt of high mountains and plateau extending along the western sides of South and North America. The most northerly segment of North American Cordillera includes all of Canada and Alaska.</p>	<ul style="list-style-type: none"> The segment that lies in B.C and Alberta is divided in two main geological and structural provinces by a long straight valley called the Rocky Mountain Trench. This trench dies out at about 60° latitude. The western part of trench is underlain mainly by plutonic, volcanic, and metamorphic rocks. The eastern part of trench has Rocky mountains and the Foothill belts formed of sedimentary strata cast into great folds and fault blocks. From 60° latitude to the south of Arctic coast, there is a boundary between eastern and western Cordillera. The western part of the Cordilleran Orogen is the site of a series of geosynclines of a kind in which volcanic and plutonic rocks as well as sediments are formed. The mountains and foothills of the Eastern Cordillera were carved by the erosion of great thickness of sediments that were deposited in geosynclines.
<ul style="list-style-type: none"> Innuitian Orogen 	<p>The Innuitian Orogen extends across much of the Queen Elizabeth Islands and northernmost Greenland. In the northeast direction, the region extends from Prince Patrick Island and includes all of Axel Heiberg Island and much of Ellesmere Island.</p>	<ul style="list-style-type: none"> It is underlain by moderately to intensely folded rocks ranging in age from probable Proterozoic to Cretaceous and Tertiary. The strata are mainly sedimentary but include some metamorphic and volcanic rocks.

Table 5.1 Continued.....

GEOLOGICAL UNIT	LOCATION	ROCKS AND STRUCTURE
4. CONTINENTAL SHELVES	Extending off Pacific and Atlantic coasts.	<ul style="list-style-type: none"> • Rock conditions more or less similar to those on nearby mainlands are present in several places beneath the shelves and, locally, extensions of faults and other structures have been traced.

Source: Geology and Canada, Natural Resources Canada, GSC.

5.2.2 SURFACE MATERIALS

The surface materials of Canada, overlying the broad geological units summarized in 5.2.1, are displayed in Figures 5.2 – 5.7. These maps were produced by modifying the digital release of the map titled "Surficial Materials of Canada, digital release, Map 1880 A", compiled by Dr. R.J. Fulton, Geological Survey of Canada. This map shows the surficial materials at 1:5 000 000 scale. The broad genetic categories are: alluvial, lacustrine, marine, glacial and bedrock, each of which are further subdivided according to texture, thickness, and landform. On this basis, the map shows 24 classes of surface material. In this study, the original classes were simplified to 13 classes of surface materials. The modifications were done in a GIS software package (Arcview, v 3.0) under the supervision of Dan Patterson, Carleton University. After reclassifying the surficial geology, the total map area was subdivided into four regions: Eastern Canada, Mid Canada, South-western Canada and North-western Canada; to enhance the detail of the presentation. Reclassifying the 13 classes in just 4 classes made an overview map. The four classes are: Glaciers, rock, soil, water. The purpose for the overview reclassification was to show not only the very broad surface geology of the study area, but also to show the location of the earthquake recording stations and the earthquake events studied in this project. The classification schemes are shown in Table 5.2. Figure 5.1 shows the overview classifications and the locations of study earthquakes and recording stations. Figures 5.2 – 5.7 show the classifications in more detail by region, and include the H/V results at frequencies of 1-hz and 5-hz (as multiplicative factors).

Table 5.2: Reclassification Scheme For The Surficial Materials Of Canada

MAP 1880A SURFACE CLASSES			RECLASSIFICATION	
NAME	SYM-BOL	COMPOSITION	DEFINED CLASSES (13 CLASSES)	OVERVIEW CLASSES (4 CLASSES)
Glaciers	I	Ice & minor morainal debris	Glaciers	Glaciers
Alluvial Deposits	A	Stratified silt, sand, clay & gravel; floodplain, delta, & fan deposits; in places overlies & includes glaciofluvial deposits.	Alluvial	Soil
Marine Mud	mM	Fluid silty clay and clayey silt; deposited as quiet water sediments.	Marine	Soil
Marine Sand	sM	Sand & locally gravel; deposited as sheet sands, lags, and beaches.	Marine	Soil
Lacustrine Mud	mL	Fluid silty clay and clayey silt; deposited as quiet water sediments.	Lacustrine	Soil
Lacustrine Sand	sL	Sand and locally gravel; deposited as sheet sands, lags, & beaches.	Lacustrine	Soil
Eolian Deposits	E	Sand & minor silt; dunes, blowouts, & undulating plains; in most places overlies deltaic sediments, coarse lacustrine sediments, or glaciofluvial deposits.	Eolian	Soil
Organic Deposits	O	Peat, muck and minor inorganic sediments; large bog, fen, & swamp areas where organic fill masks underlying surficial material; generally > 2m thick.	Organic	Soil
Colluvial Blocks	bC	Block, & rubble with sand and silt derived from crystalline bedrock, medium grade metamorphic substrate & cemented sandstone.	Colluvial	Soil
Colluvial Rubble	rC	Rubble & silt; derived from carbonate & consolidated fine clastic sedimentary rock substrate.	Colluvial	Soil
Colluvial Fines	fC	Silt, clay & fine sand; derived from substrate weakly consolidated shale & siltstone substrate.	Colluvial	Soil
Colluvial Sand	sC	Sand & gravel; derived from poorly lithified sandstone & conglomerate substrate.	Colluvial	Soil
Fine grained (Glacio) Lacustrine	fL	Silt & clay, locally containing stones; deposited as quiet water sediments	Lacustrine	Soil
Coarse grained (Glacio) Lacustrine	cL	Sand, silt, & gravel; deposited as deltas, sheet sands, & lag deposits.	Lacustrine	Soil

Table 5.2 continued.....

MAP 1880A SURFACE CLASSES			RECLASSIFICATION	
NAME	SYM-BOL	COMPOSITION	DEFINED CLASSES (13 CLASS-ES)	OVERVIEW CLASSES (4 CLASS-ES)
Fine grained (Glacio) Marine	fM	Dominantly silt & clay, locally containing stones; deposited as quiet water sediments.	Marine	Soil
Coarse grained (Glacio) Marine	cM	Sand & gravel; deposited as sheet sands, deltas, & extensive flights of beaches.	Marine	Soil
Lag (Glacio) Marine	Mv	Sand, gravel, & pockets of finer sediment; thin to discontinuous sediment veneer & residual lag developed during marine submergence; includes areas of washed till & rock.	Marine	Soil
Glaciofluvial Plain	Gp	Sand & gravel; deposited as outwash sheets, valley trains, & terrace deposits	Glaciofluvial	Soil
Glaciofluvial Complex	Gx	Sand & gravel & locally diamicton; undifferentiated ice contact stratified drift & outwash; locally includes till & rock.	Glaciofluvial	Soil
Till Blanket	Tb	Thick & continuous till.	Till Blanket	Soil
Till Veneer	Tv	Thin & discontinuous till; may include extensive areas of rock outcrop.	Till Veneer	Rock
Quaternary Volcanics	V	Consolidated lava, breccia & tephra; dominantly basaltic & andesitic in composition; includes flows, volcanic piles, & cinder cones.	Quaternary Volcanics	Rock
Alpine Complexes	Ra	Rock, colluvium, & till; rock & Quaternary deposits complex in an area, characterized by alpine & glacial landforms.	Rock	Rock
Undivided	R	Rock with minor Quaternary deposits.	Rock	Rock

Source: Digital release, Surficial Materials of Canada, Map 1880 A (1995)

Notes:

1. Soil is referred to on maps as "Surface Materials".
2. Eolian, Lacustrine, and Marine materials can be differentiated based on transportation mechanism and composition of the sediments. These can be defined as:

Eolian materials are derived by wind erosion from other soils or barren lands.

Lacustrine sediments are generally associated with activities of glaciers or glacial melt waters. They vary in texture and mineralogy. Generally they are fine textured and well sorted.

Marine sediments commonly contain glauconite or marine diatoms. (Fanning and Fanning, 1989)

5.3 ANALYSIS OF H/V IN LIGHT OF GEOLOGY OF RECORDING STATION

The recording stations of the Canadian National Seismographic Network (CNSN) are located, to the extent possible, on rock sites or rock outcrops. Figures 5.3 – 5.7 show the class that is most dominant near the recording station, although the station might actually be located on a rock outcrop. The dominant site conditions at the recording sites were compared to the H/V ratios obtained at frequencies of 1-hz and 5-hz. Two types of classifications were adopted for this purpose: (i) Data sorted (in ascending order) at 1-hz were subdivided into three classes with $H/V < 1$, $H/V = 1 - 1.2$, and $H/V > 1.2$, respectively. (ii) Data sorted (in ascending order) at 5-hz were subdivided into three classes with $H/V < 1.2$, $H/V = 1.2 - 1.4$, and $H/V > 1.4$, respectively. Sections 5.3.1 and 5.3.2 show three tables with the results of the analysis. H/V ratios are presented as multiplicative factors (i.e. not in log units).

