Surface Layer Thickness and Velocity Determined using the Multi Channel Analysis of Surface Waves (MASW) Method Compared with Microtremor Resonance Analysis-Federal Road, Greene County, Ohio

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Surface layer thickness and velocity determined using the Multi Channel Analysis of Surface Waves (MASW) method compared with microtremor resonance analysis – Federal Road, Greene County, Ohio.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science.

By

Daniel Robert Blake

B.A., The Ohio State University, 2009

2012

Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Daniel Robert Blake ENTITLED Surface layer thickness and velocity determined using the Multi Channel Analysis of Surface Waves (MASW) method compared with microtremor resonance analysis – Federal Road, Greene County, Ohio, BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT

Blake, Daniel D. M.’ M.S., Department of Earth and Environmental Sciences, Wright State University, 2012, Surface layer thickness and velocity determined using the Multi Channel Analysis of Surface Waves (MASW) method compared with microtremor resonance analysis – Federal Road, Greene County, Ohio.

Multi-Channel Analysis of Surface Waves (MASW) was performed on data collected at four locations previously occupied by 3-component broadband seismometers. The goal was to use MASW to define the velocity structure and depth to bedrock locally, and to examine how well the calculated surface layer resonance derived from this velocity structure compares with the surface layer resonance observed in the passive seismic data at that site. At the test site east of Xenia, Ohio, a clear change in lithology (glacial drift to limestone bedrock) on each of the 1-D MASW profiles is indicated by a substantial change in shear-wave velocity ($V_s$) at depth and is consistent with the depth to bedrock from water wells in the area. Both water wells and the MASW results indicate that depth to bedrock increases significantly to the east along Federal Rd toward a pre-glacial buried valley. The calculated resonant frequency of the glacial drift surface layer, using the fundamental mode equation, compares very well to the peak frequency expressed in the horizontal to vertical ratio (H/V) of passive seismometer data at the same locations. A clear and distinct surface layer resonance is evident in most passive seismic data of this study, although one seismometer station expressed a double
peak suggesting very local distinct variations in drift thickness such as expected at a bedrock ledge or a buried ravine or small valley. One practical conclusion of this study is that in settings of high velocity contrast between a surface layer and bedrock, where glacial drift overlies limestone bedrock, by determining the $V_s$ of the drift using MASW, one can use the H/V peak frequency of 3-component seismic data to calculate the regional depth to bedrock values in locations where $V_s$ is consistent.
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CHAPTER 1: INTRODUCTION

Project Objective

Broadband passive seismic observations over oil and gas reservoirs worldwide have been found to exhibit an anomalous vertical resonance in the 1-5Hz range (Saenger, 2009) although, the mechanism is still not understood (Graf, 2007). The frequency of this reported reservoir resonant signal resides in the range also observed of microtremors, which is a long-recognized resonance of \( V_s \) in the near-surface layer (Holzner, 2005). To try to recognize any reservoir resonance signal in a broadband data set one must first recognize what of the signal in the broadband data is related to the surface layer. This study uses the MASW (Multi-Channel Analysis of Surface Waves) method to define the thickness and shear-wave velocity structure of the glacial drift at sites along Federal Road in Greene County, Ohio, where ongoing studies have collected broadband passive seismic data near an exploratory oil well. The MASW results and passive data will determine what resonant microtremor signal exists within the broadband seismic data with the goal that the results can be used to guide the recognition of any reservoir resonance.

Geophysical Properties of Surface Waves

A surface wave only propagates in the near sub-surface layers and travels freely with amplitudes that decrease exponentially with depth as described in Reynolds (2011). The velocity of surface waves varies at depth; therefore surface waves of different
wavelengths are dispersive in nature. The maximum and minimum penetration depths are dependent on wavelength. The term dispersive means that different frequencies have different propagation velocities or phase velocities (Park, Miller, & Xia, 1999). Dispersion patterns of surface waves are indicative of the Vs distribution in the materials through which the waves travel (Reynolds, 2011). Analysis of these dispersion characteristics allows one to determine Vs as a function of depth.

