Evaluating the Frequency Dependence of Dynamic Soil Properties in Leda Clays

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ABSTRACT

In Ottawa, Ontario, unusually high amplification ratios have been measured in clayey silts ('Leda Clays') at low levels of earthquake-induced ground shaking. However, the contribution of material damping to the overall ground motion at soft soil sites across the city is not well understood. Therefore, low-strain dynamic properties (shear wave velocity and damping characteristics) of Leda Clays were tested in the field and through lab analyses using new and traditional approaches. Downhole seismic testing was carried out in two deep Leda Clay boreholes in the Ottawa area (96m, 54m) using monofrequency seismic signals between 10-100Hz, and two identical downhole triaxial geophones. Interval damping levels ranged from 0.2% to 0.4% between 30m and 90m depth. This indicates that in relatively homogenous Champlain Sea deposits, very little elastic energy is lost at low strains, which contributes significantly to the observed elevated amplifications experienced during small strain earthquakes in the Ottawa area. These results were compared with low-strain laboratory testing carried out on Leda Clay samples using the newly developed non-resonant (NR) approach at the University of Waterloo. The NR method evaluates the frequency dependence of damping and shear wave velocity (Vs) at various strain levels. Ongoing geotechnical research is now evaluating the frequency dependence of dynamic soil properties in Leda Clays at higher strains using the NR technique. These combined results will provide important soil parameters for ground response analyses at soft soil sites in Eastern Canada.

RÉSUMÉ

À Ottawa, en Ontario, des coefficients d'amplification inhabituellement élevés ont été mesurés dans des silts argileux ('argiles à Leda') lors de secousses de faible intensité provoquées par un séisme. Cependant, la contribution des matériaux à l'amortissement des secousses sismiques dans des sols meubles, à divers endroits de la ville, n'est pas bien comprise. Par conséquent, les propriétés dynamiques à faible contrainte (vitesse des ondes de cisaillement et caractéristiques d'amortissement) des argiles à Leda ont été testées sur le terrain et par des analyses en laboratoire au moyen de méthodes nouvelles et classiques. Des essais sismiques ont été effectués dans deux puits profonds (96 m, 54 m) dans de l'argile à Leda, dans la région d'Ottawa, en utilisant des signaux sismiques à fréquence unique entre 10 et 100 Hz, ainsi que deux géophones triaxiaux identiques en puits. Les niveaux d'amortissement des intervalles variaient de 0,2 % à 0,4 % à des profondeurs entre 30 m et 90 m. Cela indique que, dans les dépôts relativement homogènes de la Mer de Champlain, très peu d'énergie élastique est perdue dans des conditions de faible contrainte, ce qui contribue de façon importante aux amplifications élevées observées pendant des séismes à faible contrainte dans la région d'Ottawa. Ces résultats ont été comparés à des essais en laboratoire à faible contrainte effectués sur des échantillons d'argile à Leda, au moyen d'une approche de non-résonance (NR) récemment mise au point à l'Université de Waterloo. Cette méthode permet d'évaluer les variations de l'amortissement et de la vitesse des ondes de cisaillement (Vs) en fonction de la fréquence, à divers niveaux de contrainte. Des recherches géotechniques en cours portent sur l'évaluation de la dépendance des propriétés dynamiques du sol en fonction de la fréquence dans des argiles à Leda soumises à de plus grandes contraintes, en utilisant la méthode de non-résonance. Ces résultats combinés fourniront d'importants paramètres du sol en vue d'analyser le comportement des sols meubles à divers endroits de l'Est canadien.

1 INTRODUCTION

Within the St. Lawrence Lowlands, post-glacial clayey-silts (known as 'Leda Clays') were deposited by the Champlain Sea approximately 10 000 years ago. In the City of Ottawa, these soft soils make up 65% of the surficial deposits within the municipal boundary, and are present in thicknesses of up to 150m in bedrock basins (Hunter et al., 2010). Data collected during weak motion (M2-3) earthquakes at seismograph stations founded on rock and nearby thick Leda Clay sites exhibit high levels of broad band spectral amplification (Figure 1). Horizontal/vertical (H/V) ratios from thick soil sites in the area can reach 80+ times at site resonant frequencies (Motazedian et al., 2010) during low-strain earthquakes. However, the contribution of material damping to the overall ground motion at soft soil sites across the city is not well understood.

