In situ damping measurements in Leda Clay within the Ottawa, ON area

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ABSTRACT
In the Ottawa area, unusually high amplification ratios have been recently measured in Leda Clays at low levels of earthquake-induced ground shaking. However, the contribution of seismic Q, or material damping (ξ=1/2Q), on the overall ground motion at soft soil sites across the city is not well understood. This research is contributing attenuation measurements in soft soils (Vs<250m/s) for ongoing seismic hazard evaluation in the Ottawa area. The work focuses on *in situ* measurements of damping in two deep boreholes drilled into Leda Clay. A new approach to the spectral ratio technique is developed for the measurement of Q in the field using a mono-frequency vibratory source, and two identical downhole 3-component geophones. Analysis of the data yield small strain Q's ranging from 40 (Damping 1.2%) to greater than 140 (or damping of <0.4%), and stratigraphy is found to be a significant factor controlling the *in situ* soil response.

RÉSUMÉ
Dans la région d'Ottawa, des taux d'amplification inhabituellement élevés ont été récemment mesures dans les Argiles de Leda lors de faibles tremblements de terre. Cependant la contribution du facteur sismique Q, ou de l'absorption de la matière (ξ=1/2Q), sur les sols non-consolidés dans la ville n'est pas bien comprise. Cette recherche contribue à la compréhension des mesures dans les sols non-consolidés (Vs<250m/s) pour des recherches en cours dans la région d'Ottawa. Une nouvelle approche pour la méthode de rapport spectral est mise au point afin de mesurer le facteur Q sur le terrain, au moyen d'une source de vibrations monofréquence et de deux géophones identiques à trois composantes au fond des trous. L'analyse des données révèle des facteurs de Q de faible déformation allant de 40 (amortissement de 1,2 %) à plus de 140 (ou amortissement d'environ 0,4 %). Elle indique en outre que la stratigraphie est un facteur important qui régit la réponse du sol *in situ*.

1 INTRODUCTION

When earthquake waves reach the near surface, the presence of soft soil over bedrock tends to amplify ground shaking. Current 2005 National Building Code of Canada guidelines recommend average shear wave velocity measurements to a depth of 30 m (Vs_{30}) as a method of estimating amplification of seismic shaking (NRC, 2005). In 2009, the Geological Survey of Canada and Carleton University published a regional map of the Ottawa area showing the distribution of seismic site classifications across the city (Hunter et al, 2009, Hunter et al., 2010). These site classes (A - E) are used to assign a spectral amplification factor to the predicted spectral accelerations at a site based on the local site conditions.

In the Ottawa area, data collected during weak motion (M2-3) earthquakes at seismograph stations founded on rock and nearby soil sites have produced horizontal/vertical (H/V) component spectral ratios of 80^+ times at site resonant frequencies, well above expected amplification values. However, the level at which damping at low strains contributes to the attenuation of seismic waves is not well understood in the Ottawa area soils. The effects of intrinsic wave attenuation (also named seismic Q, or damping, ξ, where Q=1/2ξ) in rock have been of interest for many decades and the subject of study both in lab and *in situ*. While the effect of Q in near surface soft soils (Vs<250 m/s) has received less attention, it has important implications in the field of seismic hazard studies. Structures founded on soils with periods close to that of the soil may undergo more intense shaking due to a quasi-resonance set up between structure and soil. This building-soil interaction is important because the 2005 NBCC amplification factors may not be sufficiently high at the resonance period of a site (Canadian Geotechnical Society, 2006). This makes attenuation in soils a particularly important property to understand, as the resonance effect in soft soils will be more long lasting if soil dissipation of waves trapped in the near surface is low. Since most economic structures are built on unconsolidated sediments (i.e., soils), the determination of Q is an important physical property in the prevention of potential site hazards from earthquake seismic loading.

In a joint project undertaken by the Geological Survey of Canada (GSC) and Carleton University, low-strain dynamic properties of Leda Clay were tested by applying new and traditional approaches to damping (or seismic Q) and shear wave velocity measurements in the field.

In situ testing in two deep Leda Clay boreholes as shown in Figure 1 (BH-GSC-JSR-01: drilled to 96m, and BH-AR93-1: 54m) within the City of Ottawa was carried out in 2009 using a monofrequency Minivib seismic source over a frequency band of 10-120Hz, and two identical downhole triaxial geophones. Soil property data and downhole geophysical logs previously collected in the boreholes assisted in the selection of test intervals ranging from 15m to 60m wide. Monofrequency seismic signals were processed with a spectral ratio approach and found to produce superior results to traditional broad band spectral ratio methods and time domain methods.

