

Determination of  $V_p$ ,  $V_s$ , Glacial Drift Thickness and Poisson's Ratio at a Site in Jay County, Indiana, Using Seismic Refraction and Multichannel Analysis of Surface Wave (MASW) Analysis on a Common Data Set

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

By

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WRIGHT STATE UNIVERSITY  
GRADUATE SCHOOL

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Shamim Ahammod ENTITLED Determination of Vp, Vs, Glacial Drift Thickness and Poisson's Ratio at a Site in Jay County, Indiana, Using Seismic Refraction and Multichannel Analysis of Surface Wave (MASW) Analysis on a Common Data Set BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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## **ABSTRACT**

Ahammod, Shamim., M.S. Department of Earth and Environmental Sciences, Wright State University, 2015. Determination of  $V_p$ ,  $V_s$ , Glacial Drift Thickness and Poisson's Ratio at a Site in Jay County, Indiana, Using Seismic Refraction and Multichannel Analysis of Surface Wave (MASW) Analysis on a Common Data Set.

In July 2013, an industry-scale seismic reflection survey was conducted at a site in northern Jay County, Indiana, by geophysics students and faculty of Wright State University. As a part of that effort, a separate near-surface seismic dataset was collected to examine the  $V_p$ ,  $V_s$ , and Poisson's Ratio of the glacial drift and upper bedrock. This near-surface study successfully used a common dataset that was separately analyzed for both  $V_p$  (seismic refraction) and  $V_s$  (MASW) to calculate the Poisson's Ratio of the glacial drift and underlying bedrock.

The driller's log for a water well near the east end of this near-surface survey indicates glacial drift (unconsolidated clay and sand) overlies limestone bedrock at a depth of 110 feet. Water wells in the broader area show bedrock depth varying from 110 to 122 feet, but locally as much as 140 feet.

The near-surface seismic data were acquired using a Bison EWG (Elastic Wave Generator) assisted weight drop source that shot every station through a stationary spread of 48 channels using a pair of 24-channel Geode seismographs. Each channel recorded a

a single vertical 4.5 Hz geophone at a station spacing of 10 feet. Four weight drop records at each source point were summed to enhance the S/N ratio.

The same data volume was processed both for  $V_s$  using *SurfSeis3* MASW (Multichannel Analysis of Surface Wave) software and for  $V_p$  using *IXRefrax3* refraction software. The MASW results suggest that the depth to bedrock at the survey location ranges from 115-120 feet (~35 m) with  $V_s$  of 1,200-2,000 ft/sec (366-610 m/s) for glacial drift and 2,400-2,700 ft/sec (730-823 m/s) for bedrock. The P-wave refraction results suggest the depth to bedrock ranges from 118-122 feet (36-37 m) with average  $V_p$  of ~5,000 ft/sec (1,524 m/s) for glacial drift and ~17,000 ft/sec (5180 m/s) for limestone bedrock. The Poisson's Ratio for the glacial drift calculated using the  $V_p$  and  $V_s$  at common locations in this study is 0.470-0.473, which is consistent with published results elsewhere.

This study suggests that Poisson's ratio can be determined using velocities from different analysis methods on the same dataset with good results.

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# CHAPTER 1

## Introduction

The primary goals of this project are to determine the thickness and velocity structure of glacial drift in the study area using the Multichannel Analysis of Surface Waves (MASW) method and the seismic refraction method on a common data set (constrained by the local water well driller's logs), and from these results estimate the Poisson's ratio. P-waves and surface waves (Rayleigh waves) were analyzed in this study. Surface waves propagate along the surface of the medium, whereas body waves like P-waves propagate through the interior (<http://geo.mff.cuni.cz/vyuka/Novotny-SeismicSurfaceWaves-ocr.pdf>). Richart et al. (1970) stated that when seismic surveys are carried out, and a compressional wave source is used, more than two-thirds of total seismic energy is produced as Rayleigh waves which are the main component of ground roll. Figure 1 shows how the longer Rayleigh wavelengths (lower frequency components) penetrate more deeply than shorter Rayleigh wavelengths (higher frequency components) for a given mode. Therefore, longer wavelength Rayleigh waves exhibit greater phase velocities, and are more sensitive to the elastic properties of deeper layers. Short-wavelength components attenuate quickly with depth. Xia et al. (1999) explained that the phase velocity of Rayleigh-waves of a layered earth model is a function of frequency and four groups of earth parameters: compressional wave velocity ( $V_p$ ), shear wave velocity ( $V_s$ ), density, and thickness of the layers.

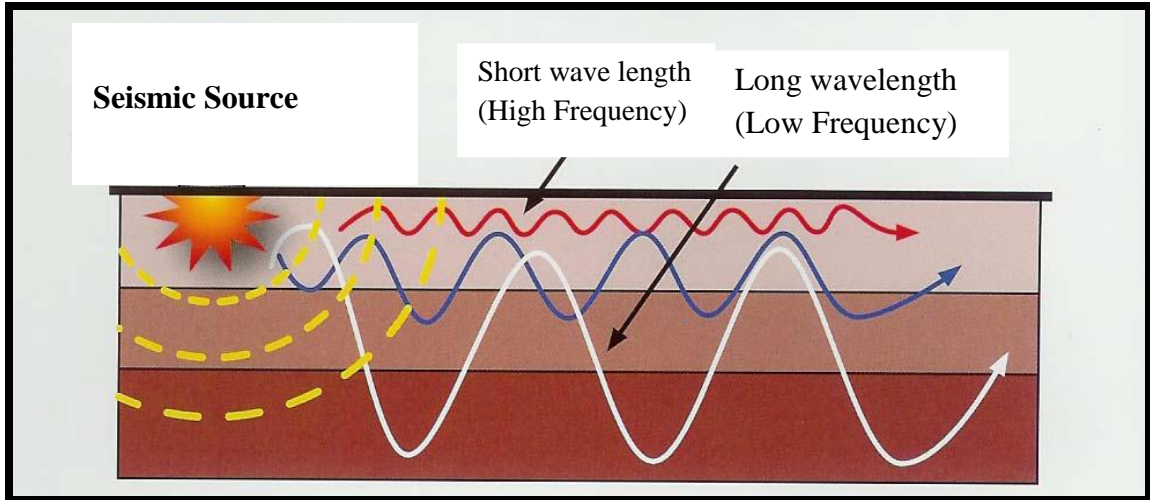


Figure 1: Conceptual diagram of surface wave propagation (Adapted from OYO brochure at <http://content.cqu.edu.au/FCWViewer/getFile.do?id=28927>).