**Site Geological History**

Passive seismometer locations at Federal Road span the margin of a buried pre-glacial valley containing glacial drift. Drift thickness data in this region is sparse, but water well driller logs from the Ohio Department of Natural Resources (ODNR) provides accurate depth to bedrock values locally. Glacial drift was deposited across the pre-glacial Teays River system during the advance of the Laurentide Ice Sheet, the last advance being the Wisconsinan approximately 14000-24000 years ago. The limestone bedrock in Greene County is part of the Niagara and Clinton Groups of Silurian age (i.e., Krolczyk, 1952).

**Previous Research**

This project is part of and ongoing effort that began in 1997, when Wright State University collected a seismic reflection line along Federal Road. Further research was conducted in 2008 and 2009 when passive seismic data were collected by Wright State University using long period seismometers on loan from IRIS and Spectraseis, respectively. Seismic reflection profiles were collected by Precision Geophysical in 2008 in the vicinity, followed by an exploratory oil well drilled in 2009 to determine if hydrocarbons exist in this region. The oil well was a dry hole. Four individual passive
seismometers locations (Station 3, 5, 7, 9) at the Federal Road site were selected for further study using the MASW method to confirm the depth to bedrock locally and shear wave velocity structure (Figure 1), for comparison with the passive seismic data at those sites.

**Motivation for Research**

The MASW method was used to determine shear wave velocity structure at passive seismometer stations on Federal Road. The velocity structure and interpreted depth to bedrock value at a particular location can be used to examine how well a calculated surface layer resonance frequency derived from this velocity model compares with the surface layer resonance observed in the passive seismic data at that location.

In settings with a high velocity contrast between a surface layer and bedrock (i.e., where glacial drift overlies limestone bedrock), by determining the $V_s$ of the drift using MASW and demonstrating this velocity is consistent across a region, one might be able to use the H/V peak frequency of 3-component seismic data to calculate the depth to bedrock in the region. Furthermore, documentation of the surface layer resonant characteristics will contribute to further analysis of the existence of any resonance associated with deeper oil and gas deposits. The presence of a dry hole nearby, however, suggests that this site is not suitable for this latter effort, so it is not a part of this study.
Figure 1: Site map showing the location of active and passive seismometers deployed at Federal Rd, Greene County, OH. The circled dots show locations where passive seismometers were previously deployed and collected broadband seismic records. The yellow dots show locations of passive seismometers data included in this study (red symbol sites were not used in this study). The yellow boxes denote locations where MASW data were collected and analyzed in this study.
CHAPTER 2: MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW)

Theory of MASW

Surface wave propagation in seismic reflection studies is regarded as noise. The study of surface waves and what they reveal about the surface layer through which they travel began with a steady state method by Van der Poel (1951), which analyzed only the fundamental mode. Further research by Heisey (1982) included a two receiver approach called Spectral Analysis of Surface Waves (SASW) that analyzed the phase spectra of surface waves generated by an impulsive source. This method changed the distance between source and receiver to cover the desired range of investigation. This inefficient method was replaced by MASW.

MASW analysis includes surface waves, body waves, reflected waves, and higher order harmonics. Rayleigh waves can only be analyzed when they are fully formed horizontally traveling planar waves. These waves exist after they have propagated a certain offset distance from the source point (Richart, 1970). Planar wave propagation of surface waves does not occur in most cases until the source offset is greater than half the maximum desired wavelength (Stokoe II, 1994).

Shot Gather

The shot gather displayed in Figure 2 shows the development of seismic waves in a multi-channel recorded from an MASW survey at a passive seismometer Station 5. These data were recorded on a 48 channel Geometrics Strataview system with low frequency 4.5 Hz vertical geophones owned by Wright State University. The data were
collected with a source offset 10 meters, reciever spacing of 2 meters, and a total spread length of 96 meters. The red line in Figure 2 represents the direct p-wave. The magenta line represents a shallow refraction arrival most likely related to the water table. The blue line represents the slower surface waves traveling across the array.