5.3.1 HV RATIOS AT 1-hz

Table 5.3: HV for 1 Hz; HV < 1 (class A-1a)

Station	1hz	90% C.I at 1 Hz	5 Hz	Geology	Detailed Geology
A54	0.67	0.45 - 1.00	1.21	Till Blanket	Tb Thick & continuous till.
A64	0.69	1.86 - 0.90	1.33	Till Blanket	Tb Thick & continuous till.
INK	0.83	0.78 - 0.90	1.03	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
WALA	0.85	0.97 - 0.74	1.31	Rock	Ra Alpine Complexes
A21	0.91	0.82 - 1.00	1.71	Marine	fM Dominantly silt & clay, locally containing stones.
MBC	0.93	0.66 - 1.32	1.36	Colluvial	sC Sand & gravel derived from poorly lithified sandstone & conglomerate
A16	0.95	0.87 - 1.04	1.22	Marine	fM Dominantly silt & clay, locally containing stones.
YKW4	0.97	N/A	1.00	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop

Table 5.4: HV for 1 Hz; HV = 1 - 1.2 (class A-1b)

Station	1hz	90% C.I at 1 Hz	5 Hz	Geology	Detailed Geology
LMQ	1.02	0.86 - 1.20	1.27	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
PMB	1.02	0.93 - 1.13	0.94	Rock	Ra Alpine Complexes
DRLN	1.02	0.90 - 1.16	1.13	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
BBB	1.04	0.99 - 1.09	1.06	Rock	R Rock with minor Quaternary deposits
MOBC	1.08	1.01 - 1.16	1.88	Colluvial	bC Block & rubble with sand and silt derived from crystalline bedrock.
PGC	1.09	1.04 - 1.13	1.72	Marine	Mv Sand, gravel & pockets of finer sediments; includes washed till & rock.
RES	1.11	1.00 - 1.22	1.07	Colluvial	rC Rubble & silt, derived from carbonate & consolidated fine clastic sed. rock.
GAC	1.11	0.86 - 1.43	1.40	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
ULM	1.14	0.83 - 1.55	undefined	Rock	R Rock with minor Quaternary deposits
PNT	1.14	1.07 - 1.21	1.15	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
YKW3	1.21	1.47 - 1.00	1.18	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
SCH	1.22	1.07 - 1.38	1.40	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
LMN	1.23	1.07 - 1.41	1.48	Rock	R Rock with minor Quaternary deposits
A61	1.23	1.05 - 1.44	3.18	Marine	fM Dominantly silt & clay, locally containing stones.
DAWY	1.23	1.16 - 1.31	2.37	Colluvial	bC Block & rubble with sand and silt derived from crystalline bedrock.
A11	1.24	1.09 - 1.40	1.44	Marine	cM Sand & gravel; deposited as sheet sands, deltas & extensive beaches.
WHY	1.26	1.20 - 1.32	1.33	Till Blanket	Tb Thick & continuous till.

Table 5.5: HVV for 1 hz; HVV > 1.3 (class A-1c)

Station	1hz	90% C.I at 1 hz	5 hz	Geology	Detailed Geology	
DLBC	1.30	1.23 - 1.38	1.71	Till Blanket	Tb	Thick & continuous till.
YKW2	1.31	1.07 - 1.61	1.29	Till Veneer	Tv	Thin & discontinuous till. May contain extensive areas of rock outcrop
YKW1	1.37	1.11 - 1.67	1.24	Till Veneer	Tv	Thin & discontinuous till. May contain extensive areas of rock outcrop
FCC	1.41	1.15 - 1.74	0.94	Marine	cM	Sand & gravel; deposited as sheet sands, deltas & extensive beaches.
FRB	1.42	1.16 - 1.74	1.25	Till Blanket	Tb	Thick & continuous till.
SADO	1.49	1.20 - 1.86	1.26	Rock	R	Rock with minor Quaternary deposits
EDM	3.84	2.90 - 5.08	1.89	Till Blanket	Tb	Thick & continuous till.

From the above tables, it is observed that at 1-hz, the H/V ratios are generally near unity. However, for station EDM the 1-hz H/V ratio attains a value of nearly a factor of 4, suggesting significant site response. The H/V ratio at EDM drops down to about a factor of 2 at 5-hz. One possible reason for this type of response could be a topographic amplification effect. The elevation of the station recorded by GSC is 730m. From the topographic map of Bittern Lake (Sheet 83 H/3, Dept. of Energy mines and resources, 1974), the topography surrounding the station was checked. It was observed that the station is located on the flank of a river valley. This particular area is very steep compared to a gentle relief for the rest of the area. (The elevation changes about 30m over a distance of 1 km in the vicinity of EDM). Hence this information points to a topographic effect. For the rest of the stations, there is not a clear pattern associating the 1-hz H/V ratios to the geological conditions. The mean H/V values at 1-hz for classes A-1a, A-1b, A-1c are 0.85, 1.14 and 1.73 respectively.

5.3.2 HV RATIOS AT 5-hz

Table 5.6: HV for 5 Hz, HV < 1.2 (class A-5a)

Station	1-hz	5-hz	90% C.I at 5 Hz	Geology	Detailed Geology
FCC	1.41	0.94	0.78 - 1.12	Marine	cM Sand & gravel; deposited as sheet sands, deltas & extensive beaches.
PMB	1.02	0.94	0.77 - 1.16	Rock	Ra Alpine Complexes
YKW4	0.97	1.00	1.10 - 0.91	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
INK	0.83	1.03	0.99 - 1.07	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
BBB	1.04	1.06	1.02 - 1.10	Rock	R Rock with minor Quaternary deposits
RES	1.11	1.07	1.02 - 1.13	Colluvial	rC Rubble & silt, derived from carbonate & consolidated fine clastic sed. rock.
DRLN	1.02	1.13	1.03 - 1.24	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
PNT	1.14	1.15	1.06 - 1.25	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
YKW3	1.21	1.18	1.09 - 1.26	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop

Table 5.7: HV for 5 Hz; HV = 1.2 - 1.4 (class A-5b)

Station	1-hz	5-hz	90% C.I at 5 Hz	Geology	Detailed Geology
A54	0.67	1.21	1.15 - 1.28	Till Blanket	Tb Thick & continuous till.
A16	0.95	1.22	1.13 - 1.32	Marine	fM Dominantly silt & clay, locally containing stones.
YKW1	1.37	1.24	1.15 - 1.33	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
FRB	1.42	1.25	1.18 - 1.33	Till Blanket	Tb Thick & continuous till.
SADO	1.49	1.26	1.18 - 1.35	Rock	R Rock with minor Quaternary deposits
LMQ	1.02	1.27	1.21 - 1.33	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
YKW2	1.31	1.29	1.17 - 1.44	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
WALA	0.85	1.31	1.16 - 1.49	Rock	Ra Alpine Complexes
WHY	1.26	1.33	1.29 - 1.37	Till Blanket	Tb Thick & continuous till.
A64	0.69	1.33	1.23 - 1.45	Till Blanket	Tb Thick & continuous till.
MBC	0.93	1.36	0.79 - 2.33	Colluvial	sC Sand & gravel derived from poorly lithified sandstone & conglomerate
GAC	1.11	1.40	1.32 - 1.48	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop
SCH	1.22	1.40	1.32 - 1.49	Till Veneer	Tv Thin & discontinuous till. May contain extensive areas of rock outcrop

Table 5.8: HV for 5 Hz; HV > 1.4 (class A-5c)