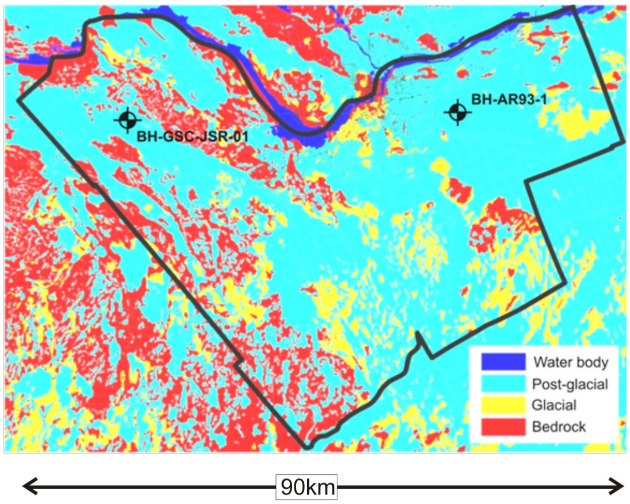

Figure 1. Simplified surficial geology map showing the locations of deep Leda Clay boreholes within the Regional Municipality of Ottawa-Carleton (black outline). Post-glacial soils (blue) are primarily the soft Champlain Sea deposits, termed Leda Clays.

2 PROCESSING APPROACHES

Numerous processing approaches have been developed to extract damping (or seismic Q) estimates from downhole seismic data in the time or frequency domains. Tonn (1991) reported on ten techniques of Q estimation in rock and compared them using synthetic seismograms of varying noise levels. Today, time domain approaches have largely fallen out of favour versus frequency domain techniques because time domain methods require true amplitude recordings. To this day, the spectral ratio method, and variations thereon, remain among the most popular techniques for Q estimation. For this research, the spectral ratio method in the frequency domain is compared with the pulse broadening time domain approach.

2.1 Pulse Broadening

The time-domain pulse broadening approach is based on changes in the shape of the first arrival at increasing distances from a source. The rate at which a signal reaches its peak depends on frequency content, and changes in signal shape can therefore be associated with the amount of loss in the signal. The shape of the first arrival pulse is characterized by its rise time (Gladwin & Stacey, 1974) and pulse width (Ricker, 1953); see Figure 2. The advantage of the pulse broadening approach is the short length of first arrival signal required, which is relatively free of other interfering waveforms.

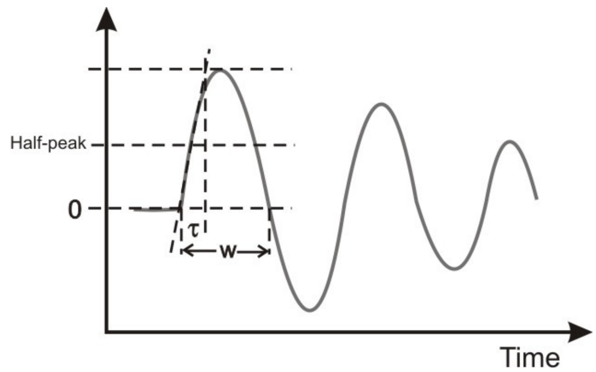

Figure 2. Definition of rise time (τ) and pulse width (w) on a seismic pulse. Pulse width is measured between two zero crossings. The first is found by a linear fit of the rising slope of the first arrival at the half peak, and the second is measured where the wavelet crosses the zero axis after the first peak. To assess pulse broadening, the first arrival pulse widths are measured from broad band downhole seismic survey data.

The method is based on the assumption that the broadening effect is due to anelastic attenuation, and that Q is approximately frequency-independent. As proposed by Gladwin and Stacy (1974) and Kjartansson (1979), the broadening is proportional to the travel time, t, and can be used to calculate Q using the equation

$$w = \left(\frac{C}{Q}\right) t + w_o \quad [1]$$

where w is the pulse width at an arbitrary depth and w_o is the width at the source. Equation 1 is simply a linear relationship between travel time and pulse width, with the C/Q term as its slope.

2.2 Spectral Ratio

The spectral ratio method, developed by Redpath (1982) and furthered by others (e.g. Badri & Mooney, 1987; Tonn, 1991; Gibbs et al, 1994), calculates a constant-Q value based on the observed amplitude attenuation in the frequency domain between two geophones placed a distance apart.