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 double resonance effect set up between structure and soil. This building-soil interaction is important because the 2010 National Building Code of Canada (NBC, 2010) 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 their dynamic properties (damping, shear wave velocity) is an important step in the prevention of potential site hazards from earthquake seismic loading. In a recent study evaluating the ability to model ground motions in soft soil basins, a structure of particular concern in Eastern Canada, soil damping was found to be a controlling factor in the behaviour of surface ground motions (Gelagoti, 2010).

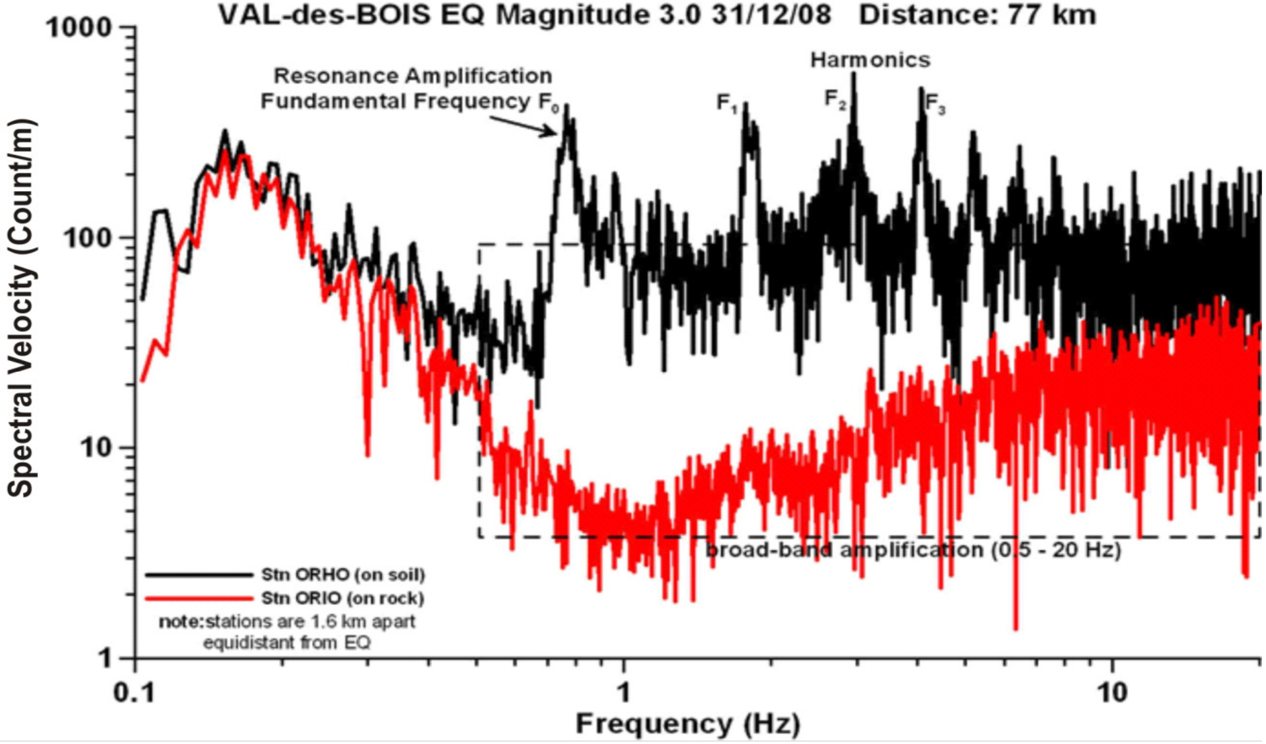


Figure 1. A comparison of horizontal spectral components from a thick soil site (black) and nearby rock site (red) showing broadband and resonance amplification in soil resulting from a M3.0 earthquake.

To investigate these soil properties in the Ottawa area, a ‘monofrequency’ *in situ* testing method for assessment of low-strain dynamic properties was developed by the Geological Survey of Canada (GSC) and Carleton University in 2009-2010. This method provided high-reliability low strain velocity and damping benchmarks in a natural state of consolidation for future higher strain laboratory testing. During this time, the feasibility of testing silty-clayey soil samples in a newly developed laboratory testing apparatus (called a non-resonant (NR) column) at the University of Waterloo was also investigated, where velocity and damping are calculated as a function of strain and frequency. Methodology and sample results from these investigations are summarised in this paper.