The dispersion curve analysis is the critical part of the MASW analysis. The fundamental mode and the higher order (harmonic) mode dispersion curves are extracted simultaneously in MASW analysis. The inversion process produces a 1D shear wave velocity function for a single analysis and a 2D shear wave velocity profile from a series of 1D analysis. For this project, the MASW processing and analysis was accomplished by the SurfeSeis3 software developed by the Kansas Geological Survey.

For the seismic refraction method, the generalized reciprocal method (GRM) was used to estimate the bedrock depth and velocity structure using the same data set used for the MASW analysis. IXRefrax3 software from Interpex3 was used for the refraction analysis. The results obtained from both MASW and seismic refraction methods were compared with existing water well driller log data, and finally, Poisson's ratio was estimated from the  $V_p$  and  $V_s$  velocity information and compared with that found in other studies.

## Location of the Study Area

The study area is in Jay County, Indiana as shown in Figure 2, which also shows information about the depth to the limestone bedrock at nearby water wells.

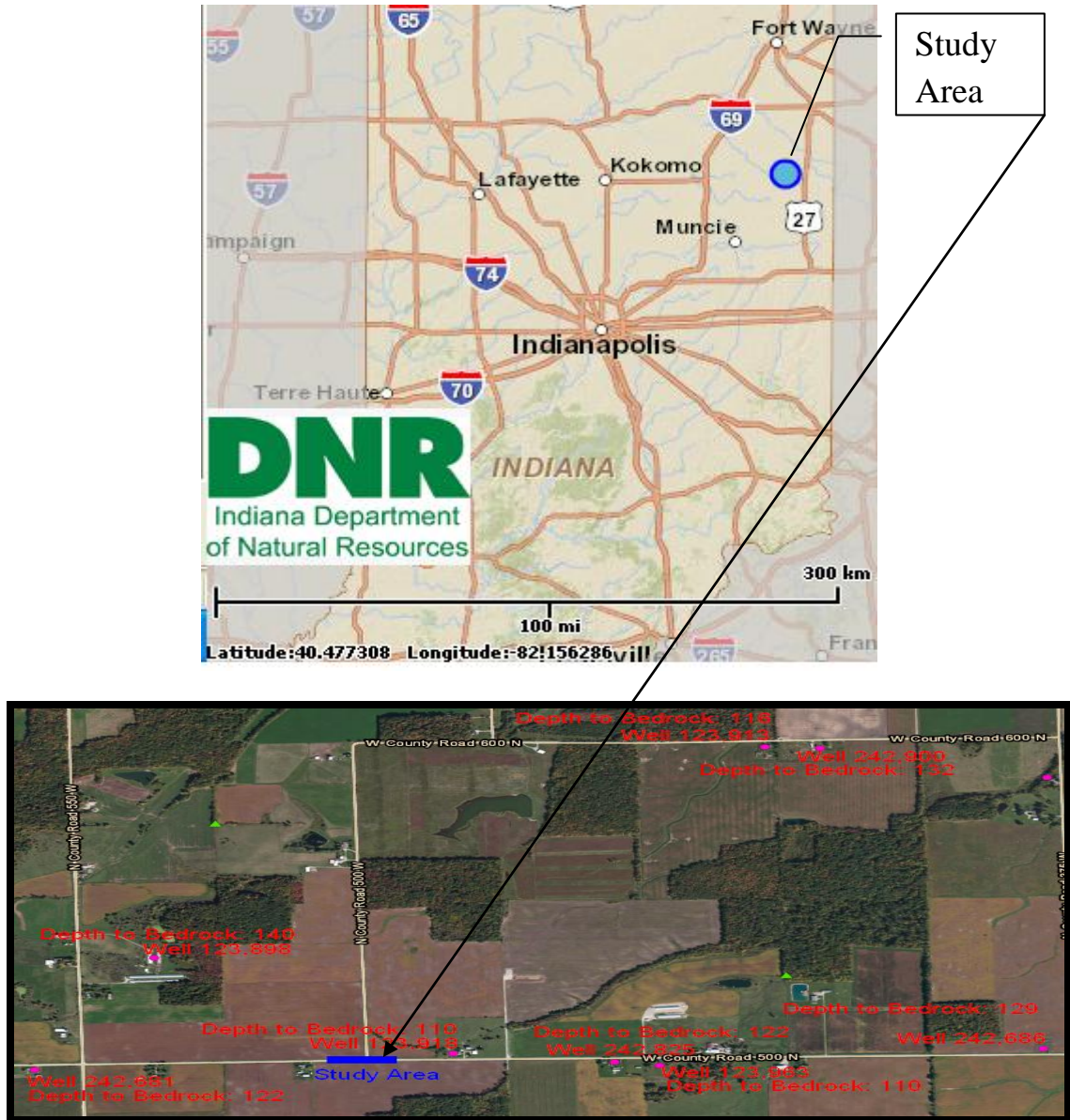


Figure 2: Location of the study area (Jay County) and nearby water well log data (in red) showing depth to limestone bedrock (Indiana Department of Natural Resources from <http://www.in.gov/dnr/water/6604.htm>).

## **Geology of the Study Area**

The bedrock surface of Indiana (Figure 3) developed by erosion at least since late Pennsylvanian time (~300 million years ago) and was covered by unconsolidated glacial materials dominantly deposited during the past 2 million years, when major glacial advances and retreats crossed the state (Indiana Geological Survey at <http://igs.indiana.edu/Bedrock/>). The study site in Jay County, Indiana (Figure 3) is situated on the western flank of the Cincinnati Arch. The geology of Jay County consists of a bedrock of Silurian age (Figure 3) and unconsolidated Quaternary glacial materials (Figure 4). Jay County is located entirely within the Tipton Till Plain physiographic subsection of Indiana (Chaturvedi, 1991). The survey area is nearly level to gently undulating. Jay County has an average elevation of about 945 feet (Chaturvedi, 1991).