Numerous derivations exist for the approach, but in general terms, the spectral amplitude of a wave, A, at a distance R from the source at frequency, f, can be thought of as the product of

$$A(R,f) = S(R,f)C(R,f)W(R,f)\frac{1}{G(R)}e^{-\alpha R} \quad [2]$$

where S is a source term, C describes the coupling of the geophone to the casing, and the casing to the surrounding formation, and W accounts for distortions due to wave propagation (scattering, etc). The G factor accounts for geometric spreading (i.e. 1/R) and changes in amplitude due to variations in impedance (layering) along the ray path (Gibbs et al, 1994). This expression forms the Fourier domain equivalent of the equation for anelastic energy loss

$$A = \frac{A_o}{R} e^{-\alpha R}$$
[3]

Dividing A_1 (near position) into A_2 (far position) forms the general equation for the spectral ratio approach

$$ln\frac{A_2}{A_1} = \frac{\pi \Delta R}{QsVs} f + ln\frac{G_1}{G_2}$$
[4]

where [4] is an equation of linear form (y=mx+b). This allows us to calculate Q from the slope of the natural logarithm of the ratio of the spectral amplitudes, where

$$m = \frac{\pi \Delta R}{QsVs}\ or,\ Qs = \frac{\pi \Delta R}{mVs}$$
[5]

The effect of the geometric spreading term is accounted for as the intercept of the trend at f≈0Hz. A linear plot of ln(A2/A1) vs. f indicates that Q is constant, while a non-linear plot shows that the assumption of constant Q is incorrect. It has been observed in this study that the inherent point scatter in the ln(A2/A1) vs. frequency plot makes the interpretation of a linear or non-linear plot subjective in traditional broad-band spectral ratio approaches.

The approach used in this study does not modify the basic spectral ratio calculations, but uses monochromatic signals, rather than a broad band source, to better observe amplitude attenuation in narrow frequency bands in the Leda Clay. Advantages of this approach include lengthening of the pulse time to improve the point density in the frequency domain, which significantly reduces the data point scatter in the amplitude ratio plots, thereby improving the estimate of Q.

3 FIELD WORK

Field data were acquired at the two borehole sites during the summer and fall of 2009. Nine depth intervals were targeted, bracketing 15 to 60 meter lengths. The intervals were chosen based on a review of the soil property data from geotechnical testing and downhole geophysical logs.

The downhole instruments chosen for this survey contained three geophone elements oriented vertically (V) and horizontally in the longitudinal (H1) and transverse (H2) orientations. Two tools were deployed in the borehole during the surveys: one clamped as a reference, and a second positioned at varying deeper positions in the borehole (Figure 3). Calibrations of the geophones in each tool were carried out to confirm the measured amplitudes were within the manufacturer's specified range of ±5%.

The GSC's low-impact vibrating Minivib seismic source is manufactured by Industrial Vehicles Inc. (IVI) of Houston, TX, and can be operated in both P- (vertical) and SH- (horizontal shear) modes. Vibrating sweeps are programmable in time (seconds) and frequency (10-550Hz). For these Q surveys, the Minivib was operated in a monofrequency mode, which is not standard operating procedure for collection of seismic profile data. A Geode seismograph mounted inside the Minivib buggy was used to record the 7 channels of data – three from each downhole tool, and the pilot trace input by the Minivib.

The experimental frequency band ranged from 10Hz to 100Hz. While it is of interest to experiment at frequencies as low as 0.1Hz, the Minivib source is not capable of vibrating at frequencies below 5Hz. On the upper end, 100Hz is considered well beyond the uppermost limit of damaging earthquake energy, but was used to collect enough data to look at velocity and attenuation trends with increasing frequency over an order of magnitude. Sample results from GSC-BH-JSR-01 are shown in Figures 4 and 5.

A monochromatic approach benefits from a longer time series, as the Minivib can be configured to set up a steady state signal for a desired length of time with tapers on either end. This allowed for the windowing of several cycles of the signal, and to choose zero crossings as window start and end points. The proper balance between signal length in the time domain and signal amplitude in the frequency domain was found through experimentation, and a one second monofrequency pulse was used for the input signal.

A consideration with this approach, however, must be that a longer time signal could experience interference (or amplitude distortion) from later reflections from the bedrock and glacial layers. As discussed by Spencer et al. (1982), reflections from significant stratigraphic horizons between or below the upper and lower geophones can constructively or destructively influence the amplitude of the measured pulses. Determining whether reflection amplitudes would interfere with a one second pulse was carried out by analyzing a dataset of impulsive wavelets versus time in the boreholes tested. It was verified for this geologic situation that the amplitudes of the returning reflections traveling upward would not interfere significantly with the amplitudes of the direct waves traveling downward. Details of this analysis can be found in Crow (2010).