Figure 2: Shot gather from Station 5. The red line indicates the direct p-wave arrival. The magenta line represents the near shallow refraction event. The blue line represents surface waves.
CHAPTER 3: METHODOLOGY

Acquisition

The procedure for generating a shear wave velocity profile consists of the three steps: (1) acquiring multichannel records, (2) extracting the fundamental-mode dispersion curves, and (3) inverting those curves to obtain 1D $V_s$ profiles.

The general site conditions were documented, including date, time, temperature, wind speed, and wind direction. These conditions were used to assess the effect of the environment on multi-channel records. At each passive seismometer station the GPS coordinates, distance from main roads, and distance from other seismometer stations was documented.

Active Approach

MASW acquisition followed a set of parameters displayed in Figure 3 and described in Park (2002). The parameters include: receiver spread (D), receiver spacing (dx), and source offset (x1). The receiver spacing was 2m for all spread lengths, resulting in a receiver spread of 96m for all 48 channel acquisitions, and a receiver spread of 48 meters for all 24 channel acquisitions. The source offset in this study was set at 10m spacing for all initial acquisitions. Since the optimum source offset is a parameter of significant interest, additional records were collected using offsets of 10m, 20m, and 40m as explained in Ivanov & Miller (2012).
Figure 3: A general MASW field setup indicating the general parameters necessary to deploy this seismic survey (MASW.COM). The main field parameters are shown above the corresponding red arrows; where (D) is the receiver array dimension, (dx) is the receiver spacing, and (x1) is the source offset.
Passive Source

Passive MASW data was collected at one site (Station 5) together with active source MASW data. This passive MASW effort recorded ambient vibrations (traffic) and attempted to record waves created from the Bison Elastic Wave Generator, a weight drop source.

For the passive data acquisition a circular array was deployed (Figure 4). The recording parameters included a spread length equal to the diameter of the circle and a set receiver spacing.

Figure 4: A general MASW field setup for the Passive Remote array indicating the general parameters necessary to deploy this seismic survey (MASW.COM). The main field parameters are highlighted in yellow above; where (D) is the receiver array dimension, (dx) is the receiver spacing, and (x1) is the source offset.
The resulting records showed no usable dispersion patterns. The ambient vibrations at this location were very weak; therefore no low frequency surface wave dispersion was analyzed in this study on ambient vibrations. As a result, the passive method was abandoned for later sites where only active source data were collected.

CHAPTER 4: DISPERSION CURVE ANALYSIS

Dispersion curve analysis is the most critical part of MASW method. Dispersion curve extraction requires that a range of velocities is analyzed over a defined frequency range to assist in defining the fundamental and 1st order harmonic. The Surfseis3 program is capable of separating the fundamental mode from other noise if the receiver spread is large enough, as described in Park & Miller (2001). The dispersion curve is an expression of phase velocity (m/sec) vs. Frequency (Hz); where the signal to noise ratio (S/N) is expressed as the highest amplitude region of the dispersion curve. A best fit curve is extracted based on that highest amplitude (S/N) for a given mode. The multi-channel approach to dispersion curve analysis can significantly improve the S/N as well as the abilities of pattern recognition (Park et al, 1998a) that enable the identification of different types of seismic waves from their arrival and attenuation pattern.

High Contrast Model

Due to the local geology of glacial drive overlying limestone bedrock, a high contrast velocity model assessment (Ivanov & Miller, 2012) was implemented in my field acquisition at Station 5. This involved testing various source offsets: 10m, 20m, and 40m, but the receiver spacing, receiver spread, and impulse source (i.e., hammer) were kept constant. By varying the source offset one can quantify how the source offset
component affects the dispersion results and ultimately the 1-D inversions. The ranges of
source offset tested are those recommended by Ivanov & Miller (2012) from analysis of
synthetic data from a 2 layered model created by Levshin & Panza (2006). Those
synthetic seismic data indicate that higher mode energy below a certain frequency
dominates the dispersion curve image at more conventional short source offsets (Ivanov
& Miller, 2012).