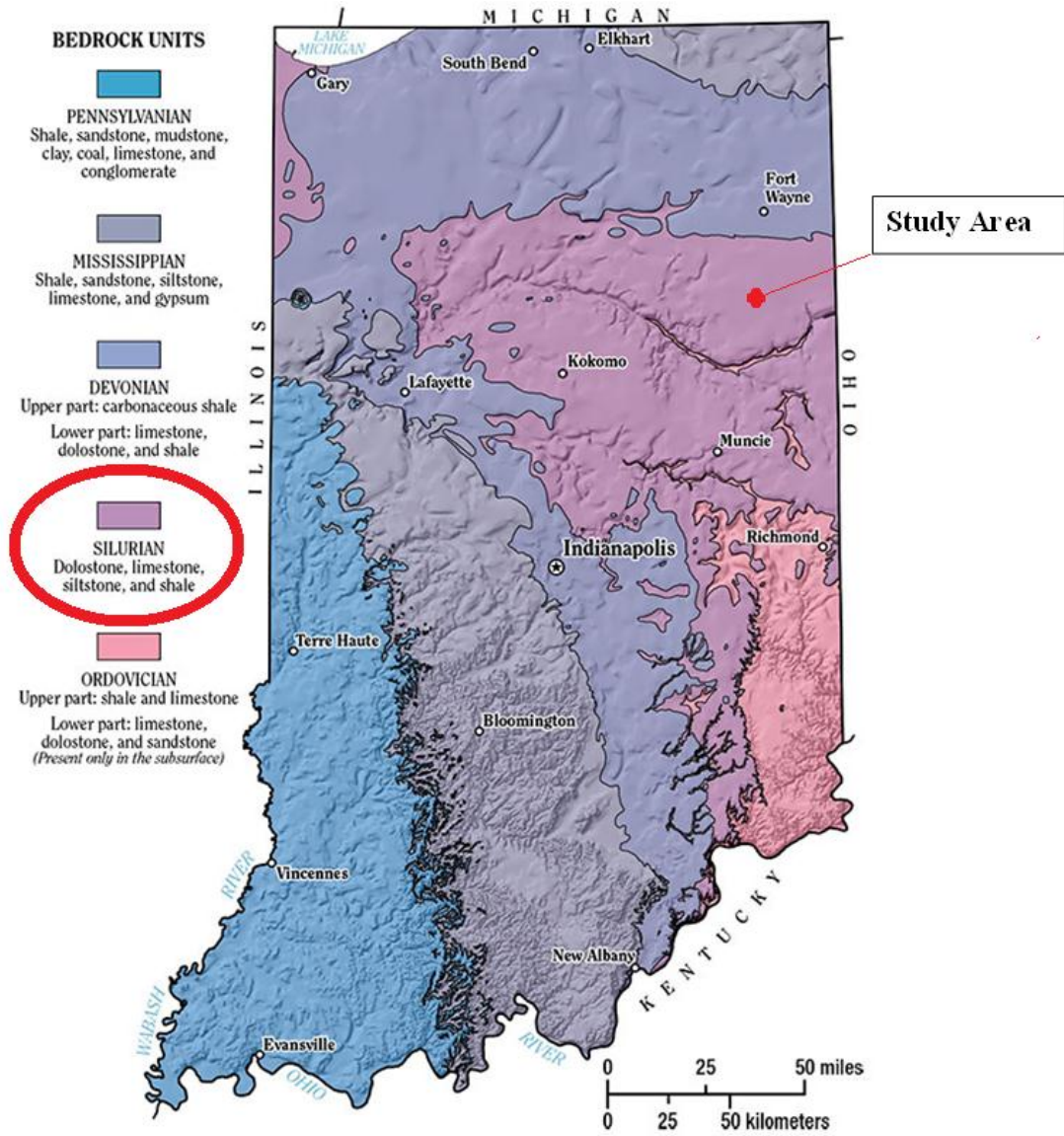


Figure 3: Bedrock Geology of Indiana (Indiana Geological Survey at <http://igs.indiana.edu/images/bedrock/about1.jpg>). The purple color (red circle in the figure) indicates the bedrock geology of Jay County is of Silurian age. The red circle shows the study area in NE Indiana.



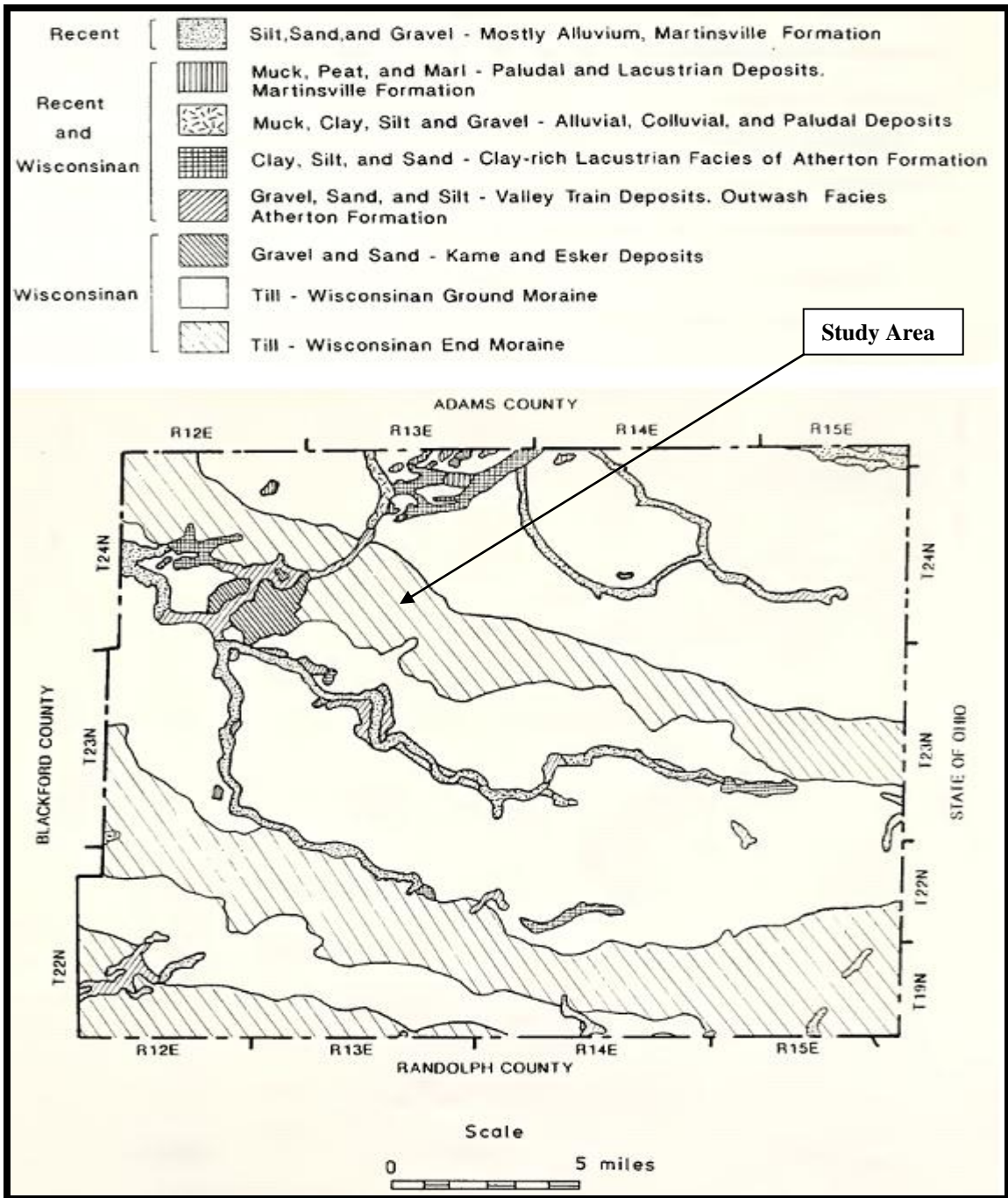


Figure 4: Unconsolidated deposits of Jay County, Indiana (Chaturvedi, 1991).