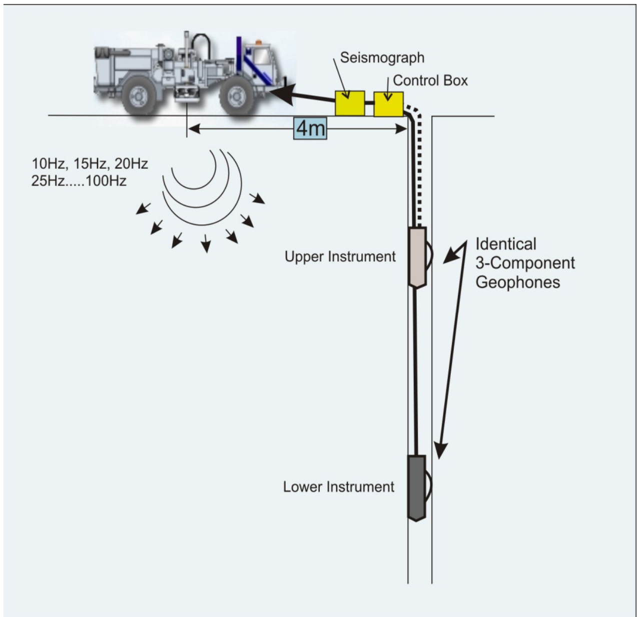

Figure 3. Schematic of the two-instrument testing configuration and the vibrating source (Minivib). The upper instrument was clamped in place and provided a reference, while the lower instrument was moved in the hole to various positions, bracketing zones of varying geotechnical properties. The control box and the seismograph were connected to a computer in the Minivib which controlled the input signal and recorded data.

4 ANALYSIS AND RESULTS

4.1 Spectral Ratio

To carry out the spectral ratio processing, the time domain horizontal components (H1 & H2) from the upper and lower tools were imported into Signal Analyzer software (developed by Dew Research Inc.) one frequency interval at a time. The signals were filtered (as necessary for 10Hz & 15Hz signals), windowed, and truncated at zero crossings. Signals were then converted to the frequency domain using a Fourier transform, and exported. The root mean square (RMS) value of the spectral amplitudes of the H1 and H2 components were calculated for each tool at each frequency and plotted at 5Hz intervals, as shown in Figures 4b and 5b. Using an RMS value accounts for any misalignment of the compasses between the two downhole tools, and any rotation of the waveforms which occurred during transmission.

The ratio of the peak of the lower to upper component was computed and shown in the figures over each frequency peak. The natural logarithm of the ratios were then computed and plotted against frequency. Using a least squares regression, the slope of the values is determined and Q can be calculated from this value using Equation 5. The average velocity over that interval, Vs, used in the calculations is derived from the downhole shear wave logs previously collected in each borehole (e.g. Fig. 4a).

If the spectral amplitudes of the pulses decrease with frequency but the ratios between lower and upper frequencies vary linearly, we would have evidence that damping was remaining (nearly) constant while the attenuation increased with frequency. However, if the ratios varied non-linearly with frequency, we'd have evidence for a frequency-dependant damping. If the ratios remained almost constant, damping would be low. In Figure 4a, the soil within the 30m-50m interval is quite homogenous and varies very little in grainsize or porosity. The figure displays the amplitudes of the monofrequency pulses in the frequency domain of the upper (30m) and lower (50m) geophones (Fig. 4b). The ratios of these peaks are calculated and the natural logarithms of the ratios ($Ln(A_2:A_1)$) are plotted against frequency (Fig. 4c). The slope of these points is used to calculate Q (or ξ).

Figure 5 presents the results from the monofrequency tests in the test interval between 20m – 30m. Across this depth interval (Fig. 5c) damping is relatively low (0.3%, Q~162) for wavelengths ($\lambda = v/f$) greater than 3m (10-60Hz), but at frequencies greater than 60Hz a significant change in damping behaviour is observed (damping of 1.23%, Q~41). Borehole geophysical logs, seismic reflection data, and core logs reveal that sediment textural changes occur in this interval of overburden at meter and sub-meter scales. At the deeper test intervals within the borehole, the soil has fewer visible textual variations and no prominent reflections, and the damping remains fairly constant (0.2% to 0.4%) across the 10-100Hz frequency band. These results indicate a strong stratigraphic influence on the damping values in the upper soil column.

Figure 6 presents a comparison of the spectral ratio technique using broadband and monofrequency signals in BH-GSC-JSR-01. In the traditional spectral ratio approach, taking ratios in frequency bands where little energy exists produces erratic or scattered values, as very small numbers are being divided by very small numbers. With the monofrequency approach, discrete frequency bands are transmitted into the soil, permitting us to observe the relative amplitude decay between two downhole tools, even though the measured amplitudes are decreasing with increasing frequency. Although the three approaches produce a similar linear fit through the data, the uncertainty is significantly reduced, and observations on the change of relative amplitude reduction vs. frequency can be made more confidently

4.2 Pulse Broadening

The dataset used for the pulse broadening calculations in BH-GSC-JSR-01 was a downhole shear wave dataset previously collected using the GSC's Minivib vibratory source using a swept frequency input signal from 20Hz-300Hz. The Minivib mass was in shear horizontal (SH) mode and readings were collected at 0.5m increments up the borehole using a triaxial downhole tool.