Station	1-hz	5-hz	90% C.I at 5 Hz	Geology	Detailed Geology
A11	1.24	1.44	1.39 - 1.50	Marine	Sand & gravel; deposited as sheet sands, deltas & extensive beaches.
LMN	1.23	1.48	1.39 - 1.57	Rock	Rock with minor Quaternary deposits
DLBC	1.30	1.71	1.63 - 1.78	Till Blanket	Thick & continuous till.
A21	0.91	1.71	1.64 - 1.79	Marine	Dominantly silt & clay, locally containing stones.
PGC	1.09	1.72	1.59 - 1.86	Marine	Sand, gravel & pockets of finer sediments; includes washed till & rock.
MOBC	1.08	1.88	1.79 - 1.98	Colluvial	Block & rubble with sand and silt derived from crystalline bedrock.
EDM	3.84	1.89	1.45 - 2.46	Till Blanket	Thick & continuous till.
DAWY	1.23	2.37	2.30 - 2.45	Colluvial	Block & rubble with sand and silt derived from crystalline bedrock.
A61	1.23	3.18	3.10 - 3.27	Marine	Dominantly silt & clay, locally containing stones.
ULM	1.140	undefined	N/A	Rock	Rock with minor Quaternary deposits

At the frequency of 5-hz, the following observations were made: of a total of 32 stations, 9 stations show H/V ratio less than 1.2, 13 stations show amplifications between 1.2 and 1.4, and 9 show an amplification higher than 1.4. Station ULM has an undefined value of H/V at 5-hz (due to insufficient observations with $S/N \geq 2$). The average amplifications for classes A-5a, A-5b, A-5c are 1.06, 1.30 and 1.93 respectively. At 5-hz, the correlation with geology becomes more obvious than at 1-hz. Stations with low to moderate amplifications are mostly located in rocks or rock-like environments. Stations that show amplifications of more than 1.4 are mostly located on marine, thick till or colluvial materials. The maximum amplification is about a factor of 3 for the station A61 (Charlevoix array). It is surrounded by Marine material composed of silt and clay with stones. An interesting setting of this station is that it is installed in between the stations A64, LMQ and A54. These three stations are installed where the surrounding material is mostly Till Blanket and the amplification factors are 1.3, 1.3 and 1.2 respectively. So the amplification for A61 might have been strongly influenced by the local geological conditions (marine materials).

•

FIG 5-2 EARTHQUAKES AND RECORDING STATIONS WITH SURFACE GEOLOGY

LEGEND

▲ Stations

Earthquakes

• 2.5 - 2.9

• 3 - 3.4

• 3.5 - 3.9

• 4 - 4.4

• 4.5 - 4.9

• 5 - 5.4

• 5.5 - 6

Surface Materials

■ Glaciers

■ Rock

■ Surface Material

■ Water

2500

0

2500 Kilometers

Projection Information:

Projection: Lambert Conformal Conic

Central Meridian: -95

Ref. Latitude: 49

Standard Parallels: 49 N, 77 N

Map Ref: Surficial Materials of

Canada, Map 1880 A

FIG 5-3 SURFACE GEOLOGY AND MEAN HV VALUES FOR NW-CANADA

FIG. 5-4 SURFACE GEOLOGY AND MEAN HV VALUES FOR SW-CANADA

FIG.5-5 SURFACE GEOLOGY AND MEAN H/V VALUES FOR MID-CANADA

▲ Mid-Canada Stations

Surface Geology

- Alluvial
- Colluvial
- Eolian
- Glaciers
- Glaciofluvial
- Lacustrine
- Marine
- Organic
- Quat. Volcanics
- Rock
- Till Blanket
- Till Veneer
- Water

LEGEND

200 0 200 400 600 Kilometers

Projection Information:

Projection: Lambert Conformal Conic

Central Meridian: 95 W

Ref. Latitude: 49 N

Standard Parallels: 49 N, 77 N

Map Ref: Surficial Materials of
Canada, Map 1880 A

Stat Loc.	Amplitude	Phase
YK44	0.18	1.23
YK41	1.26	1.26
YK42	1.21	1.22
YK43	1.21	1.17
YK44	0.14	1.22
YK45	2.04	1.00
YK46	1.14	1.04
YK47	1.01	0.04

FIG.5-6 SURFACE GEOLOGY AND MEAN H/V VALUES FOR EASTERN CANADA

FIG. 5-7 SURFACE GEOLOGY MAP FOR CHARLEVOIX AREA

CONCLUSIONS

6.1 INTRODUCTION

This chapter presents the conclusions of the study. The conclusions are based on a possible correlation with geology and a comparison of results with previous work. From the point of view of seismological properties, a survey of previous studies is presented and H/V ratio results are compared in the light of past research. From the geological point of view, the conclusions are based on the analysis presented in chapter 5. The prospects for future work are explored with reference to the work done in different parts of the world (an outline of which is presented in chapter 2.)

6.2 SEISMOLOGICAL PROPERTIES

It has been suggested that the observed H/V ratios may be a measure of the amplification of seismic ground motions due to their transit through the crustal or near-surface velocity gradient . In this section, I survey studies pertaining to H/V and ground motion amplification, in eastern and western Canada. Tables 6.1 and 6.2 present a brief overview of the studies. After this review, the results obtained from the current study will be compared with the findings of the previous studies.

Table 6.1: Site Effect Studies for Western Canada

STUDY	FOCUS OF STUDY	FINDINGS
Atkinson & Boore 1997	To develop preliminary ground motion relations for the Cascadia region for rock sites.	The average H/V is larger at high frequencies than the ratio obtained by Atkinson 1993 (see table 6.2) for eastern hard rock sites. WCTN sites have lower near surface velocities than ECTN sites. (For example 1.5 km/sec vs. 2.8 km/sec.)
Boore & Joyner, 1997	To present average velocity versus depth and amplification versus frequency for rock sites in Eastern & Western North America.	The average shear wave velocity for Western North America ¹ for the top 30 m is 620 m/s. The amplifications of rock sites can be in excess of 3.5 at high frequencies. The combined effect of attenuation and amplification for rock sites peaks between about 2 and 5-hz with a maximum level of less than 1.8. At 1-hz, the combined effect is a factor of 1.5

¹ For the Western site, the authors have considered mostly California sites. These sites are very similar to British Columbia sites, with the top 100m of the California profile removed for the B.C sites.

Table 6.1 continued....

Atkinson & Cassidy, Feb., 2000	To present a new method to estimate soil amplification using regional seismographic data for sites in Fraser Delta, B.C.	Fraser Delta soils amplify weak motions three to five times for frequencies of 0.3 to 4-hz. Motions are de-amplified for $f > 10$ -hz. The H/V ratio appears to be correlated with the site amplification. Rock sites in western region show similar H/V characteristics, except sites located on batholithic rocks (BBB, PMB, PNT). These sites have higher shear wave velocities and lower H/V.
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Table 6.2: Site Effect Studies for Eastern Canada

STUDY	FOCUS OF STUDY	FINDINGS
Atkinson 1993	Determine H/V ratio for hard rock sites in ENA.	H/V ratio for the hard rock ECTN (Eastern Canada Telemetered Network) sites increases with frequency from a value of 1.1 at 1hz to 1.5 at 10-hz.
Boore & Joyner, 1997	To present average velocity versus depth and amplification versus frequency for rock sites in Eastern & Western North America.	The amplification factors are less than 1.2 on very hard rock sites of Eastern North America. The average shear wave velocity for top 30 m is 2.88 km/s.
Beresnev and Atkinson 1997	Obtain information about pre-dominant site effects from shear wave refraction survey in Ontario.	The amplification for an average hard rock site in Ontario is about a factor of 1.3. For south and southeast Ontario, velocity structure was determined to a depth of about 70m. Near surface S-wave velocities of hard rock sites range from 1.7 to 3.1 km/s, the average being 2.6 km/s. Surveyed Eastern seismograph stations have minimal site effects.

6.3 RESULTS OF THE STUDY

In this section the results of the current study will be presented for eastern and western Canada and will be compared with the findings of the previous studies. Tables 6.3 – 6.6 present the mean H/V values and the range indicated by the 90% confidence limits on the mean. It is assumed in these comparisons that the H/V ratio is a measure of site amplification.