## CHAPTER 2

### Seismic Data Acquisition

Seismic data was acquired using a weight drop energy source and recorded using a pair of 24 channel Geometrics Geode seismographs. These 48 channels each recorded a single 4.5 Hz geophone at a spacing of 10 feet (3.048 meters) for a spread length of 480 feet (146.3 meters). A total of 84 shot points were collected through a stationary spread. A summary of the seismic data acquisition parameters is presented in Table 1.

Source	300 kg weight drop
Drop height	1m (3.28 feet) approximately
Vertical stack	4
Geophone frequency	4.5 Hz
No. of geophone per spread	48
Geophone interval	10 feet ( 3.048 meter)
Recorder	Geode
No. of channels	48
Sampling interval	0.5 ms
Record length	2s

Table 1: Seismic data acquisition parameters that applied in this study.

#### Seismic Source

A seismic source is defined as any device that releases energy into the earth in the form of seismic waves (Sheriff, 1991). Seismic data for this study were acquired using a Bison EWG (Elastic Wave Generator) weight drop seismic source.

#### Seismic Receivers

A geophone is a sensor that converts ground movement into voltage, which is then recorded by a seismograph. The deviation of this measured voltage indicates a seismic response and represents the passage of seismic waves. Single 4.5 Hz

geophones/receivers (Figure 5) were deployed. The geophones were connected to a pair of Geometrics Geodes (Figure 6) via a cable that transmits the motion-induced electrical signals from individual geophones to the seismograph. The electrical signals are digitized and recorded by the Geodes as SEG-2 Rev1 32-bit integer data.



Figure 5: 4.5 Hz single-component geophone was deployed to receive the seismic signal for the study.

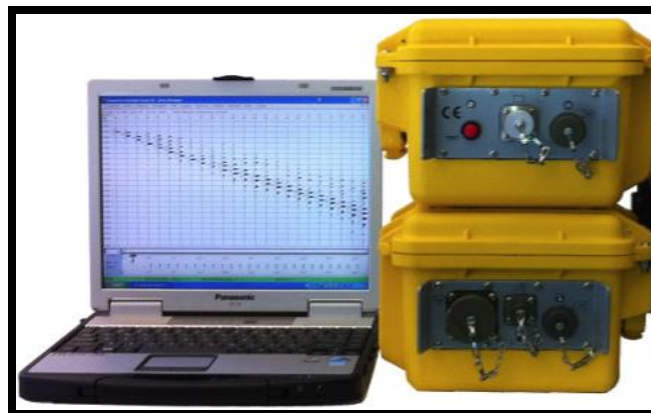


Figure 6: Geode Seismograph like those used in this study (<https://www.passcal.nmt.edu/content/instrumentation/dataloggers/multi-channel-dataloggers-0>).

## Shot Gather

The shot gather shown in Figure 7 is from this study and shows the development of seismic waves across the 48-channel stationary spread.

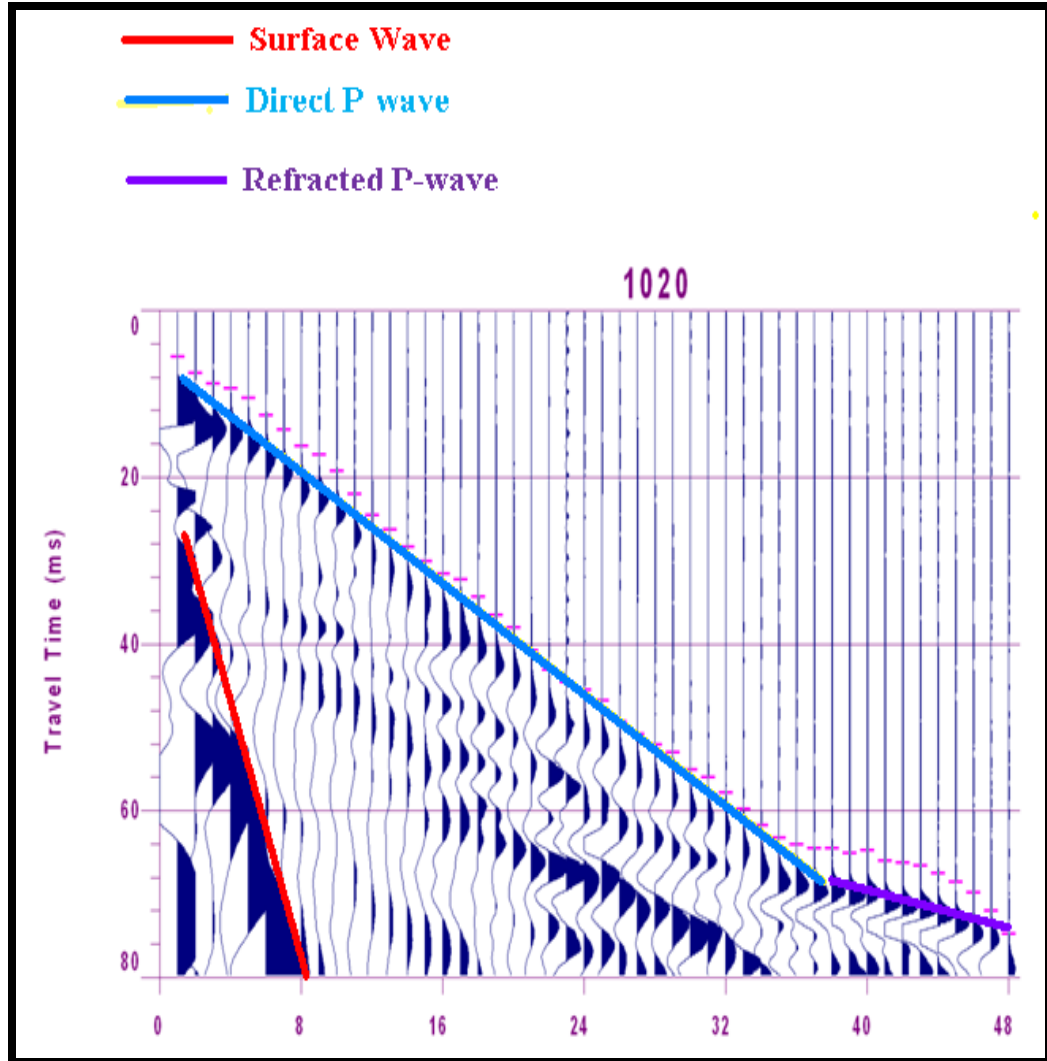


Figure 7: Shot gather from station 100. The red line indicates the surface waves. The light blue line represents direct P-wave arrival, and the purple line indicates a shallow refraction event.