The results from the pulse broadening dataset reveal very slight broadening of the pulse over the borehole depth, which also indicates very little damping, or elevated Q's (Figure 7). The analysis of the dataset shows a downshift of 2Hz (from 44Hz at the top of the borehole to 42Hz at the base), corresponding to a Q of greater than 200, or a damping of less than 0.25%. Slight fluctuation of the trend between 25-35m likely indicates the pulse shape has been influenced by the stratigraphy/soil conditions. Although the time domain approach indicates a damping level even lower than the frequency domain approach, (perhaps even below the detection limit of the approach), the two methods confirm that the losses in the soil at low strains are quite small.

5 SUMMARY AND CONCLUSIONS

Field research into a new approach for spectral ratio calculation has produced a technique using monochromatic signals which greatly reduces the uncertainty encountered in the traditional broad band approach. This technique allows the interpreter to observe the relative attenuation of a single frequency signal between two geophones, thereby allowing better conclusions to be drawn about the frequency dependence of damping *in situ*, and about the overall shape of the amplitude reduction with frequency over the frequency band tested.

In intervals of massive clayey silt, results show damping levels ranging from 0.2 to 0.4%, indicating that Leda Clays can be a very low-loss material at low strains. Results also suggest negligible frequency-dependence of damping between 10Hz and 100Hz within the homogenous soil zones tested. Within intervals containing layered rhythmite (1-2cm laminated) deposits, damping remained below 0.4% between 10-65Hz, but was observed to increase to 1.2% at frequencies greater than 70Hz. This is attributed to interaction of seismic waves with deposits of package thickness of 3m and less, where slight variation of grain size and porosity occur between units. While interference from stratigraphic effects does cause an increase in damping, it occurred at frequencies higher than would be of concern from earthquake-derived ground motions.

These results indicate that in addition to inherent soil properties (grain size, mineralogy, void ratio, age) and external forces (confining pressure and strain amplitude) which control the dynamic properties of the soil, *in situ* tests identify 'large-scale' geologic features which may not be observed on the sample scale. Well controlled in situ testing can therefore reveal important properties of the soil mass which are not observable from borehole samples.

The elevated amplification ratios observed during frequent low magnitude earthquakes (M2-3) in the Ottawa area can be explained in part due to the low levels of damping. Resonance effects set up within the soft soil are therefore able to 'ring' for longer lengths of time than would be expected in soils with greater damping characteristics.

These studies form a base for ongoing research into *in situ* damping measurements using vibratory sources at the GSC. Current research is comparing these field results with lab testing. Future areas of research include resonant column (RC) and non-resonant column (NR) procedures (Khan et al. (2008), Lai et al. (2001)) and ongoing field testing.

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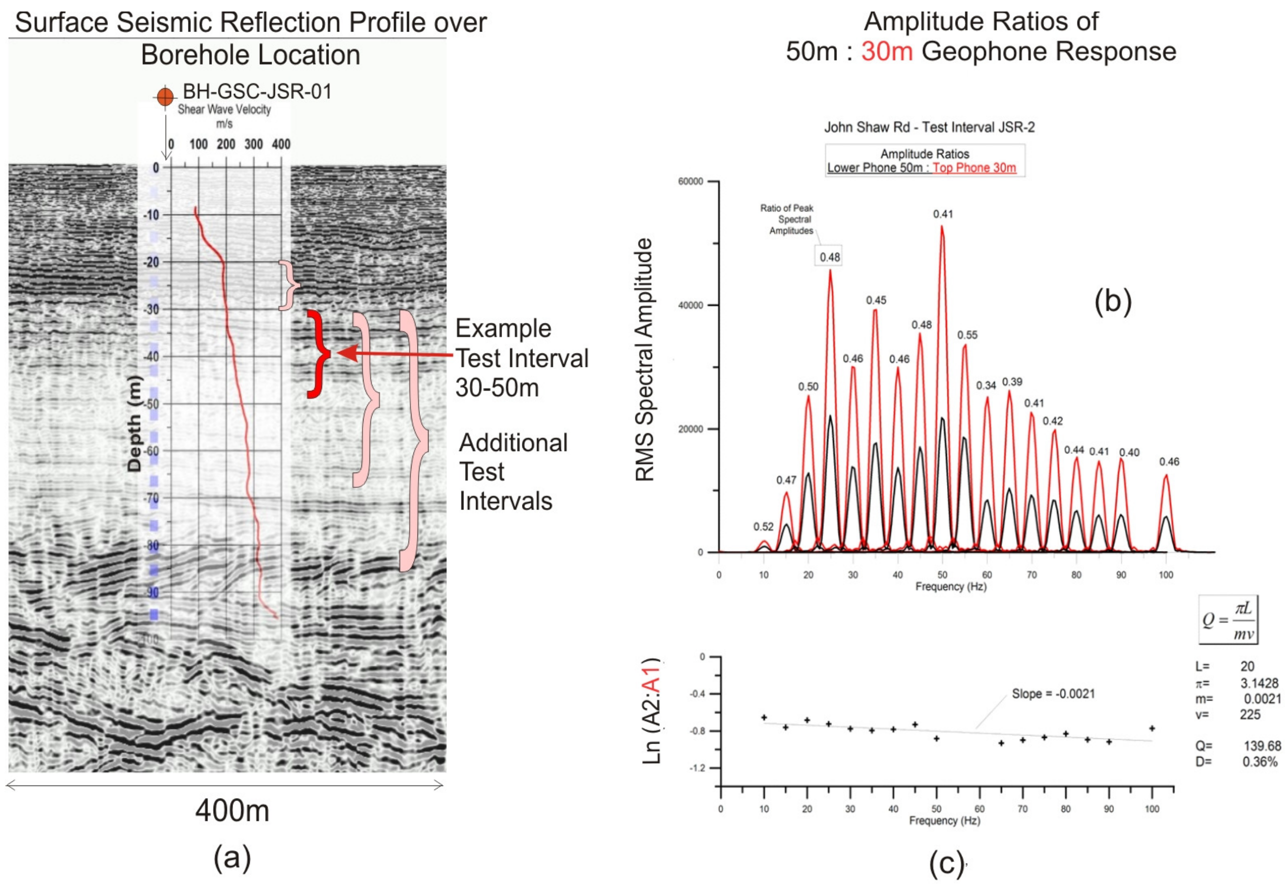