Figures 5, 6, and 7 display the dispersion characteristics for source offsets of 10m, 20m, and 40m, respectively, and show how altering source offset can affect dispersion
development in the fundamental and higher order modes. As indicated by Ivanov &
Miller (2012) one can reduce higher mode domination in the lower frequency ranges by
optimizing the acquisition parameters, especially the source offset. By optimizing the
source offset parameter the surface wave dispersion quality in the data significantly
improves. Receiver spacing and spread length in this case only has a limited impact on
multi-modal dispersion, as was previously indicated by Ivanov & Miller (2012).
Figure 5: Station 5 with a 40 meter source offset where the white dots indicate the extracted dispersion curve. Each dispersion curve shows how a change in source offset effects the planar development of surface waves. The Signal to Noise ratio is a measure of high amplitude wave energy at a given frequency, which assists in dispersion curve picking.
Figure 6: Station 5 with a 20 meter source offset where the white dots indicate the extracted dispersion curve. Each dispersion curve shows how a change in source offset effects the planar development of surface waves. The Signal to Noise ratio is a measure of high amplitude wave energy at a given frequency, which assists in dispersion curve picking.
Figure 7: Station 5 with a 10 meter source offset where the white dots indicate the extracted dispersion curve. Each dispersion curve shows how a change in source offset affects the planar development of surface waves. The Signal to Noise ratio is a measure of high amplitude wave energy at a given frequency, which assists in dispersion curve picking.
CHAPTER 5: INVERSION MODELING

1-D Inversions

The inversion process requires layered models, which are compared to theoretical earth-based models defined within Surfseis3. Models can be specified as having equal, variable, or user-defined thicknesses. Each model includes an infinite half space as its bottom layer.

Abrupt changes in lithology (i.e., drift to bedrock) can be interpreted on the 1-D modeled inversions as a significant increase in velocity. However, a wide range of $V_s$ layers and boundaries can be defined for the inversion process and the number of layers can impact the determination depth to bedrock. Selecting too many layers will over-fit the model to the curve creating an overly complex scenario having gradients that may not exist and where significant structures are not apparent. However, choosing the correct number of layers for your model, the program will accurately portray the variation in the sub-surface, which can be fit to known geologic information such as driller’s logs. The correct number of layers typically fits with the stratigraphic units and geologic information that is already known about the study area. The RMS for the computational model should improve significantly when the correct number of layers for your model is calculated. For this study where low velocity glacial drift overlies limestone bedrock, the high velocity contrast model as described by Ivanov & Miller (2012), having 3 equal weighted layers (the bottom one being an infinite half space) appears best suited.
Modeling the Inversions

Layer 1 is defined as the low velocity layer or glacial drift. Layer 2 is defined as the high velocity layer or limestone bedrock. Layer 3 is defined as the half space. Surfseis3 assumes a fixed Poisson's Ratio of 0.4 that is common for most earth materials. The earth based inversion model automatically defines $V_s$, $V_p$, $\rho$ and Possions ratio. To create the 1-D model Surfseis iterates through a series of calculated dispersion curves for a 3-layer model to converge upon a match with the empirical dispersion curve. This forward modeling involves assuming an initial $V_s$ profile, and then comparing the theoretical dispersion curve with the empirical (Stokoe II, 1994). The velocity model is modified until the two curves match closely. This forward modeling is an automated process, but computationally intensive method. The inversion controls allow the operator to set stopping criteria such as maximum iterations, assumed Poisson’s Ratios, and other properties. The program uses a weighting of individual points to ensure a high accuracy which is controlled by S/N. The resulting 1-D profile defines the low velocity/high velocity contrast inferred to define the depth to bedrock, having layer velocities that should correspond to that expected for the subsurface materials.