Results for SW-Canada:

Table 6.3: Amplification Factors for SW-Canada

Station	1 hz		5 hz	
	Mean H/V	90% C.I Range	Mean H/V	90% C.I Range
PNT	1.14	1.07 - 1.21	1.15	1.06 - 1.25
PMB	1.02	0.93 - 1.13	0.94	0.77 - 1.16
PGC	1.09	1.04 - 1.13	1.72	1.59 - 1.86
BBB	1.04	0.99 - 1.09	1.06	1.02 - 1.10

Average amplification at 1 hz: 1.07 Standard deviation: +, - 0.05
Average amplification at 5 hz: 1.22 Standard deviation: +, - 0.29

Table 6.4: Amplification Factors for NW-Canada

Station	1 hz		5 hz	
	Mean H/V	90% C.I Range	Mean H/V	90% C.I Range
DLBC	1.30	1.23 - 1.38	1.71	1.63 - 1.78
WHY	1.26	1.20 - 1.32	1.33	1.29 - 1.37
MOBC	1.08	1.01 - 1.16	1.88	1.79 - 1.98
MBC	0.93	0.66 - 1.32	1.36	0.79 - 2.33
INK	0.83	0.78 - 0.90	1.03	0.99 - 1.07
DAWY	1.23	1.16 - 1.31	2.37	2.30 - 2.45
RES	1.11	1.00 - 1.22	1.07	1.02 - 1.13

Average amplification at 1 hz: 1.11 Standard deviation: +, - 0.16
Average amplification at 5 hz: 1.54 Standard deviation: +, - 0.45

The study of Boore & Joyner, 1997 proposes that the combined effect of amplification and attenuation at 1-hz is 1.5 and that between 2 and 5-hz it is less than a factor of 1.5, for generic western rock sites. The results of this study suggest that, if amplification is represented by H/V, the amplification levels for SW-Canada are 1.1 and 1.2 for 1-hz and 5-hz respectively. For NW-Canada, the amplification levels are 1.1 and 1.5 for 1-hz and 5-hz, respectively. These ratios are generally consistent with the amplifications presented by Boore and Joyner (1997). Atkinson & Cassidy, (2000) show that the H/V ratios for stations in SW-B.C are consistent with theoretical estimates of site amplification based on impedance changes in the near-surface materials.

Table 6.5: Amplification Factors for Eastern Canada

Stations	1 hz		5 hz	
	Mean H/V	90% C.I Range	Mean H/V	90% C.I Range
FRB	1.42	1.16 - 1.74	1.25	1.18 - 1.33
GAC	1.11	0.86 - 1.43	1.40	1.32 - 1.48
SADO	1.49	1.20 - 1.86	1.26	1.18 - 1.35
DRLN	1.02	0.90 - 1.16	1.13	1.03 - 1.24
SCH	1.22	1.07 - 1.38	1.40	1.32 - 1.49
LMQ	1.02	0.86 - 1.20	1.27	1.21 - 1.33
LMN	1.23	1.07 - 1.41	1.48	1.39 - 1.57
A11	1.24	1.09 - 1.40	1.44	1.39 - 1.50
A16	0.95	0.87 - 1.04	1.22	1.13 - 1.32
A21	0.91	0.82 - 1.00	1.71	1.64 - 1.79
A54	0.67	0.45 - 1.00	1.21	1.15 - 1.28
A61	1.23	1.05 - 1.44	3.18	3.10 - 3.27
A64	0.69	1.86 - 0.90	1.33	1.23 - 1.45

Average at 1 hz: 1.09 Standard deviation: +, - 0.24
Average at 5 hz: 1.48 Standard deviation: +, - 0.51

The results of this study for Eastern Canada are very consistent with the results of four studies outlined in Table 6.2. The amplification factor increases from 1.1

at 1-hz to 1.5 for higher frequencies. Outside the Charlevoix region, most stations have a 5-hz H/V ratio of 1.3 to 1.4. Based on impedance effects discussed in Chapter 2 ($[(\rho_2 \beta_2) / (\rho_1 \beta_1)]^{0.5}$), this would imply typical near-surface shear-wave velocities of 1.9 to 2.2 km/s (for deep crustal velocity of 3.8 km/s), consistent with the refraction results of Beresnev and Atkinson (1997).

Table 6.6: Amplification factors for Mid-Canada

Stations	1 hz		5 hz	
	Mean H/V	90% C.I Range	Mean H/V	90% C.I Range
WALA	0.85	0.97 - 0.74	1.31	1.16 - 1.49
YKW1	1.36	1.11 - 1.67	1.24	1.15 - 1.33
YKW2	1.31	1.07 - 1.61	1.29	1.17 - 1.44
YKW3	1.21	1.47 - 1.00	1.17	1.09 - 1.26
YKW4	0.81*	N/A	1.00	1.10 - 0.91
FCC	1.41	1.15 - 1.74	0.94	0.78 - 1.12
EDM	3.84	2.90 - 5.08	1.89	1.45 - 2.46
ULM	1.14	0.83 - 1.55	N/A	N/A

Average Amplifications at 1 hz: 1.49 Standard deviation: +/- 0.91
Average Amplifications at 5 hz: 1.26 Standard deviation: +/- 0.29

* Value for Mean extrapolated from data.

Average except EDM at 1 hz: 1.16 Standard deviation: +/- 0.22
Average except EDM and ULM at 5 hz: 1.16 Standard deviation: +/- 0.14

The average amplification factors for mid-Canada at 1-hz are biased by a high response of EDM. The rest of the stations do not show a high amplification level at 1-hz. At a frequency of 5-hz, the average amplification factor for mid-Canada stations is 1.26, which is lower than the response of Eastern and Western stations. (1.49 and 1.53 respectively at 5-hz.) If the response of EDM is excluded from the average, then the amplification levels at both 1-hz and 5-hz are 1.16. The low H/V ratios in mid-Canada imply high near-surface shear-wave velocities, which is consistent with the highly-competent Canadian Shield rock conditions.

We compare the results of mean H/V ratios, considering the standard deviation and 90% confidence interval of the average for each region. It is observed that the average H/V for typical rock sites is 1.1 ± 0.1 at 1 Hz, and it is in the range of 1.2 to 1.5 at 5 Hz. This trend is the same all over the country. Table 6.7 shows these observations.

Table 6.7: Comparison of Mean H/V, Standard Deviation and 90% C.I at 1-Hz and 5-Hz

Region	Values at 1-Hz:			Values at 5-Hz:		
	Mean	S.D	90%CI	Mean	S.D	90%CI
SW-Canada	1.07	0.05	0.04	1.22	0.29	0.24
NW-Canada	1.11	0.16	0.09	1.54	0.45	0.28
Eastern Canada	1.09	0.24	0.07	1.48	0.51	0.23
Mid-Canada	1.19	0.91	0.53	1.26	0.29	0.18
Mid-Canada (except EDM)	1.16	0.22	0.14	1.16	0.14	0.09

6.4 FUTURE PROSPECTS AND SUMMARY OF CONCLUSIONS

Based on the survey presented in Chapter 2, this work can be further extended in several areas. For example, one of the most active seismic regions of Canada is the Charlevoix zone. It has seven closely-located three-component recording stations on rock to monitor the seismic activity of the region. Following Duval et al (1995) site amplification maps of the Charlevoix seismic zone can be produced if further stations are placed on typical soil sites in the area. Duval et al (1995) produced site amplification maps in Nice, France based on H/V ratio curves obtained for that region. From these H/V ratio curves, they chose one value each for the frequency (of maximum amplitude) and maximum amplitude. They then proceeded with interpolating these values to produce the site amplification maps. They also found that these maps agreed reasonably well with the geological

conditions of the area. A similar study could be performed in Charlevoix. A further enhancement of the study could be to correlate H/V with rock type (e.g. granite, etc) or geological history. In this study, H/V seems similar for various regions at most stations. Therefore, shear wave velocity is probably more important rather than the rock type.

Many parts of Canada have relatively low seismicity. For such areas, Lermo and Chavez-Garcia (1994) suggest that micro-tremor measurements can complement other site effect studies. Since the H/V ratio technique is originally proposed for micro-tremor recordings, it can be usefully applied in low-seismicity regions to obtain information about the site effects. Once this information is obtained, it can especially be used in urban areas. For example, Lachet and Bard (1994) find that the knowledge of the resonance frequency of soil can be used to identify the kinds of buildings most prone to damage.

In site effect studies, the most popular technique used is the standard spectral ratio technique. In this technique, site response of soil sites is determined relative to a nearby hard rock site. Comparing the standard spectral ratio technique with the H/V ratio technique, Theodulidis et al (1996) find that there is a difference in amplitude between the H/V ratio and the standard spectral ratio. In this study, we have obtained an estimate of amplifications using the H/V ratio method. For regions where accurate information of site response is required, calculating the

response by standard spectral ratio technique as well can refine the results of this study.

Some of the important applications of this work are:

- H/V ratio can be used as a simple estimate of site amplification.
- H/V ratio can be used as a measure of regional variability of crustal amplification effects through the velocity gradient.
- H/V can be used to estimate the horizontal component for the many older seismograph recordings for which only the vertical component of motion was measured.