IN SITU LOW-STRAIN DYNAMIC TESTING

Research carried out by the GSC and Carleton University in 2009-2010 led to the development of a new *in situ* low-strain damping measurement technique, termed ‘monofrequency spectral ratio’. The testing was carried out using two identical downhole triaxial geophones and a Minivib seismic source. The source was vibrated horizontally, one frequency at a time, over a frequency band of 10-120Hz. The low-strain damping ratio was measured by comparing the reduction in spectral amplitude of the upper to lower geophone across the frequency test band. Analysis of these data found that a monofrequency approach produced superior results to traditional broad band spectral ratio methods and time domain methods (pulse broadening). The field testing was considered to be important because the ability to measure low-strain dynamic properties in the laboratory is compromised by even slight sample disturbance. In addition, downhole testing allows us to bracket intervals of a few to several tens of meters, allowing us to infer how damping and shear wave velocity vary with changes in soil properties over a larger scale than laboratory samples will permit (e.g. porosity, density, grain size, age, etc.). Details of these tests have been reported in Crow et al. (2011) and Crow (2010).

Field Work

Field data were acquired in 2009 at two boreholes (96m, 54m) in Ottawa which intersected thick sequences of Leda Clay. Nine depth ranges were targeted, bracketing 10 to 60 meter depth intervals. The downhole geophone spacings were chosen to bracket soils of varying properties based on a review of data from geotechnical testing (porosity, undisturbed and remoulded shear strength, and grain size) and downhole geophysical logs (natural gamma, conductivity, magnetic susceptibility, and shear wave velocity). These data are collated by Crow (2010) and Medioli et al. (2011).

The two downhole instruments used in this survey contained three identical 15Hz block-mounted geophone elements oriented vertically (V) and horizontally in the longitudinal (H1) and transverse (H2) orientations. Calibrations of the geophones in each instrument were carried out to confirm that the measured amplitudes were within the manufacturer's specified range of ±5%. The tool has a motor-driven bowspring clamping arm which can be extended using a control console at surface when the tool is lowered to a desired measurement depth. Each tool contains a fluxgate magnetometer and a rotating motor to orient the geophone block's H1 component in-line with magnetic north after the tool is clamped. The tools were deployed in the boreholes as shown in Figure 2.

The GSC's low-impact vibrating Minivib seismic source, manufactured by Industrial Vehicles Inc. (IVI), 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 surveys, the Minivib was configured to produce horizontal shear motion (SH) with a ground force of 2000 lb/ft^2 (9800 kg-force/m^2), and operated in a monofrequency mode, which is not standard operating procedure for collection of seismic profile data. While it would be of interest to experiment at frequencies as low as 0.1Hz for earthquake engineering studies, the Minivib source is not capable of vibrating at frequencies below 10Hz. In this geological environment, SH energy is significantly attenuated beyond 110Hz, therefore, the high frequency cut off for these field tests was set at 100Hz. Although 100Hz is considered well beyond the uppermost limit of damaging earthquake energy, the frequency range of 10-100Hz (at monochromatic 5Hz increments) was used to collect enough data to look at attenuation trends over an order of magnitude. A Geode seismograph mounted inside the Minivib buggy was used to record 7 channels of data – three from each downhole tool and the pilot trace input by the Minivib. The seismograph was configured with a sampling rate of 0.125ms, or 8000 samples/sec. For each depth interval, the mass on the Minivib was rotated first to be in line with the H1 component of the downhole instruments, and then secondly, at 45°, evenly between the H1 and H2 components. This allowed for repeated testing to ensure that the calculation of damping and velocity was consistent no matter the source orientation for each test.