Figure 4. Measurement of damping using the monofrequency spectral ratio method, showing little interpretable variation of damping with frequency between 10Hz-100Hz. a) 400m section of a high-resolution seismic reflection profile acquired by the GSC passing over the 96m JSR borehole. Superimposed on the seismic section is a plot of shear wave interval velocities down the borehole. The soil between 30m and 80m is characterized by few reflections and is a fairly homogenous silt (70%) and clay (30%) based on grain size measurements. b) Results of the monofrequency tests in this interval between 30 and 50m. c) Using the spectral ratio processing approach, the natural logarithm of the spectral ratio of the lower to upper geophone (Ln(A2:A1)) is plotted against frequency. The slope of these points is used to calculate a damping value of 0.4%.

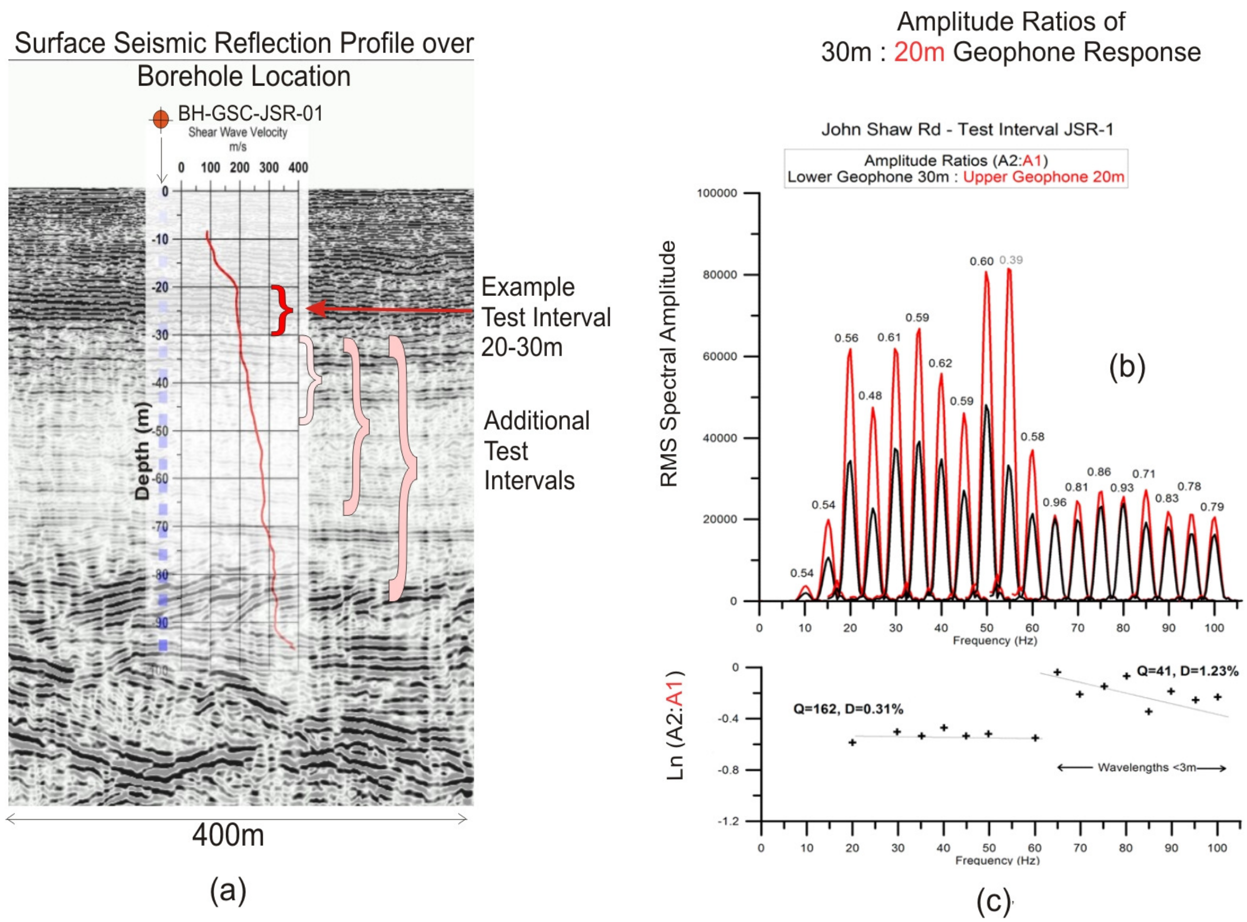

Figure 5. Evidence of frequency-dependant damping within 10-100Hz. a) Fig 4a but in this case highlighting the example test interval from 20-30 m depth. Note the density of reflections observed within this test interval. b) Results of the monofrequency tests over this interval. Beyond 60Hz, the signal attenuates significantly, corresponding to wavelengths <3m. c) Using the spectral ratio processing approach, the natural logarithm of the spectral ratio of the lower to upper geophone (Ln(A2:A1)) is plotted against frequency, and shows two distinct groups of points. The slope of these points is used to calculate damping.