## CHAPTER 3

### **Multichannel Analysis of Surface Wave (MASW) Analysis**

Seismic field methods that involve the drilling of boreholes are quite expensive and intrusive, and are impractical to be used in urban areas. On the other hand, non-invasive methods using a weight drop or vibratory source can produce sufficient energy to produce abundant surface waves for analysis of their dispersive characteristics.

SurfSeis3 software developed by Kansas Geological Survey (KGS), was used to process the data for the multichannel analysis of surface waves (MASW) method. Surface waves are characterized by low velocity, low frequency, and high amplitude. The SurfSeis3 software has four main components in the MASW method (Miller et al., 1999): (1) roll-along data acquisition, (2) dispersion-curve imaging (Park et al., 1998; Xia et al., 2007), (3) dispersion-curve inversion to get a 1-D shear-wave velocity ( $V_s$ ) profile (Xia et al., 1999), and (4) accumulating multiple 1-D results into 2-D images (Miller et al., 1999, 2003) applying interpolation algorithms (Matheron, 1967). The active MASW method is the most common type of MASW survey and can produce a 1D velocity function and 2D profile (Park et al., 1999; Xia et al., 2000). During the transmission of energy, each frequency component of a surface wave has a different propagation velocity, called a phase velocity ( $C_f$ ), at each unique frequency ( $f$ ) component. These unique characteristics result in a different wavelength ( $\lambda_f$ ) for each frequency propagated. This property is called dispersion. Although ground roll is considered noise on a body wave survey, but instead using MASW analysis the surface waves can be used to estimate near-surface earth parameters.

In SurfSeis3 the steps for determining the shear wave velocity profiles are : (1) acquiring multichannel records and converting the DAT file to KGS file format (2) extracting the fundamental-mode and higher order mode dispersion curves, and (3) inverting those curves to obtain 1D/2D  $V_s$  profile (i.e., Blake, 2012). The entire process is shown in the flow chart Figure 8.

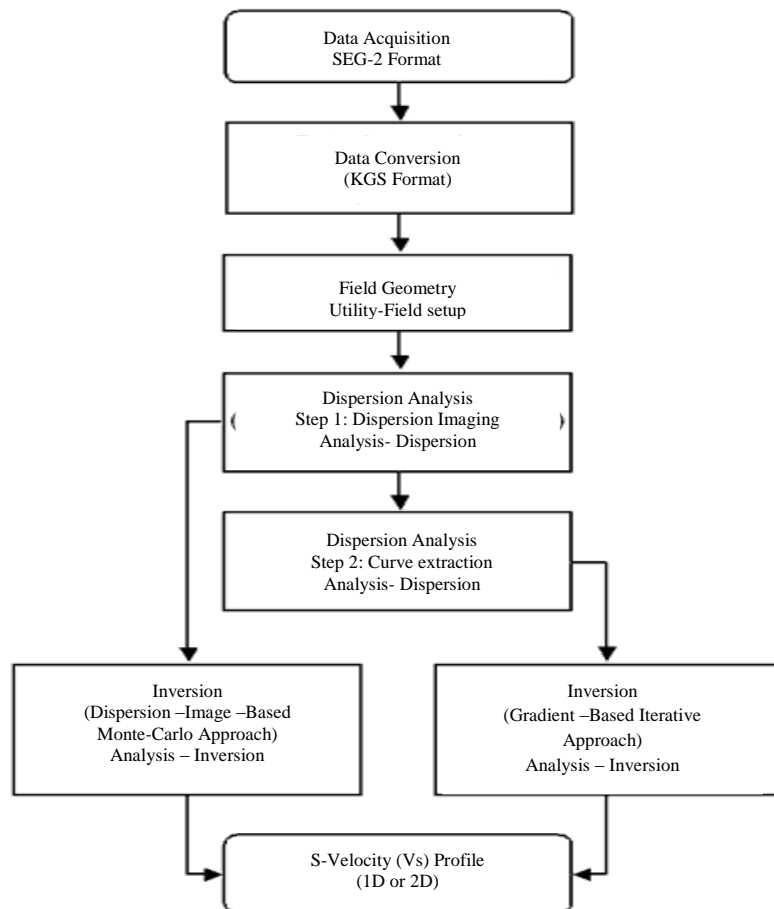


Figure 8: Flow chart of MASW processing steps.  
(<http://www.kgs.ku.edu/software/surfseis/s2intro.html>)

### Dispersion Curve Analysis

Dispersion curve analysis is the most important part of MASW method because the interpretation of subsurface geology depends on an accurate extraction of the

dispersion curve. The Surfseis3 software package is capable of separating the fundamental mode from other signals if the receiver spread is large enough, as described in Park and Miller (2001). The dispersion curve is an expression of phase velocity (feet/sec or m/sec) versus frequency (Hz); where the signal to noise ratio (S/N) is expressed as the highest amplitude region of the dispersion curve at a given frequency. It is also called a phase velocity curve. The phase velocity of a surface-wave is 0.9 to 0.95 times that of an S-wave. The phase velocity curve reflects the averaged velocity model beneath the receiver array. A best-fit curve is extracted based on that highest (S/N) amplitude for a given mode. The multi-channel approach to dispersion curve analysis can significantly improve the S/N as well as benefit from pattern recognition (Parker et al., 1998) that enables the identification of various kinds of seismic waves from their arrival and attenuation patterns.

### **MASW Method Modeling**

In this study, six MASW models were produced to seek a consistent result in determining the bedrock depth and velocity structure. Four models used a subset of the total 48 channels (i.e., 24 and 36) rolled through the 48 channel spread, with two of these pushed and two pulled. ‘Pushed’ refers to a shot position leading a rolled set of receivers, and ‘pulled’ refers to a shot position that is behind a set of rolled receivers. The last two models were shot through a stationary spread of 24 and 48 channels. The following is a summary of these six models:

Model 1: Push 24 rolled through 48 channels (receiver array is not fixed)

Model 2: Pull 24 rolled through 48 channels (receiver array is not fixed)

Model 3: Push 36 rolled through 48 channels (receiver array is not fixed)

Model 4: Pull 36 rolled through 48 channels (receiver array is not fixed)

Model 5: Shoot through stationary 48 channels (receiver array is fixed)

Model 6: Shoot through stationary 24 channels, channels 13-36 of 48 channels (receiver array is fixed).

The processing steps and analysis for Models 1 through 6 are explained in Appendices A through F, respectively.