Overall, I conclude:

- The H/V ratios are broadly consistent with typical amplification values suggested for North American crust.
- The results of the study are consistent with the results of previous studies. For Western North America (particularly California), Boore and Joyner (1997) suggested that the combined effect of amplification and attenuation for frequencies between 2 and 5-hz is less than a factor 1.5. The results of this study indicate amplification levels to be 1.2 and 1.5 at 5-hz for southwestern and northwestern Canada respectively. For Eastern Canada, Atkinson (1993) finds that H/V ratio increases with frequency from 1.1 at 1-hz to 1.5 at 10-hz. Boore and Joyner (1997) suggest that amplification factors are less than 1.2 on very hard rock sites of Eastern North America.

The findings of this study indicate that H/V ratio at 1-hz is 1.1 and that at 5-hz is 1.5. For the hard rock stations of eastern Canada (DRLN, A54, SADO, A64) the amplification is indeed of the order of 1.2 at 5-hz.

- A correlation exists between H/V ratios at 5-hz and the general geology of the recording stations. Amplifications based on H/V ratio are generally high where the local geological conditions indicate relatively soft marine rock conditions. For example, the amplification factors inferred from H/V ratios are between 0.9 – 1.2 for hard rock (or hard rock outcrop) sites, while for sites where marine materials predominate, H/V ratios vary between 1.4 to as high as 3.2.
- At 1-hz, the amplification for hard rock stations in all regions of Canada is low, approximately 1.1 ± 0.1 . At 5-hz the H/V ratio is in the range from 1.2 – 1.5 on average.

APPENDIX: TABULATED RESULTS

Tabulated Statistics* for Station: A11

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.18	0.08	0.06
-0.9	-0.05	0.27	0.17
-0.8	-0.24	0.08	0.07
-0.7	-0.23	0.11	0.09
-0.6	-0.03	0.07	0.06
-0.5	-0.18	0.22	0.11
-0.4	-0.03	0.12	0.06
-0.3	-0.01	0.13	0.06
-0.2	-0.04	0.16	0.07
-0.1	0.07	0.19	0.07
0.0	0.09	0.16	0.05
0.1	0.09	0.18	0.05
0.2	0.11	0.13	0.03
0.3	0.11	0.11	0.02
0.4	0.13	0.11	0.03
0.5	0.11	0.11	0.02
0.6	0.15	0.08	0.02
0.7	0.16	0.08	0.02
0.8	0.15	0.10	0.02
0.9	0.13	0.10	0.02
1.0	0.13	0.09	0.02
1.1	0.10	0.08	0.02
1.2	0.07	0.10	0.02
1.3	0.06	0.10	0.03

Tabulated Statistics* for Station: A16

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.22	0.00	0.00
-0.9	-0.32	0.27	0.18
-0.8	0.05	0.38	0.36
-0.7	-0.12	0.28	0.15
-0.6	-0.31	0.16	0.09
-0.5	-0.05	0.26	0.13
-0.4	-0.06	0.30	0.15
-0.3	-0.12	0.17	0.08
-0.2	0.00	0.20	0.09
-0.1	-0.01	0.16	0.06
0.0	-0.02	0.13	0.04
0.1	0.05	0.15	0.04
0.2	0.03	0.11	0.03
0.3	0.07	0.12	0.03
0.4	0.00	0.11	0.02
0.5	0.09	0.11	0.02
0.6	0.09	0.09	0.02
0.7	0.09	0.14	0.03
0.8	0.09	0.08	0.02
0.9	0.16	0.06	0.02
1.0	0.01	0.27	0.07
1.1	0.10	0.05	0.02
1.2	0.08	0.07	0.02
1.3	-0.01	0.15	0.04

Tabulated Statistics* for Station: A21

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.20	0.18	0.17
-0.9	0.33	0.00	0.00
-0.8	0.00	0.07	0.06
-0.7	-0.05	0.08	0.07
-0.6	0.07	0.14	0.09
-0.5	-0.06	0.24	0.14
-0.4	-0.08	0.18	0.08
-0.3	-0.03	0.08	0.03
-0.2	-0.01	0.18	0.07
-0.1	0.03	0.12	0.04
0.0	-0.04	0.14	0.04
0.1	0.11	0.14	0.04
0.2	0.09	0.17	0.04
0.3	0.09	0.11	0.02
0.4	0.09	0.09	0.02
0.5	0.16	0.13	0.02
0.6	0.21	0.11	0.02
0.7	0.23	0.12	0.02
0.8	0.23	0.11	0.02
0.9	0.23	0.08	0.01
1.0	0.21	0.06	0.01
1.1	0.21	0.09	0.02
1.2	0.22	0.07	0.01
1.3	0.12	0.05	0.01

Tabulated Statistics* for Station: A54

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.12	0.43	0.36
-0.9	0.18	0.80	0.93
-0.8	0.08	0.37	0.25
-0.7	-0.01	0.10	0.06
-0.6	0.09	0.16	0.11
-0.5	0.32	0.43	0.24
-0.4	-0.06	0.24	0.14
-0.3	-0.09	0.12	0.06
-0.2	-0.16	0.44	0.19
-0.1	-0.16	0.46	0.16
0.0	-0.17	0.49	0.17
0.1	-0.28	0.57	0.15
0.2	-0.30	0.54	0.12
0.3	-0.26	0.49	0.10
0.4	-0.23	0.45	0.08
0.5	-0.13	0.33	0.05
0.6	0.02	0.23	0.04
0.7	0.08	0.15	0.02
0.8	0.18	0.18	0.03
0.9	0.25	0.23	0.04
1.0	0.27	0.19	0.04
1.1	0.18	0.13	0.03
1.2	0.11	0.10	0.02
1.3	0.01	0.10	0.02

Tabulated Statistics* for Station: A61

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.13	0.52	0.49
-0.9	-0.22	0.27	0.16
-0.8	0.17	0.13	0.12
-0.7	9.99	0.00	0.00
-0.6	9.99	0.00	0.00
-0.5	0.30	0.14	0.10
-0.4	0.43	0.30	0.15
-0.3	0.41	0.37	0.18
-0.2	0.27	0.16	0.07
-0.1	0.27	0.21	0.09
0.0	0.09	0.20	0.07
0.1	0.16	0.15	0.04
0.2	0.23	0.11	0.02
0.3	0.25	0.13	0.02
0.4	0.32	0.10	0.02
0.5	0.38	0.12	0.02
0.6	0.41	0.08	0.01
0.7	0.50	0.07	0.01
0.8	0.55	0.08	0.01
0.9	0.55	0.09	0.02
1.0	0.57	0.18	0.03
1.1	0.63	0.17	0.03
1.2	0.60	0.15	0.03
1.3	0.64	0.12	0.02

Tabulated Statistics* for Station: A64

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.02	0.16	0.15
-0.9	0.07	0.28	0.26
-0.8	-0.09	0.04	0.05
-0.7	-0.11	0.12	0.10
-0.6	-0.37	0.40	0.33
-0.5	-0.11	0.04	0.03
-0.4	-0.24	0.34	0.20
-0.3	-0.15	0.15	0.10
-0.2	0.04	0.16	0.09
-0.1	-0.01	0.25	0.09
0.0	-0.16	0.34	0.11
0.1	-0.17	0.35	0.10
0.2	-0.20	0.27	0.06
0.3	-0.03	0.15	0.03
0.4	0.09	0.12	0.02
0.5	0.13	0.30	0.05
0.6	0.15	0.27	0.04
0.7	0.13	0.22	0.04
0.8	0.15	0.19	0.03
0.9	0.17	0.18	0.03
1.0	0.16	0.18	0.04
1.1	0.20	0.17	0.04
1.2	0.24	0.14	0.03
1.3	0.23	0.17	0.04

Tabulated Statistics* for Station: BBB

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.09	0.19	0.05
-0.9	0.00	0.17	0.04
-0.8	0.01	0.23	0.05
-0.7	0.06	0.19	0.05
-0.6	0.14	0.16	0.04
-0.5	0.08	0.18	0.04
-0.4	0.09	0.20	0.05
-0.3	0.07	0.16	0.03
-0.2	-0.02	0.14	0.03
-0.1	-0.01	0.16	0.03
0.0	0.02	0.13	0.02
0.1	0.00	0.15	0.02
0.2	0.07	0.14	0.02
0.3	0.14	0.13	0.02
0.4	0.12	0.13	0.02
0.5	0.15	0.12	0.01
0.6	0.02	0.12	0.01
0.7	0.03	0.13	0.02
0.8	0.10	0.10	0.01
0.9	0.16	0.12	0.01
1.0	0.16	0.12	0.01
1.1	0.22	0.13	0.02
1.2	0.23	0.12	0.02
1.3	0.15	0.21	0.03