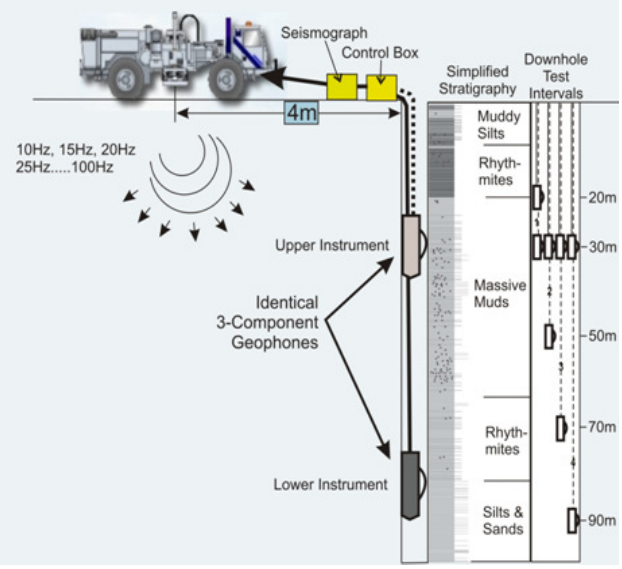


Figure 2. Schematic of the two-instrument testing configuration and the vibratory seismic source (Minivib) in one of the boreholes tested. The upper instrument was clamped in place and provided a reference, while the lower instrument was moved in the hole to various positions, bracketing zones of varying geotechnical properties. The simplified borehole stratigraphy is shown alongside the bracketed soil investigation intervals.

This 'monofrequency' approach benefits from a time series of longer duration and higher energy than an impulsive broadband wavelet, and therefore provides greater definition of the signal in the frequency domain. As the Minivib can be configured to set up a steady state signal for a desired length of time, several cycles can be windowed, and zero crossings can be chosen as window start and end points. A consideration with this approach, however, must be that a longer time signal could experience interference (or amplitude distortion) from later reflections from major impedance boundaries (here, bedrock and glacial layers). Reflections from significant stratigraphic horizons between or below the upper and lower geophones can constructively or destructively influence the amplitude of the measured pulses (Spencer et al., 1982). These factors influenced the length of pulse chosen for the input signal, and their effect was verified by inspecting a dataset of impulsive wavelets in the boreholes tested. Based on these analyses, it was decided that a one second monofrequency pulse gave adequate resolution in the frequency domain, but the amplitudes of the returning reflections traveling upward did not interfere significantly with the amplitudes of the direct waves traveling downward.

Data Processing – 'Monofrequency 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

$$A = \frac{A_0}{R}e^{-\alpha R} \quad [3]$$

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

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

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

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

The effect of the geometric spreading term is accounted for as the intercept of the trend at $f \approx 0$Hz. 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 monofrequency 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 increased energy content of the monofrequency signals versus typical broadband source techniques (e.g. hammer, Minivib sweep), and lengthening of the pulse time to improve the point density in the frequency domain. These factors significantly reduce the data point scatter in the amplitude ratio plots, thereby improving the estimate of Q.

To carry out the spectral ratio processing, the time domain horizontal components (H1 & H2) from the upper and lower tools for each monofrequency packet were filtered (as necessary for 10Hz & 15Hz signals), then windowed and truncated at zero crossings over the same portion of the signal (offset by the travel time distance between). Signals were then converted to the frequency domain using a Fourier transform (Figure 3), and 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 (Figure 4a). 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.