### Summary of MASW Results

All models were used to calculate the thickness of the glacial drift as defined by the abrupt increases of Vs at depth (Table 2 and Figure 9). The different MASW models give almost the same results with minor variation.

Model No.	Velocity profile	Depth to bedrock (ft)
Model 1	MASW 2D roll 24 through 48 channels pushed	113
Model 2	MASW 2D roll 24 through 48 channels Pulled	118
Model 3	MASW 2D roll 36 through 48 channels Pushed	113
Model 4	MASW 2D roll 36 through 48 channels Pulled	105
Model 5	MASW 1D 1 through 48 stationary channels	120
Model 6	MASW 1D 13 through 36 stationary channels	112

Table 2: Summary of MASW 2D and 1D shear wave of modeling parameters.

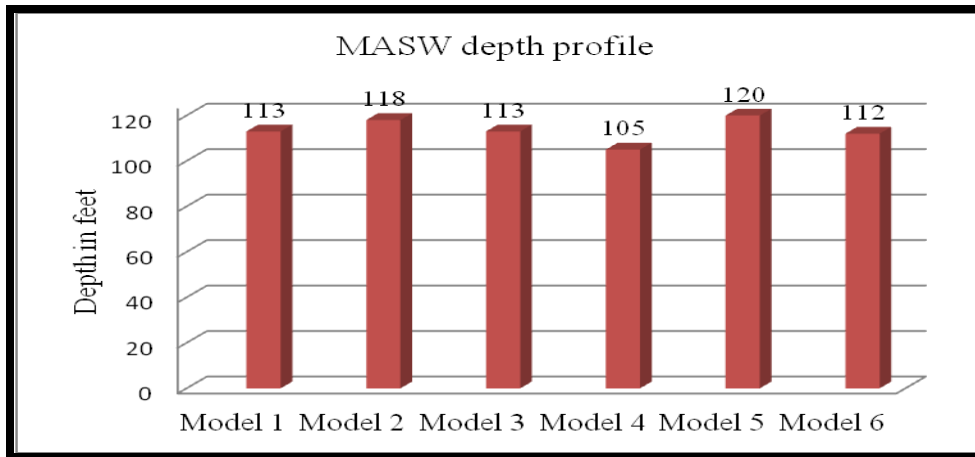


Figure 9: Bedrock depth is found from the different model using MASW method.



## CHAPTER 4

### Seismic Refraction Analysis

Seismic refraction analysis is based on measuring the time for seismic waves to travel down to, and along a boundary of the faster material, and then back to the surface. Seismic waves are produced from a source (weight drop) and then geophone record seismic signals received along the survey profile. Since P-waves travel at the fastest speeds, the first seismic signal received by a geophone represents the P-wave arrival as shown in Figure 10 (Reynolds, 2011).

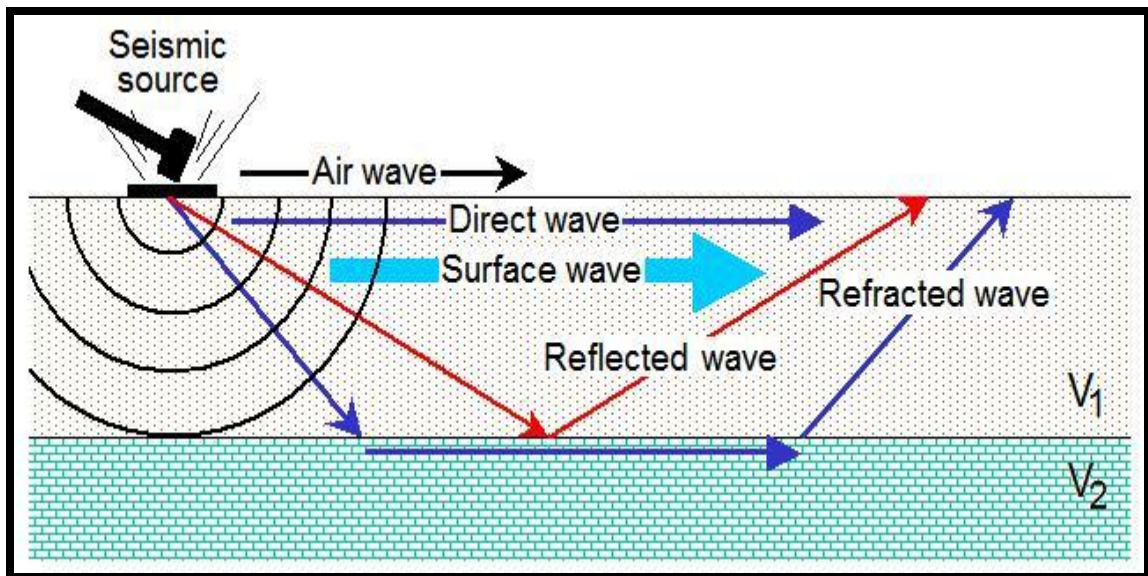


Figure 10: Schematic diagram showing the respective paths for direct, reflected and refracted rays (<http://www.parkseismic.com/images/ThreeTypes.JPG>).

The schematic diagram illustrates the path of seismic waves generating from a source at the surface. Some of the seismic energy travels at the surface as a direct wave. When a seismic wave meets an interface between two different soil and rock layers, a portion of the energy is returned as a reflection, and the remainder scatters through the layer boundary at a refracted angle. At the critical angle of incidence, the wave is

refracted and will progress parallel to the interface at the velocity of the underlying layer. Energy from this critically refracted wave returns to the surface in the form of a head wave, which may arrive at the more distant geophones before the direct wave. The IXRefraX3 software, developed by Interpex, and used in this study applies the generalized reciprocal method (GRM).

### **Generalized Reciprocal Method (GRM)**

Various seismic refraction software has been developed to process and interpret seismic refraction data, among these are REFLEXW (Sandmeier, 2007), SeisOpt<sup>R</sup>α2D<sup>TM</sup> (Optim LLC, 2002) and IXRefraX3 (Reynolds, 2010). IXRefraX3 is an integrated software package for processing and interpreting seismic refraction data using the Generalized Reciprocal Method of Derek Palmer. In 1980, Palmer (1980) launched the theory of Generalized Reciprocal Method (GRM). GRM is an inversion procedure that uses travel-time data from both forward and reverse shots and which provides a graphical solution to resolve the geometry of subsurface refractors (Palmer, 1980). The method uses refraction migration to obtain the detailed structure of a refractor and information about any localized lateral variations within it. Refraction migration uses offset distance that is the horizontal separation between a point on the refractor where a ray is critically refracted, and that at the surface where the ray emerges (Reynolds, 2011).