Tabulated Statistics* for Station: DAWY

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.18	0.48	0.18
-0.9	0.02	0.31	0.12
-0.8	0.04	0.28	0.09
-0.7	0.00	0.23	0.07
-0.6	0.02	0.19	0.05
-0.5	0.08	0.20	0.05
-0.4	0.03	0.19	0.05
-0.3	0.05	0.15	0.03
-0.2	0.06	0.16	0.03
-0.1	0.09	0.18	0.04
0.0	0.09	0.14	0.03
0.1	0.05	0.13	0.02
0.2	0.09	0.12	0.02
0.3	0.14	0.13	0.02
0.4	0.21	0.14	0.02
0.5	0.24	0.12	0.02
0.6	0.35	0.10	0.01
0.7	0.38	0.09	0.01
0.8	0.23	0.08	0.01
0.9	-0.01	0.07	0.01
1.0	-0.16	0.07	0.01
1.1	-0.15	0.09	0.02
1.2	0.14	0.11	0.02
1.3	0.13	0.22	0.05

Tabulated Statistics* for Station: DLBC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.02	0.18	0.08
-0.9	0.05	0.25	0.09
-0.8	0.04	0.20	0.05
-0.7	0.05	0.12	0.04
-0.6	0.08	0.18	0.06
-0.5	0.14	0.16	0.05
-0.4	0.11	0.20	0.05
-0.3	0.10	0.17	0.04
-0.2	0.11	0.14	0.03
-0.1	0.08	0.12	0.02
0.0	0.12	0.13	0.03
0.1	0.10	0.16	0.03
0.2	0.09	0.15	0.03
0.3	0.13	0.11	0.02
0.4	0.10	0.12	0.02
0.5	0.17	0.10	0.02
0.6	0.22	0.09	0.02
0.7	0.23	0.11	0.02
0.8	0.22	0.12	0.02
0.9	0.25	0.10	0.02
1.0	0.16	0.13	0.03
1.1	0.20	0.14	0.04
1.2	0.24	0.13	0.04
1.3	0.19	0.22	0.15

Tabulated Statistics* for Station: DRLN

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	-0.21	0.18	0.17
-0.7	-0.42	0.07	0.08
-0.6	-0.12	0.00	0.00
-0.5	-0.12	0.31	0.36
-0.4	-0.11	0.04	0.05
-0.3	-0.03	0.18	0.21
-0.2	0.09	0.12	0.09
-0.1	0.08	0.23	0.16
0.0	0.01	0.11	0.06
0.1	0.07	0.15	0.07
0.2	0.02	0.12	0.05
0.3	0.05	0.14	0.06
0.4	0.04	0.11	0.04
0.5	0.08	0.09	0.03
0.6	0.08	0.10	0.04
0.7	0.05	0.11	0.04
0.8	0.11	0.07	0.03
0.9	0.16	0.06	0.03
1.0	0.15	0.05	0.03
1.1	0.24	0.08	0.05
1.2	0.19	0.08	0.05
1.3	9.99	0.00	0.00

Tabulated Statistics* for Station: EDM

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.22	0.27	0.14
-0.9	0.37	0.28	0.15
-0.8	0.25	0.17	0.08
-0.7	0.24	0.14	0.07
-0.6	0.17	0.16	0.06
-0.5	0.18	0.15	0.05
-0.4	0.18	0.15	0.06
-0.3	0.39	0.17	0.06
-0.2	0.61	0.23	0.09
-0.1	0.68	0.27	0.13
0.0	0.58	0.27	0.12
0.1	0.45	0.18	0.07
0.2	0.44	0.26	0.10
0.3	0.47	0.23	0.08
0.4	0.41	0.29	0.11
0.5	0.28	0.29	0.11
0.6	0.27	0.25	0.12
0.7	0.28	0.24	0.12
0.8	0.30	0.22	0.11
0.9	0.14	0.15	0.09
1.0	-0.05	0.17	0.09
1.1	-0.06	0.20	0.12
1.2	0.03	0.17	0.12
1.3	0.37	0.31	0.23

Tabulated Statistics* for Station: FCC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	-0.10	0.00	0.00
-0.7	-0.15	0.05	0.06
-0.6	9.99	0.00	0.00
-0.5	0.27	0.26	0.30
-0.4	0.12	0.23	0.17
-0.3	-0.03	0.17	0.14
-0.2	-0.12	0.11	0.11
-0.1	0.01	0.19	0.15
0.0	0.15	0.12	0.09
0.1	0.04	0.18	0.15
0.2	0.08	0.21	0.14
0.3	0.09	0.15	0.08
0.4	0.11	0.09	0.04
0.5	0.01	0.07	0.04
0.6	0.14	0.09	0.06
0.7	-0.03	0.14	0.08
0.8	-0.04	0.14	0.10
0.9	9.99	0.00	0.00
1.0	-0.11	0.00	0.00
1.1	-0.22	0.19	0.22
1.2	-0.06	0.04	0.04
1.3	-0.05	0.00	0.00

Tabulated Statistics* for Station: FRB

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	9.99	0.00	0.00
-0.7	-0.11	0.00	0.00
-0.6	-0.20	0.07	0.07
-0.5	0.02	0.27	0.32
-0.4	0.11	0.16	0.18
-0.3	0.42	0.00	0.00
-0.2	0.19	0.28	0.33
-0.1	0.16	0.20	0.14
0.0	0.15	0.11	0.09
0.1	0.25	0.20	0.14
0.2	0.12	0.13	0.07
0.3	0.07	0.15	0.06
0.4	0.07	0.14	0.04
0.5	0.05	0.12	0.03
0.6	0.06	0.12	0.03
0.7	0.10	0.09	0.03
0.8	0.07	0.08	0.02
0.9	0.06	0.06	0.02
1.0	0.10	0.08	0.03
1.1	0.10	0.07	0.02
1.2	0.09	0.05	0.02
1.3	-0.06	0.47	0.29

Tabulated Statistics* for Station: GAC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	-0.10	0.00	0.00
-0.8	-0.14	0.11	0.13
-0.7	-0.16	0.09	0.11
-0.6	-0.07	0.18	0.17
-0.5	0.15	0.30	0.15
-0.4	0.07	0.28	0.19
-0.3	0.03	0.19	0.13
-0.2	0.08	0.07	0.05
-0.1	0.04	0.12	0.06
0.0	0.05	0.20	0.11
0.1	0.09	0.18	0.09
0.2	0.12	0.17	0.08
0.3	0.09	0.12	0.05
0.4	0.07	0.14	0.04
0.5	0.12	0.12	0.03
0.6	0.11	0.12	0.02
0.7	0.15	0.13	0.02
0.8	0.16	0.14	0.03
0.9	0.20	0.11	0.02
1.0	0.18	0.13	0.03
1.1	0.17	0.13	0.03
1.2	0.15	0.14	0.03
1.3	0.07	0.11	0.06

Tabulated Statistics* for Station: INK

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.14	0.18	0.07
-0.9	-0.12	0.21	0.09
-0.8	-0.11	0.13	0.05
-0.7	-0.09	0.22	0.08
-0.6	-0.09	0.15	0.05
-0.5	-0.04	0.17	0.05
-0.4	0.01	0.23	0.06
-0.3	0.02	0.17	0.05
-0.2	-0.07	0.17	0.04
-0.1	-0.05	0.15	0.04
0.0	-0.08	0.13	0.03
0.1	-0.02	0.12	0.03
0.2	-0.03	0.15	0.03
0.3	-0.03	0.10	0.02
0.4	0.01	0.11	0.02
0.5	0.01	0.10	0.02
0.6	0.00	0.09	0.02
0.7	0.01	0.09	0.02
0.8	0.08	0.09	0.02
0.9	0.07	0.10	0.02
1.0	0.07	0.13	0.03
1.1	0.12	0.09	0.02
1.2	0.15	0.15	0.03
1.3	0.14	0.21	0.05