The 1-D inversion uses the dispersion characteristics to define the fundamental frequency ($F_0$) of the low velocity layer using the closed tube case where the length of the tube ($L$) is equal to the wavelength ($\lambda$) divided by 4. In this case I can define the fundamental frequency ($F_0$) as the $V_s$ divided by 4 times the thickness of the glacial drift.
CHAPTER 6: MASW INTERPRETATIONS AND RESULTS

In cases where a high contrast velocity model is assumed, the depth to bedrock is defined as a significant jump in velocity on the 1-D profile. The optimum model for this study, as previously discussed, comprises 3 layers. Layers 1-2 of the model fit to the geological setting of glacial till overlying limestone bedrock. Layer 3 is included for the modeling of an infinite half space. The depth to bedrock value is determined for each site as the depth to the boundary of Layer 1 and 2 where the modeled velocity of Layer 1 is consistent with that of glacial drift and the modeled velocity of Layer 2 is consistent with that of Paleozoic limestone. Only records with an overall S/N of 99% were considered for inversion. Vs structure at Station 3, 5, 7, and 9 is consistent with the high velocity contrast model assumed by Ivanov & Miller (2012). All model inversions were performed using the program Surfseis3 from the Kansas Geological Survey.
Figure 8: Shows a 3 layer velocity model calculated using the seismic processing software Surfseis3. The blue line indicates the calculated Vs structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dots). The lithology change is interpreted as glacial till over limestone bedrock at 17.5 meters.
Figure 8 displays a 1-D depth vs. shear wave velocity structure model for Station 3. The significant increase in velocity at a depth of 17.5m is interpreted as the boundary between glacial drift and limestone bedrock. The inversion indicates that the Vs of glacial till at this location is approximately 450 m/sec, which is consistent across all sites studied. Depth to bedrock from the inversion of several separate recordings at Station 3 varied between 15-18m which correlates with depth to bedrock reported in water well data to the west. The analysis of the highest quality surface wave dispersion of the data at Station 3 (Figure 8) determines a bedrock depth of approximately 17.5m.
Figure 9: Shows a 3 layer velocity model calculated using the seismic processing software Surfseis3. The blue line indicates the calculated Vs structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dots). The lithology change is interpreted as glacial till over limestone bedrock at 20 meters.
At Station 5 a significant increase in velocity at 20.5m depth (Figure 9) is interpreted as the boundary between glacial drift and limestone bedrock. The inversion indicates that at Station 5 the Vs of glacial till is approximately 445 m/sec, which is consistent across all sites studied. For individual recordings the depth to bedrock from the inversions varied between 18-21m, but the highest quality surface wave dispersion data resulted in a depth of 20.5m (Figure 9). The velocity of limestone bedrock at this site is anomalously low, which could be attributed to weathered limestone or fractured bedrock.
Figure 10: Shows a 3 layer velocity model calculated using the seismic processing software Surfseis3. The blue line indicates the calculated Vs structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dots). The lithology change is interpreted as glacial till over limestone bedrock at 21.2 meters.
At Station 7 a significant increase in velocity at 21.2m is interpreted as the boundary between glacial drift and limestone bedrock (Figure 10). The inversion indicates that the Vs of glacial till is approximately 445 m/sec, which is consistent across all sites studied. Depth to bedrock from the modeled inversions of individual recordings at Station 7 varied between 20-22m, but the inversion of the highest quality data gave a depth of approximately 21.2 m. The velocity for limestone bedrock (~900m/s) is anomalously low at this station, which could be attributed to weathered or fractured limestone.
Figure 11: Shows a 3 layer velocity model calculated using the seismic processing software Surfseis3. The blue line indicates the calculated Vs structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dots). The lithology change is interpreted as glacial till over limestone bedrock at 29 meters.
At Station 9 a significant increase in velocity at a depth of about 29m (Figure 11) is interpreted as the boundary between glacial drift and limestone bedrock. The inversion model suggests that the Vs of glacial drift is approximately 500 m/sec at Station 9, which is consistent across all sites studied. Depth to bedrock from the inversion of individual recordings at Station 3 varied between 25-30m. Analysis of only the highest quality surface wave dispersion data at this site determined a bedrock depth of approximately 29.2m (Figure 11).
CHAPTER 7: LONG PERIOD PASSIVE SEISMIC INTERPRETATION