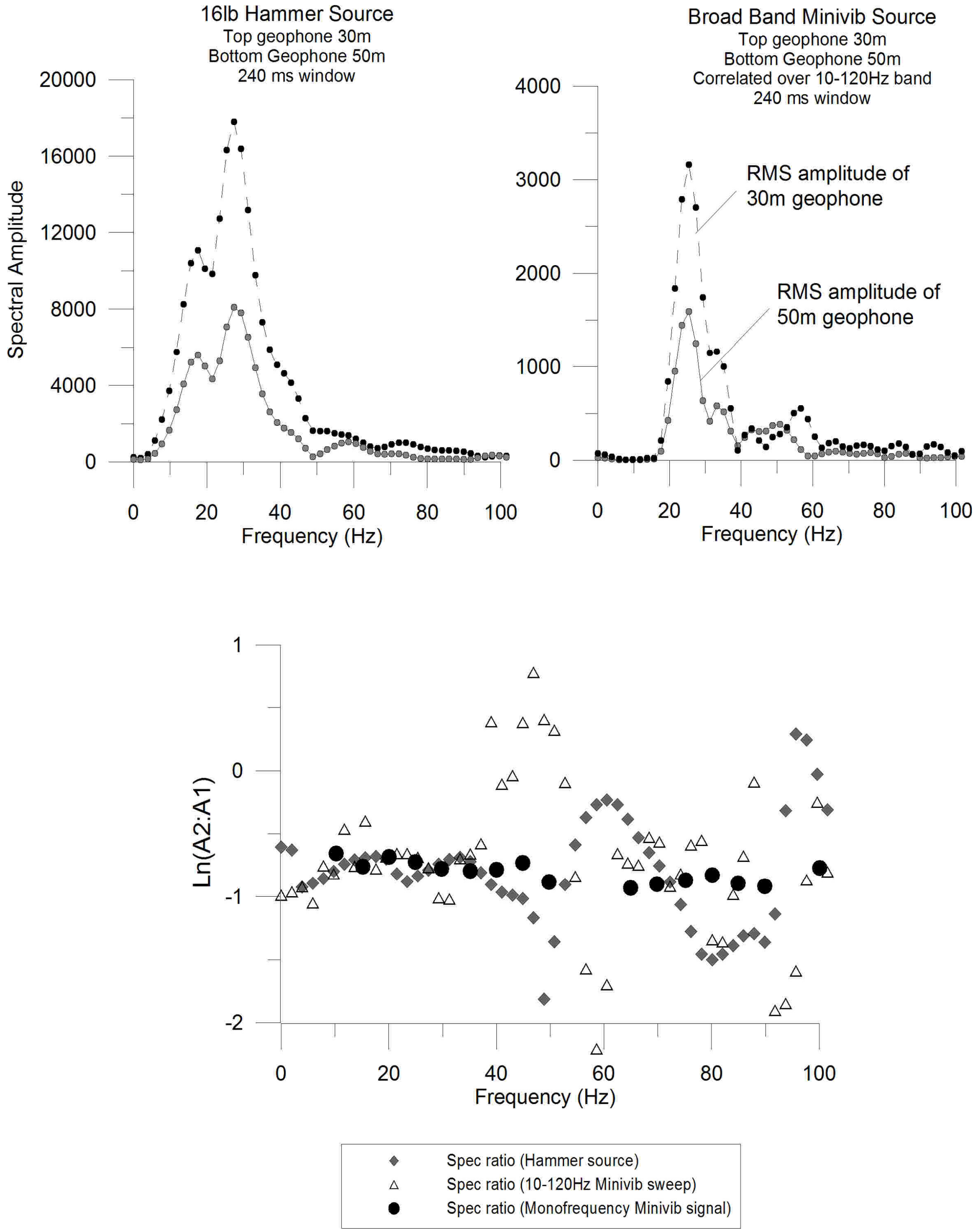

Figure 6. Improved frequency testing range with the monofrequency spectral ratio approach. The top panel shows the spectral amplitudes of horizontal shear wave (SH) energy reaching 30m and 50m geophones. The amplitudes represent an RMS value of the H1 and H2 components. The lower panel shows the natural logarithm of the spectral ratios for the broad band and monochromatic approaches. The monochromatic approach produces less data point scatter due to the discrete energy pulses at narrow frequency ranges.