Tabulated Statistics* for Station: LMN

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.05	0.00	0.00
-0.9	-0.10	0.00	0.00
-0.8	-0.12	0.16	0.16
-0.7	-0.18	0.06	0.05
-0.6	-0.26	0.32	0.26
-0.5	-0.11	0.11	0.07
-0.4	-0.10	0.10	0.06
-0.3	-0.02	0.14	0.08
-0.2	-0.04	0.10	0.06
-0.1	-0.05	0.16	0.08
0.0	0.09	0.13	0.06
0.1	0.18	0.14	0.06
0.2	0.14	0.16	0.07
0.3	0.11	0.14	0.05
0.4	0.08	0.11	0.03
0.5	0.08	0.13	0.03
0.6	0.16	0.11	0.03
0.7	0.17	0.10	0.03
0.8	0.16	0.10	0.03
0.9	0.21	0.13	0.03
1.0	0.26	0.19	0.05
1.1	0.27	0.09	0.03
1.2	0.29	0.09	0.02
1.3	0.28	0.17	0.06

Tabulated Statistics* for Station: LMQ

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.12	0.02	0.03
-0.9	-0.04	0.10	0.09
-0.8	-0.01	0.25	0.24
-0.7	-0.08	0.32	0.30
-0.6	-0.03	0.16	0.09
-0.5	-0.13	0.15	0.08
-0.4	-0.07	0.16	0.07
-0.3	-0.08	0.18	0.08
-0.2	0.03	0.19	0.08
-0.1	0.00	0.19	0.07
0.0	0.01	0.20	0.07
0.1	0.07	0.20	0.07
0.2	0.06	0.16	0.05
0.3	0.07	0.15	0.04
0.4	0.14	0.10	0.02
0.5	0.14	0.09	0.02
0.6	0.13	0.13	0.02
0.7	0.10	0.13	0.02
0.8	0.14	0.10	0.02
0.9	0.22	0.13	0.02
1.0	0.29	0.11	0.02
1.1	0.25	0.19	0.04
1.2	-0.05	0.32	0.06
1.3	-0.21	0.26	0.08

Tabulated Statistics* for Station: MBC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.15	0.38	0.28
-0.9	0.22	0.34	0.28
-0.8	-0.07	0.16	0.13
-0.7	-0.14	0.11	0.09
-0.6	-0.01	0.13	0.09
-0.5	0.02	0.13	0.11
-0.4	-0.08	0.17	0.12
-0.3	-0.12	0.16	0.10
-0.2	-0.10	0.20	0.13
-0.1	0.10	0.15	0.09
0.0	-0.03	0.23	0.15
0.1	-0.02	0.28	0.23
0.2	0.05	0.20	0.15
0.3	0.06	0.23	0.19
0.4	0.08	0.22	0.18
0.5	0.12	0.24	0.23
0.6	0.24	0.23	0.26
0.7	0.13	0.25	0.24
0.8	0.25	0.22	0.26
0.9	0.24	0.23	0.26
1.0	0.25	0.22	0.26
1.1	0.24	0.22	0.26
1.2	0.25	0.22	0.26
1.3	0.24	0.23	0.26

Tabulated Statistics* for Station: MOBC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.24	0.22	0.10
-0.9	0.22	0.37	0.16
-0.8	0.07	0.23	0.08
-0.7	0.08	0.27	0.09
-0.6	0.12	0.30	0.10
-0.5	0.13	0.22	0.07
-0.4	0.06	0.17	0.05
-0.3	0.04	0.14	0.04
-0.2	0.05	0.13	0.04
-0.1	0.03	0.11	0.03
0.0	0.03	0.10	0.03
0.1	0.09	0.13	0.03
0.2	0.14	0.13	0.03
0.3	0.18	0.15	0.03
0.4	0.14	0.13	0.02
0.5	0.18	0.14	0.02
0.6	0.34	0.15	0.02
0.7	0.27	0.14	0.02
0.8	0.28	0.14	0.02
0.9	0.26	0.15	0.03
1.0	0.23	0.14	0.03
1.1	0.26	0.13	0.03
1.2	0.03	0.16	0.04
1.3	-0.04	0.20	0.10

Tabulated Statistics* for Station: PMB

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.00	0.33	0.08
-0.9	-0.01	0.26	0.07
-0.8	-0.03	0.28	0.08
-0.7	-0.05	0.22	0.06
-0.6	0.06	0.24	0.06
-0.5	-0.01	0.22	0.05
-0.4	0.02	0.24	0.05
-0.3	0.05	0.20	0.04
-0.2	0.10	0.22	0.04
-0.1	0.08	0.21	0.04
0.0	0.01	0.22	0.04
0.1	0.00	0.22	0.04
0.2	0.05	0.23	0.05
0.3	-0.02	0.25	0.05
0.4	-0.03	0.26	0.05
0.5	0.03	0.28	0.06
0.6	0.05	0.30	0.06
0.7	-0.03	0.36	0.09
0.8	-0.07	0.46	0.14
0.9	-0.07	0.38	0.11
1.0	-0.07	0.36	0.11
1.1	-0.05	0.34	0.11
1.2	0.03	0.34	0.12
1.3	0.06	0.36	0.13

Tabulated Statistics* for Station: PGC

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.06	0.18	0.04
-0.9	0.10	0.17	0.04
-0.8	0.05	0.16	0.04
-0.7	0.04	0.12	0.03
-0.6	-0.01	0.18	0.05
-0.5	-0.02	0.11	0.03
-0.4	-0.02	0.13	0.03
-0.3	0.01	0.12	0.03
-0.2	0.01	0.11	0.02
-0.1	0.01	0.11	0.02
0.0	0.04	0.09	0.02
0.1	0.04	0.11	0.02
0.2	0.05	0.12	0.02
0.3	0.14	0.16	0.03
0.4	0.18	0.16	0.03
0.5	0.12	0.15	0.03
0.6	0.20	0.20	0.04
0.7	0.24	0.18	0.03
0.8	0.22	0.18	0.04
0.9	0.26	0.21	0.05
1.0	0.21	0.21	0.05
1.1	0.10	0.23	0.06
1.2	-0.01	0.24	0.08
1.3	0.07	0.32	0.12

Tabulated Statistics* for Station: PNT

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.07	0.14	0.06
-0.9	0.03	0.14	0.05
-0.8	-0.01	0.17	0.06
-0.7	0.03	0.18	0.06
-0.6	0.12	0.20	0.07
-0.5	0.00	0.22	0.07
-0.4	-0.02	0.14	0.04
-0.3	0.03	0.16	0.04
-0.2	0.08	0.15	0.03
-0.1	0.05	0.15	0.03
0.0	0.06	0.13	0.03
0.1	0.08	0.12	0.03
0.2	0.04	0.13	0.03
0.3	0.07	0.12	0.03
0.4	0.03	0.13	0.03
0.5	0.08	0.14	0.03
0.6	-0.01	0.16	0.04
0.7	0.06	0.15	0.04
0.8	0.05	0.19	0.05
0.9	0.06	0.16	0.04
1.0	0.03	0.13	0.04
1.1	0.07	0.17	0.05
1.2	-0.01	0.19	0.06
1.3	0.01	0.22	0.09

Tabulated Statistics* for Station: RES

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	-0.06	0.00	0.00
-0.8	-0.04	0.14	0.10
-0.7	-0.01	0.16	0.12
-0.6	0.22	0.22	0.21
-0.5	0.07	0.22	0.12
-0.4	0.19	0.27	0.13
-0.3	0.10	0.13	0.06
-0.2	0.14	0.14	0.06
-0.1	0.13	0.14	0.06
0.0	0.05	0.14	0.04
0.1	0.00	0.13	0.04
0.2	0.00	0.14	0.04
0.3	0.02	0.11	0.03
0.4	0.08	0.12	0.03
0.5	0.02	0.09	0.02
0.6	0.04	0.08	0.02
0.7	0.03	0.08	0.02
0.8	0.08	0.08	0.02
0.9	0.11	0.05	0.01
1.0	0.13	0.06	0.02
1.1	0.15	0.06	0.02
1.2	0.16	0.07	0.02
1.3	0.25	0.25	0.11

Tabulated Statistics* for Station SCH:

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	-0.08	0.00	0.00
-0.7	-0.08	0.02	0.02
-0.6	-0.04	0.00	0.00
-0.5	-0.22	0.00	0.00
-0.4	0.06	0.14	0.16
-0.3	0.17	0.15	0.10
-0.2	0.03	0.13	0.07
-0.1	0.08	0.15	0.06
0.0	0.09	0.14	0.06
0.1	0.10	0.13	0.05
0.2	0.10	0.13	0.04
0.3	0.09	0.13	0.04
0.4	0.07	0.13	0.03
0.5	0.17	0.11	0.02
0.6	0.17	0.13	0.03
0.7	0.15	0.10	0.03
0.8	0.18	0.09	0.03
0.9	0.19	0.11	0.04
1.0	0.22	0.08	0.03
1.1	0.26	0.08	0.03
1.2	0.26	0.11	0.04
1.3	0.22	0.15	0.08