H/V Interpretation

Microtremor analysis defines low amplitude ambient vibrations caused by excitations at the surface. This method estimates the ratio between the Fourier amplitude spectra of the Horizontal (H) to the Vertical (V) components of ambient noise vibrations at one single station (Nakamura, 1989). This theory of the method (Nakamura, 1989) indicates that H/V ratios in the peak frequency range are not affected by the fundamental-mode Rayleigh wave but instead by the local site characteristics, allowing for a direct comparison with the s-wave transfer function (Fah, 2000).

An H/V analysis was conducted in the present study using the program Geopsy to define the peak frequency of spectral ratios of the vector sum of the two horizontal components (H) to the vertical component (V) using data recorded on 3-component broadband seismometers. The 3-component data used were previously collected simultaneously at all the stations of this study using broadband (60s-50Hz) Guralp CMG-3ESP3D seismometers. H/V plots created in Geopsy were provided to me by Dr. Hauser, my advisor, from broadband data acquired in 2006. It should be emphasized that these H/V data were not available when creating models in Surfseis3, to ensure that there was no subjectivity in picking dispersion curves and modeling. The peak frequency of the H/V spectral ratio can be viewed as a constructive resonance of $V_s$ within the surface layer. The broadband seismometer H/V spectral ratio data were analyzed at each of the
MASW analysis sites of this study (Figure 12, Stations 3,5,7,9), as well as the seismometer stations between (Figure 12, Stations 4,6,8,10).

Figure 12: A site map showing the location of active and passive seismometers deployed at Cardinal 1 in Greene County, OH. The red circles show passive seismometers previously deployed that collected long period records. The numbered yellow circles show locations where both passive and MASW data were collected at identical locations. Water wells are indicated on the map as locations where depth to bedrock has been previously determined.
CHAPTER 8: COMPARISON OF MASW AND MICROTREMOR RESULTS

Comparison

H/V plots created in Geopsy allowed me to directly compare the observed site-specific H/V spectral peak frequency of the long period passive seismic data to a calculated resonant frequency based upon the bedrock depth and glacial drift velocity determined by the MASW inversion results. The frequency of constructive resonance of $V_s$ in a surface layer should be related to the $V_s$ and thickness of the surface layer, as determined independently from the MASW analysis, according to the following equation:

$$F_0 = \frac{V_s}{4H}$$

The passive 3-component data analyzed for all stations was of a contemporaneous 1-hour time span (0700-0800 GMT, 2-3am local time) to avoid temporal differences in surface layer resonance. Within that 1-hour time span the data were divided into 30s increments for individual H/V frequency analysis. The resulting Geopsy plots show the superimposed spectra of all 30s increments during that 1 hour period, which reveal a consistent pattern of little variation of spectra during the 1-hour span of data.

At all 4 locations where both MASW and 3-component data exist (Stations 3, 5, 7, 9), I also calculated the expected resonant frequency based upon the till velocity and bedrock depth determined from the MASW analysis described previously.
H/V ANALYSIS USING GEOPSY

The Geopsy displays show individual 30s spectra using a line color keyed to where that time increment is positioned in the 1-hour time span according to the color code in Figure 13.

![Figure 13](image.png)

Figure 13: Each individual color represents a specific recording time in a 1 hour period for long period passive seismic data collection. This scale is applied in Geopsy for Figures 15-20 below (GEOPSY.ORG).

The black curve across each Geopsy H/V display represents the average H/V of the individual 30s spectra, with the two dashed lines representing +/- one standard deviation (GEOPSY.ORG). The grey shaded frequencies represent the averaged peak frequency and it’s +/- one standard deviation. Filtering was applied to each H/V plot by using a time rejection method that allows one to edit 30s increments having anomalous noise bursts in the time series. The filtering removed the same time intervals for all other records for consistency.
Figure 14: H/V spectra for Station 3 from 7-8 GMT (1-2 A.M LOCAL). Station 3 shows a well-defined peak frequency at 6.6 Hz that agrees well with the calculated fundamental frequency of 6.5-6.8 Hz from MASW results at that location.