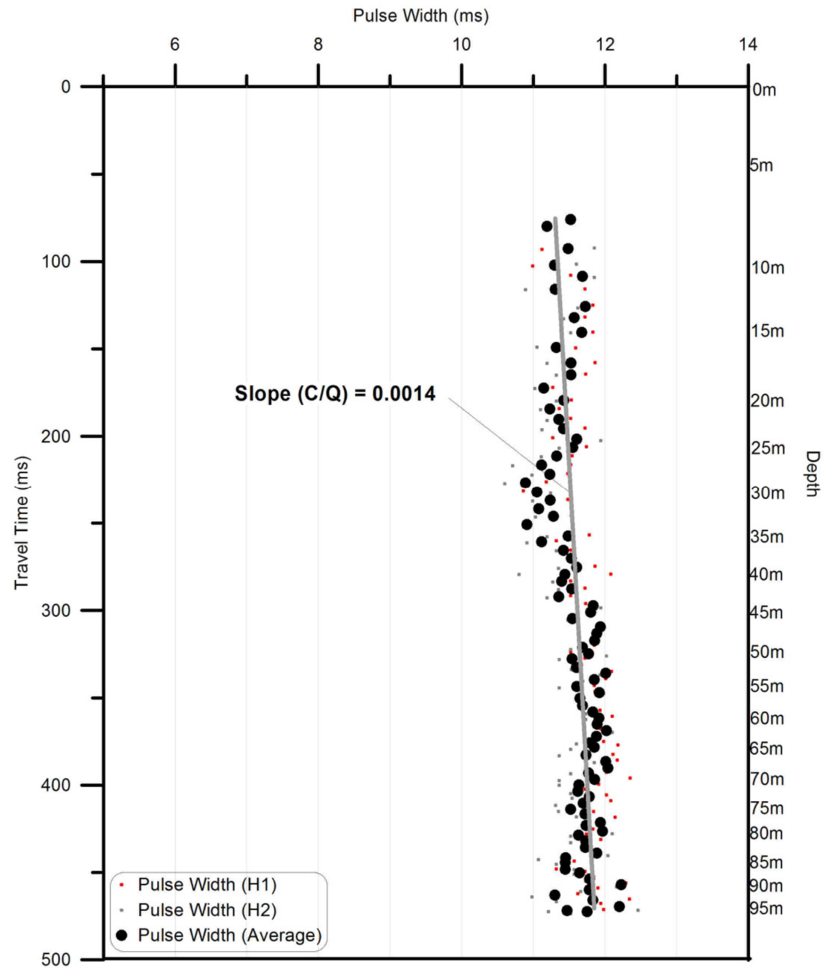

Figure 7. Variation of pulse width over the length of the JSR borehole using the pulse broadening approach. The trend indicates a gradual 0.5ms widening of the shear pulse between 10m and 95m, equivalent to a loss of approximately 2Hz over the entire borehole. These results indicate there is very little energy lost to anelastic attenuation in these soils.

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