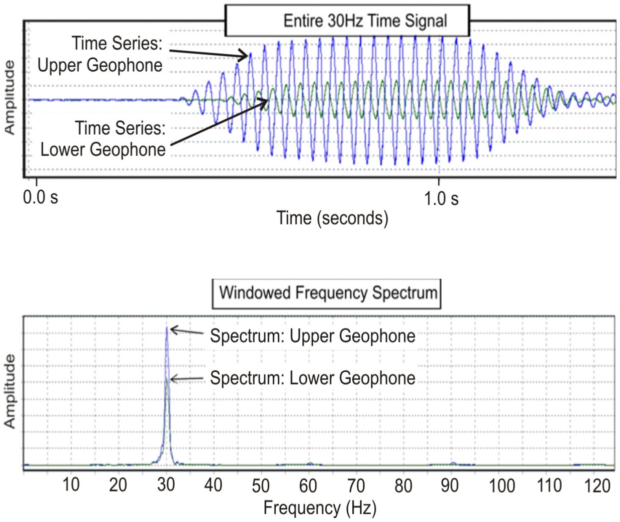
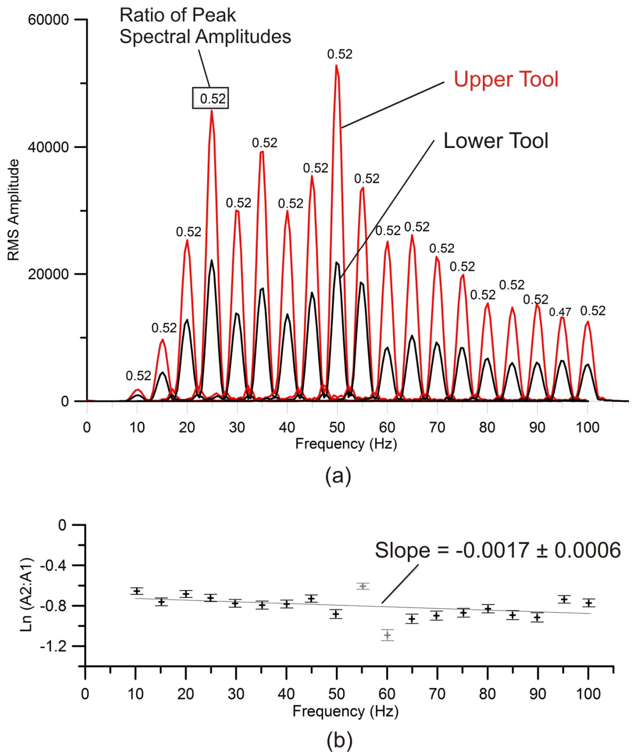


Figure 3. Upper panel shows 30Hz time signals received at upper and lower geophones. Bottom panel shows the resulting frequency spectrum of the signals.

The ratio of the peak of the lower to upper component was computed for each frequency. The natural logarithm (Ln) of the ratios were then computed and plotted against frequency. Using a least squares regression, the slope of the Ln(ratios) is determined and damping can be calculated from this value using [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 (Crow, 2010).

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.



(a)

(b)

Figure 4. Example of the in-situ testing results from one depth interval in the 96 m deep borehole in West Ottawa. (a) Composite plot of the upper (**30m**) and lower (**50m**) geophone spectral amplitudes from the monofrequency Minivib signals plotted at 5Hz intervals. The numbers above each peak indicate the spectral ratio of the lower to upper geophone. While variations in the peak heights are due to the frequency filtering effects of the ground itself or variations in the input signal strength, the ratios at the center frequency remain fairly consistent. (b) The natural logarithm of the ratios from (a) are plotted against frequency. The slope value of the trend is used in the calculation of damping (or Q). The slight decrease in the slope indicates there is very little amplitude loss due to intrinsic attenuation across the 10-100Hz frequency band (damping=0.30±0.11%). Numbers in grey indicate noise interference from the Minivib motor vibration. These ratios were removed from slope calculations.

In Figure 4a, the soil within the 30m-50m interval is quite homogenous and varies 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. The ratios of these peaks were calculated and the natural logarithms of the ratios ($Ln(A_2:A_1)$) are plotted against frequency (Figure 4b). The slope of these points was used to calculate a damping ratio of 0.30 ±0.11%. Similar and fairly constant damping values (0.2% to 0.4%) were observed across the 10-100Hz frequency band for all the deeper test intervals in this borehole (West Ottawa).

Similar tests carried out in intervals of increased porosity at shallower depths in the borehole indicate that damping is relatively low (0.3%) for wavelengths ($\lambda=v/f$) greater than 3m (10-60Hz), but at frequencies greater than 60Hz an increase in damping (to 0.60%) is observed. Borehole geophysical logs, seismic reflection data, and core logs reveal that sediment textural changes occur in this shallower interval at meter and sub-meter scales. An advantage of *in situ* testing is that these changes in soil properties which occur on a large (meter +) scale would not have been seen at the smaller sample (cm) scale.

The monofrequency method was compared to traditional broadband techniques using data acquired with a hammer source and correlated Minivib data in the same borehole (Figure 5). In the traditional spectral ratio approach, taking ratios in frequency bands where little energy exists produces erratic or scattered values. With the monofrequency approach, discrete, user-selected, frequency bands with higher energy content are transmitted into the soil, permitting observation of the relative amplitude decay between two downhole tools, even though the measured amplitudes are decreasing with increasing frequency. As can be observed from the data plot, the scatter in the data points is significantly reduced with the monofrequency method, producing a slope of greatly reduced error and therefore a damping ratio with a smaller margin of error. This is also achieved over a larger frequency band than can be realized with impulsive sources.