At Station 3 the H/V spectra produced using Geopsy (Figure 14) are consistent over the one hour time span and exhibit a distinct peak frequency of 6.6 Hz with a standard deviation of ± 0.3. Using the glacial drift velocity and depth to bedrock from the MASW inversion results at Station 3 one calculates an expected resonant frequency of 6.5-6.8 Hz for the series of records analyzed.
Figure 15: H/V for Station 5 for 7-8pm GMT (1-2 A.M LOCAL). Station 5 shows a well-defined peak frequency of 5.1 Hz that agrees well with the fundamental frequency calculation of 4.9-5.2 Hz at the same seismometer location using MASW results.

At Station 5 the H/V spectra (Figure 15) produced using Geopsy are consistent over the one hour time span and exhibit a distinct peak frequency of 5.1 Hz with a standard deviation of ± 0.3. Using the glacial drift velocity and depth to bedrock from the MASW inversion results at Station 5 one calculates an expected resonant frequency of 4.9-5.2 Hz for the series of records analyzed.
Figure 16: H/V plot for Station 7 for 7-8pm GMT (1-2 A.M LOCAL). Station 7 shows a double peak frequency of 4.0 Hz and 5.1 Hz, the latter agreeing well with the fundamental frequency calculation of 4.8-5.5 Hz from MASW results at the same location. The second peak may suggest bedrock topography.

At Station 7 the H/V spectra produced using Geopsy (Figure 16) are consistent over the one hour time span and exhibit a distinct double peak at 4.0 Hz and 5.1 Hz with a standard deviation of ± 0.5. Using the glacial drift velocity and depth to bedrock from the MASW inversion results at Station 5 one calculates an expected resonant frequency of 4.8-5.5 Hz for the series of records analyzed, which is in close agreement with the 5.1
Hz peak in the H/V plot. The double peak may suggest bedrock topography locally.

Figure 17: H/V for Station 9 from 7-8pm GMT (1-2 A.M LOCAL). Station 9 shows a well-defined peak frequency of 3.8 Hz that agrees well with the fundamental frequency calculation of 3.8-4.2 Hz from MASW results at the same location.

At Station 9 the H/V spectra produced using Geopsy (Figure 17) are consistent over the one hour time span and exhibit a distinct peak frequency of 3.8 Hz with a standard deviation of ± 0.3. Using the glacial drift velocity and depth to bedrock from the MASW inversion results at Station 9 one calculates an expected resonant frequency of 3.8-4.2 Hz for the series of records analyzed which is in close agreement with the 3.8 Hz peak in the H/V plot.
Figure 18: Summary of the calculated resonant frequency obtained from MASW inversion modeling compared to the observed H/V peak frequency obtained from the 3-component seismometer data analyzed using Geopsy. The peak frequencies obtained from the H/V plots created in Geopsy are in close agreement with the resonant frequency calculated from MASW results.
Figure 19: Peak frequency shifts to lower values as the array moves eastward from Stations 3 to Station 9. A 5 Hz baseline shown in black is included to better reveal the change in peak frequency from plot to plot. A single peak frequency is observed at stations 3, 4, 5, 6, and 9. This suggests that most sites have a simple surface layer over bedrock, but that the double peaks at stations 7 and 8 may be areas of bedrock relief.
Figure 20: Average spectra of the H/V spectra for each station. Each color corresponds to a unique seismometer station. The shift of resonant peak frequency from Station 3 to Station 10 gradually shifts from higher to lower frequency, corresponding to the increasing depth to bedrock across that region.
CHAPTER 9: SUMMARY AND CONCLUSION

The surface layer thickness (drift thickness) and shear wave velocity structure at Federal Road, Greene County, Ohio was determined using MASW. MASW modeling produced 1-D depth vs. velocity profiles that expressed a significant increase in Vs at depth, which is interpreted as the change from glacial drift to limestone bedrock. This abrupt increase in Vs is defined as depth to bedrock and this depth varies significantly and systematically at Federal Road getting deeper to the east.