Tabulated Statistics* for Station: SADO

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	0.00	0.32	0.26
-0.7	-0.16	0.20	0.16
-0.6	-0.07	0.14	0.16
-0.5	0.07	0.12	0.13
-0.4	0.16	0.21	0.18
-0.3	-0.06	0.25	0.13
-0.2	0.14	0.26	0.13
-0.1	0.11	0.23	0.12
0.0	0.17	0.18	0.10
0.1	0.20	0.18	0.08
0.2	0.16	0.17	0.06
0.3	0.04	0.15	0.04
0.4	0.09	0.18	0.04
0.5	0.06	0.16	0.03
0.6	0.05	0.13	0.03
0.7	0.10	0.14	0.03
0.8	0.12	0.09	0.02
0.9	0.13	0.09	0.02
1.0	0.15	0.08	0.02
1.1	0.13	0.05	0.01
1.2	0.15	0.06	0.01
1.3	0.15	0.08	0.03

Tabulated Statistics* for Station: ULM

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	9.99	0.00	0.00
-0.8	9.99	0.00	0.00
-0.7	-0.14	0.00	0.00
-0.6	-0.25	0.00	0.00
-0.5	-0.23	0.00	0.00
-0.4	-0.20	0.00	0.00
-0.3	-0.10	0.00	0.00
-0.2	0.11	0.29	0.24
-0.1	0.24	0.15	0.12
0.0	0.06	0.16	0.14
0.1	0.17	0.09	0.08
0.2	0.16	0.13	0.09
0.3	0.18	0.14	0.09
0.4	0.01	0.08	0.07
0.5	0.08	0.01	0.01
0.6	9.99	0.00	0.00
0.7	9.99	0.00	0.00
0.8	9.99	0.00	0.00
0.9	9.99	0.00	0.00
1.0	9.99	0.00	0.00
1.1	9.99	0.00	0.00
1.2	9.99	0.00	0.00
1.3	9.99	0.00	0.00

Tabulated Statistics* for Station: WALA

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.11	0.23	0.10
-0.9	-0.12	0.33	0.14
-0.8	-0.09	0.35	0.14
-0.7	-0.10	0.31	0.13
-0.6	-0.12	0.27	0.11
-0.5	-0.02	0.23	0.08
-0.4	0.07	0.12	0.04
-0.3	0.05	0.15	0.05
-0.2	-0.04	0.18	0.06
-0.1	-0.07	0.14	0.05
0.0	-0.07	0.15	0.06
0.1	0.00	0.13	0.05
0.2	-0.05	0.13	0.05
0.3	0.04	0.17	0.06
0.4	0.04	0.19	0.06
0.5	0.15	0.24	0.07
0.6	0.20	0.26	0.08
0.7	0.12	0.17	0.05
0.8	0.17	0.27	0.08
0.9	0.16	0.29	0.09
1.0	0.16	0.31	0.10
1.1	0.16	0.29	0.09
1.2	0.24	0.32	0.11
1.3	0.43	0.49	0.26

Tabulated Statistics* for Station: WHY

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	0.08	0.20	0.08
-0.9	0.06	0.14	0.05
-0.8	0.04	0.15	0.04
-0.7	0.06	0.17	0.05
-0.6	0.10	0.19	0.05
-0.5	0.05	0.17	0.04
-0.4	0.12	0.19	0.04
-0.3	0.10	0.14	0.03
-0.2	0.09	0.16	0.03
-0.1	0.08	0.14	0.02
0.0	0.10	0.15	0.02
0.1	0.09	0.14	0.02
0.2	0.15	0.14	0.02
0.3	0.10	0.13	0.02
0.4	0.13	0.12	0.01
0.5	0.12	0.11	0.01
0.6	0.15	0.12	0.01
0.7	0.12	0.12	0.01
0.8	0.10	0.11	0.01
0.9	0.11	0.10	0.01
1.0	0.16	0.10	0.01
1.1	0.22	0.10	0.01
1.2	0.20	0.10	0.02
1.3	0.13	0.21	0.05

Tabulated Statistics* for Station: YKW1

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.10	0.12	0.14
-0.9	-0.06	0.00	0.00
-0.8	0.12	0.36	0.20
-0.7	0.08	0.40	0.21
-0.6	0.04	0.19	0.09
-0.5	-0.03	0.20	0.09
-0.4	0.03	0.27	0.10
-0.3	0.13	0.16	0.07
-0.2	0.02	0.26	0.11
-0.1	0.14	0.16	0.07
0.0	0.14	0.21	0.09
0.1	0.08	0.25	0.09
0.2	0.10	0.20	0.07
0.3	0.10	0.17	0.05
0.4	0.09	0.14	0.04
0.5	0.09	0.12	0.03
0.6	0.07	0.13	0.04
0.7	0.09	0.09	0.03
0.8	0.13	0.11	0.04
0.9	0.18	0.09	0.04
1.0	9.99	0.00	0.00
1.1	9.99	0.00	0.00
1.2	9.99	0.00	0.00
1.3	9.99	0.00	0.00

Tabulated Statistics* for Station: YKW2

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.16	0.00	0.00
-0.9	-0.27	0.06	0.05
-0.8	-0.17	0.15	0.10
-0.7	-0.07	0.10	0.07
-0.6	0.00	0.15	0.09
-0.5	-0.05	0.19	0.07
-0.4	0.14	0.14	0.07
-0.3	0.14	0.14	0.08
-0.2	0.08	0.15	0.07
-0.1	0.09	0.19	0.09
0.0	0.12	0.20	0.09
0.1	0.08	0.21	0.09
0.2	0.08	0.21	0.08
0.3	0.03	0.17	0.06
0.4	0.03	0.14	0.04
0.5	0.05	0.09	0.03
0.6	0.08	0.11	0.04
0.7	0.11	0.13	0.05
0.8	0.07	0.08	0.04
0.9	0.06	0.13	0.08
1.0	0.15	0.00	0.00
1.1	9.99	0.00	0.00
1.2	9.99	0.00	0.00
1.3	9.99	0.00	0.00

Tabulated Statistics* for Station: YKW3

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	-0.15	0.00	0.00
-0.9	-0.15	0.13	0.08
-0.8	0.03	0.25	0.11
-0.7	0.02	0.23	0.10
-0.6	-0.01	0.23	0.09
-0.5	0.04	0.23	0.10
-0.4	0.10	0.18	0.08
-0.3	0.14	0.20	0.08
-0.2	0.06	0.17	0.06
-0.1	0.06	0.19	0.07
0.0	0.08	0.23	0.08
0.1	0.04	0.14	0.05
0.2	0.08	0.19	0.06
0.3	0.06	0.17	0.05
0.4	-0.02	0.14	0.04
0.5	0.05	0.14	0.04
0.6	0.11	0.10	0.03
0.7	0.07	0.10	0.03
0.8	0.10	0.08	0.03
0.9	0.11	0.08	0.03
1.0	-0.03	0.02	0.02
1.1	9.99	0.00	0.00
1.2	9.99	0.00	0.00
1.3	9.99	0.00	0.00

Tabulated Statistics* for Station: YKW4

*All statistics given in log units

Frequency	Mean H/V	Standard Deviation	90% Confidence Interval
-1.0	9.99	0.00	0.00
-0.9	-0.29	0.17	0.14
-0.8	-0.05	0.20	0.13
-0.7	-0.12	0.29	0.21
-0.6	-0.20	0.23	0.17
-0.5	0.00	0.16	0.10
-0.4	0.20	0.21	0.20
-0.3	0.14	0.22	0.21
-0.2	0.20	0.09	0.11
-0.1	9.99	0.00	0.00
0.0	9.99	0.00	0.00
0.1	-0.14	0.14	0.13
0.2	-0.05	0.23	0.16
0.3	-0.09	0.17	0.10
0.4	-0.09	0.11	0.05
0.5	-0.08	0.16	0.07
0.6	-0.03	0.16	0.07
0.7	0.00	0.10	0.04
0.8	0.04	0.10	0.05
0.9	0.07	0.07	0.05
1.0	9.99	0.00	0.00
1.1	9.99	0.00	0.00
1.2	9.99	0.00	0.00
1.3	9.99	0.00	0.00

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