HIGH-STRAIN DYNAMIC LABORATORY TESTING

As most surface vibratory sources cannot induce even moderate strain levels in the ground at more than a few meters from the source (Menq et al., 2010), higher-strain dynamic properties of subsurface materials must be tested in the laboratory using carefully extracted (undisturbed) samples. The resonant column (RC) apparatus traditionally used for these tests vibrates a cylindrical sample of soil in first mode torsional resonance. Shear wave velocity and damping ratio are computed separately by solving the equation of motion for a column mass system (ASTM D4015-92 2000). Dynamic soil properties are therefore evaluated at the resonant frequency of the sample. This resonant frequency is dependent on the sample material, dimensions of the sample, and the conditions of end restraint, and is generally greater than 20Hz in standard (76mm diameter x 144mm length) samples.

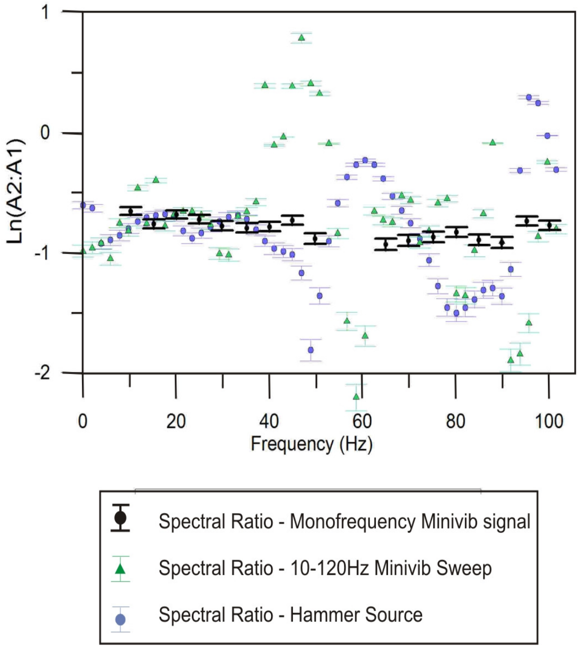


Figure 5. Comparison of the spectral ratio techniques using traditional broadband wavelets versus monofrequency signals. This plot shows the natural logarithm of the spectral ratios of the monofrequency method (black) along with those determined from the broadband wavelet method using both a hammer (blue) and Minivib (green) as the seismic source.

However, damping and velocity in a low frequency range (0.1-20Hz) is of interest in earthquake engineering for site assessment and prediction of earthquake-derived ground motions. Unfortunately, frequency-dependant properties of soils are difficult to measure with the RC device. Although a multi-frequency sweep is used in the RC test, the excitation voltage is constant, which results in varying shear strain levels imposed on the sample at the different frequency components of the signal. Also, the damping and velocity of the specimen are determined at the resonant frequency of the sample, which is generally higher than the frequency range of damaging earthquake motions.

Non-resonance (NR) methods have recently been developed to evaluate frequency-dependant soil properties in the resonant column device at different strain levels (Lai, et al. 2001, Khan, et al. 2008). The method is based on the solution to the equation of motion for the forced vibration of a cylindrical soil specimen which is assumed to be homogenous, continuous, and viscoelastic. An important aspect of the method is the assumption of a viscoelastic medium. In order to fulfill the principle of causality, a wave travelling in a viscoelastic medium at low strains must have a phase velocity and attenuation which satisfy the Kramers-Krönig equation. This states that the real and imaginary parts of a body wave's complex wave number are Hilbert transforms of one another, and are therefore not independent quantities (Lai et al. 2001). This principle forms the basis of the non-resonant method, and allows for the calculation of the shear wave velocity and the damping ratio simultaneously, as a function of frequency. Rix and Meng (2005) have applied non-resonant testing to a sandy silty clay sample and observed a slight dependence of damping and shear wave velocity within the earthquake band (0.01-10 Hz) at very low strains.