The study area spans the flank of an ancient buried valley system, which is part of the pre-glacial Teays River Valley. The modeled thickness of glacial drift increases from 13-15 meters at Station 3 to 25-30 meters at Station 9. Depths to bedrock measurements in this region are sparse, but the MASW findings agree with water well borings collected by ODNR. Well borings indicate that glacial drift increases from 5 meters slightly west of Station 3 to 30 meters in close proximity Station 9.

Vs estimates calculated in Surfseis, the MASW modeling software, agree with values suggested in the NEHRP site classification index (ICC, 2000). Estimates for a soil like glacial till (Site Class C), the Vs should fall between 366 to 762 m/sec (ICC, 2000). A consistent shear wave velocity of 350-425 m/sec was determined for each 1-D profile and fit within the constraints of Site Class C.

Varying the source offset parameter confirmed that higher order modes influence the low frequency dispersion properties. Dispersion curve properties are critical in accurately defining shear wave velocity structure. Optimizing the recording parameters
allow for the full range of frequencies to be analyzed along with higher order modes. Analysis of higher order modes along with the fundamental mode lowers the percent error in the calculated models from 15% to 3% when compared to borehole data. The low frequency range in dispersion curve images might be strongly influenced and dominated by higher mode energy. This is clear in Figure 3 and 4 between 15-25 Hz where there are significant shifts in the modeled dispersion curves. The increase in source offset allows for full planar development and multi-modal development, but influence of the higher order modes is evident in certain regions of the curve. In Figure 5 a noticeable shift towards the lower frequencies occurs. This shift has no apparent effects at Station 5, but other stations showed non-planar wave propagation resulting in dispersion curves that are non-discernible. The source offset component requires further work to best define optimal parameters as indicated in Ivanov, 2012.

The microtremor signal is expressed as the peak frequency identified on the H/V plots. This peak corresponds to the natural site period and amplification factor (Nakamura, 1989). The comparison of peak frequency and resonant frequency assumes that the shear wave dominates the microtremor signal. The increase in drift thickness observed at Federal Road corresponds to an overall decrease in resonant frequency calculated from the fundamental mode equation as expected. The peak frequency calculated from the long period passive seismic matches the calculated resonant frequency from the fundamental mode equation. This relationship is expressed in Figure 20, where the peak frequency of the H/V fits the calculated resonant frequency from individual MASW records. I can state with confidence that this “resonance” is related to the near surface layer.
Stations 7 and 8 exhibit a dual peak frequency that is related to a change in thickness at the location where resonance is being measured. This phenomenon can be explained by several processes including bedrock topography, subsidiary valleys, and dipping strata. This double peak is most likely attributed to topography on the bedrock surface. Station 7 showed a significant variation in depth to bedrock in the roll along study. A 2 meter variation over the 48 meter spread was observed, which would significantly alter the resonance in long period passive seismic if you are measuring the resonance of a two different thicknesses. Station 8 shows less of a double peak indicating that there is less topography on bedrock and a more planar surface as observed in other stations. The spread could also be located over the flank of subsidiary valleys in the region; which is also a likely scenario where dual peak frequencies could occur.

The glacial drift velocity does not vary significantly laterally in this study, therefore it may be possible in settings of high velocity contrast between a surface layer and bedrock, where glacial drift overlies limestone bedrock, by determining the $V_s$ of the drift using MASW, one can use the H/V peak frequency of 3-component seismic data to calculate the regional depth to bedrock values in locations where $V_s$ is consistent. NEHRP estimates that for a hard rock like limestone (Site Class A), the $V_s$ should be greater than 1524 m/sec. The shear wave velocity of limestone bedrock varied significantly in the models between 1200-3000 m/sec. The calculated values fit within the constraints of Site Class A.
Works Cited