### **Creating Spread**

The “creating spread” operation is the first step to process seismic refraction data using the IXRefraX3 software. Shot records are imported implicitly as SEG-Y format and the spread should contain at least seven shots per spread: minimum of two end-on, one

mid-spread, and at least two off-end shots (this includes forward and reverse shots). Additional off-end shots should be considered with different offsets from the spread to ensure underground ray path coverage (Reynolds, 2011). For this study, there are 84 shots in 84 computer files recorded by 48 channels with a single 4.5 Hz geophone at a 10-foot spacing ranging from station 101 through 148 at distances 1010 through 1480 feet as shown in Figure 11.

### Picking First Break

First break picking is combined into the system, and can be examined and re-picked from almost any point in the interpretation flow. Picking first breaks as shown in Figure 12 through the entire sequence of shot records and saved frequently (<http://www.interpex.com/SoftwareIndex.htm>).

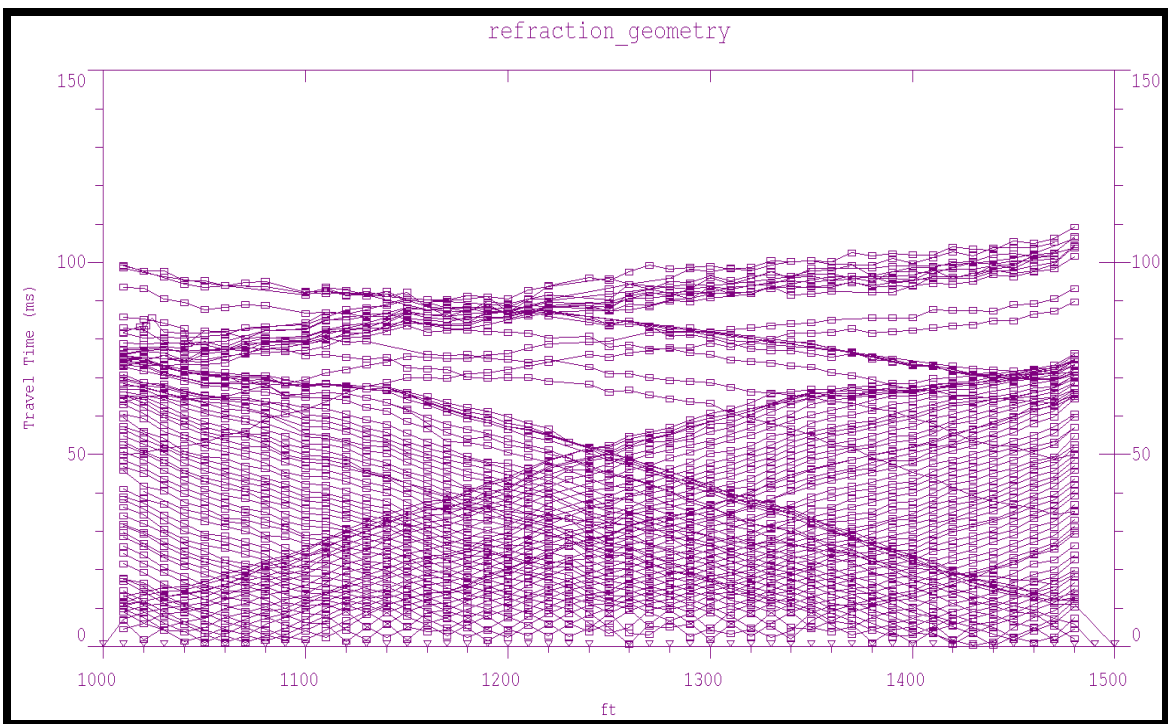


Figure 11: The data points and lines are color coded to reflect the arrival's layer assignment.

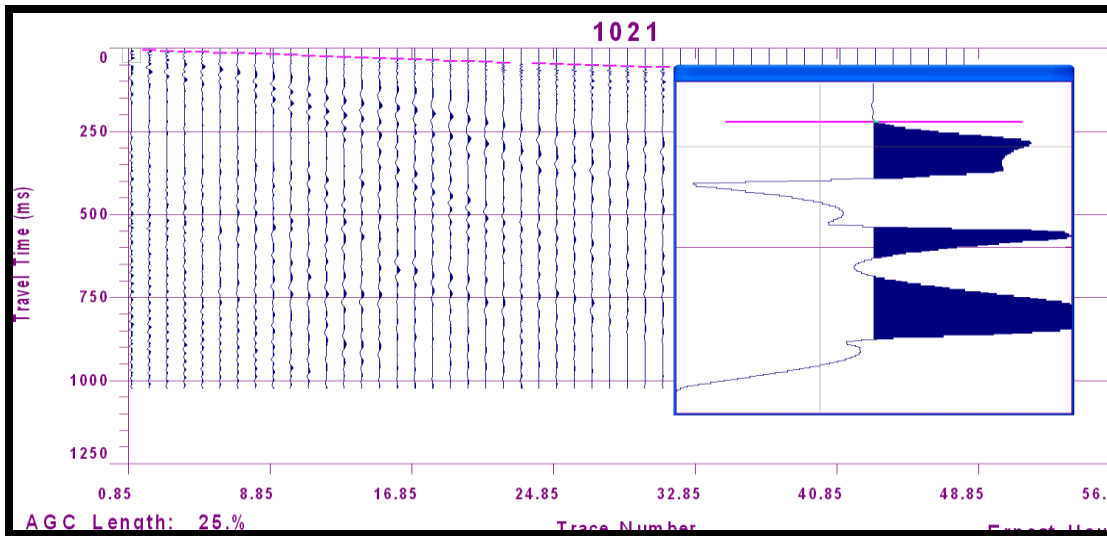


Figure 12: IXRefrax3 screen showing a shot record with magnified window of a first break pick.

### Flat Layer Interpretation

After picking the first break of all shot records, the picks can be interpreted as two layer or three layer models using the software (Appendix G). This interpretation gives a quick estimate of the velocity of different layers and bedrock depth. According to the flat refraction analysis, the bedrock with a P-wave velocity of 13,542 ft/sec (4,128 m/sec) is at a depth of 119 feet (36.3 meters), and the overlying glacial drift has a P-wave velocity of 5,651 ft/sec (1,722 m/sec).

### Model Estimation

Model estimation is the first step to generate subsurface mapping with lateral variations. The following things should be examined before making a model.

1. The number of layers
2. Surface velocity, refractor velocity and depth to bedrock

Before assigning these parameters to make a model, one should have examined the data and used the knowledge of the geology of the study area to assign the number of layers, the velocities and depths. Based on existing water well data and flat refraction interpretation, the average P-wave velocity for the surface layer is found about 7,000 ft/sec (2,134 m/sec), and the bedrock refractor velocity is found about 17,000 ft/sec (5,182 m/sec), and bedrock depth is found about 120 ft (36.6 meters). These parameters were used for the starting model for GRM analysis.