Until our Leda Clay testing program began in 2009, non-resonant testing had not been carried out on Leda Clay samples from Eastern Canada. Four soil samples from one of the Ottawa boreholes were taken to the University of Waterloo Civil Engineering lab to conduct preliminary RC and NR tests at low strains for comparison with the results of the *in situ* dynamic property tests. Figure 6 presents NR results from a sample extracted from 50m depth and tested at a strain level of 10^{-5}%. Within the frequency band of 65-85Hz, there is evidence that velocity and damping are slightly frequency dependent.

In comparison, the velocity measured *in situ* was 255 ± 1 m/s and damping between the interval of 30m and 50m was 0.30 ± 0.11% with little indication of frequency dependence. However, these in situ results were obtained from a strain of less than 10^{-6}%, so it is assumed that the slightly lower damping and higher velocity determined by the NR testing is related to the higher strains (10^{-5}%) applied in the lab. However, the samples may have been disturbed during coring, as they had not initially been intended for undisturbed testing.

These initial NR tests on Leda clay samples have been encouraging, and have led to updates to the NR system specifically for soft soil testing. An upcoming higher strain testing program will attempt to minimize sample disturbance through a program of careful Shelby tube sampling, and experimentation with varying sample diameters. As it is known that small levels of sample disturbance affect the low-strain results of laboratory tests, good agreement between lab and *in situ* results will indicate high quality samples have been obtained.

CONCLUSIONS AND UPCOMING WORK

The presence of soft soil ("Leda Clays") in regions of high seismic hazard in eastern Canada increases the risk of damage to structures due to amplified ground motion. However, little is known about these soils' high-strain dynamic properties and behaviour when subjected to damaging low-frequency earthquake waves (0.1-20Hz). In 2009, a study program of *in situ* and laboratory methods was initiated to investigate the low-strain properties of these soils and any potential frequency dependence. It was discovered that a monofrequency method of *in situ* damping measurements produced a

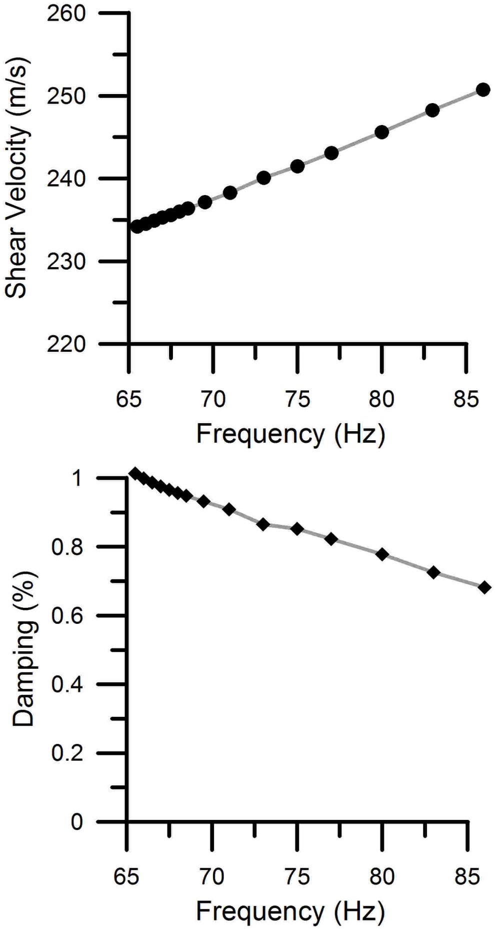


Figure 6. Preliminary results from Leda Clay tests in the non-resonant column (strain shown here=10^{-5}%).

more reliable damping estimate than traditional broadband methods, and that the non-resonant (NR) method of lab testing at similarly low strains produced comparable results. More importantly, the NR method has excellent potential for higher strain frequency-dependent testing in earthquake frequency ranges, providing undisturbed samples could be obtained. These results will prove useful to predict the levels of ground motion resulting from the local design earthquake.

The shear modulus and damping curves resulting from this and future work on Leda clay, both as a function of strain and frequency, will allow for more accurate nonlinear numerical modeling of earthquake hazards. These results could also be used for engineering applications to evaluate the response of structures to other forms of dynamic stresses, such as wind loading, blasting, and large machine vibration.

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