### **Estimate Layer Assignments**

Estimate layer assignment is the second step to produce a model. This model can be used to calculate the layers from which each arrival comes. For each arrival on the travel time curve, a travel path including the direct path and a path along each available refractor is calculated (<http://www.interpex.com/SoftwareIndex.htm>).

### **Estimate Reciprocal Times**

Reciprocal times are calculated as follows: IXRefrax3 creates a table of all shot positions. This allows the generation of forward and reverse shots for each shot position using all available data for each pair of opposing shots and each refractor.

- If there is overlap for both shots, the reciprocal times are averaged.
- If there is overlap for one shot only, this value is used.
- If there is no overlap of shot and receiver for either shot, the reciprocal time is determined from the simple 2-D model (<http://www.interpex.com/SoftwareIndex.htm>).

### **Forward (MRG) Calculation**

The software implements a forward calculation using the existing data and 2-D model, which resides in IXRefrax3. The results are drawn on the screen, and the RMS and average fitting errors are displayed (<http://www.interpex.com/SoftwareIndex.htm>).

### **Inverse Model Calculation**

This process is performed by Ridge regression (Inman, 1975). This calculates the Jacobian matrix of partial derivatives by perturbing each velocity and vertex in turn and recalculating the forward model to find the partial derivatives using a finite difference method (Palmer, 1980, 1981).

### **GRM Interpretation**

While the simple 2D model was calculated, and the layers were assigned to arrivals and the reciprocal times have been estimated, the GRM interpretation was performed. Full GRM analysis uses the X-Y values determined from the model and allows editing them if required. The optimum GRM analysis is a two-pass process. The first pass uses zero for all X-Y values. The second pass uses the model determined in the first pass to calculate the optimum X-Y values from the layer velocities and thicknesses to make a composite model (depth and velocity). Figures 13 and 14 show that the depth of bedrock at the study site ranges 118-122 feet (36-37.2 meter) with an average P-wave velocity of 17,500 ft/sec (5,344 m/sec) for bedrock and 5,000 ft/sec (1,524 m/sec) for the glacial drift layer. The error bars in Figure 13 indicate uncertainties from the averaging GRM values. Figure 15 shows the refractor surface beneath the receivers obtained from the generalized reciprocal method. In summary, the depth to bedrock is about 120 feet (36.6 m), but probably varies some across the profile.

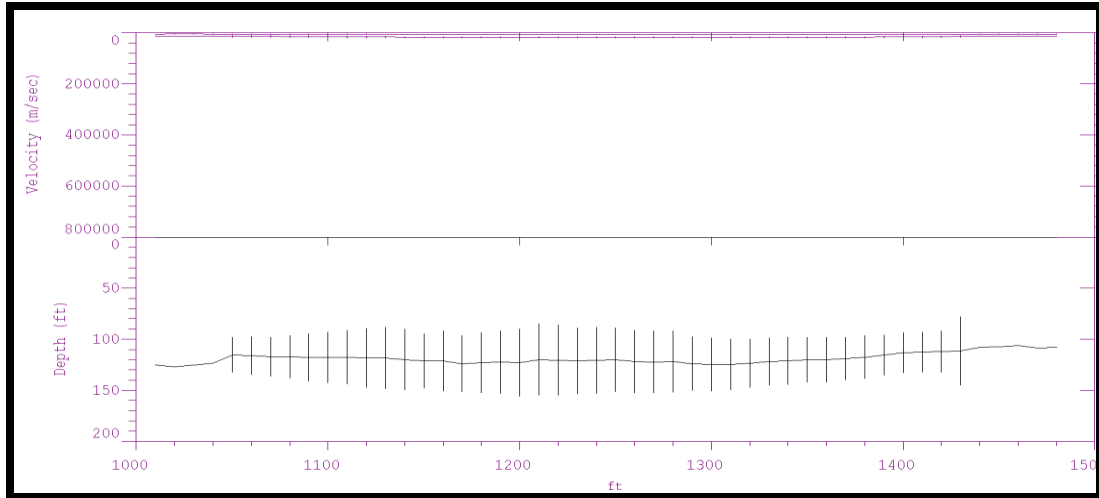


Figure 13: P-wave refraction velocity model with depth. The upper part of the diagram indicates the velocity beneath the station between 1050 feet (320 m) and 1430 feet (436 m) and lower part show the depth to bedrock.

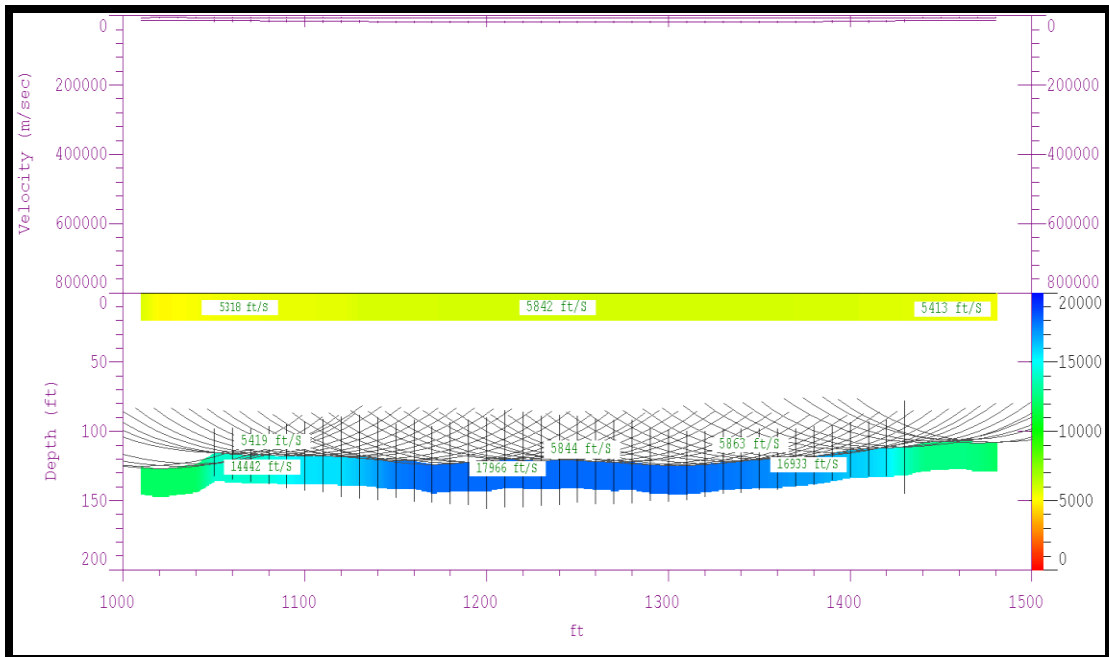


Figure 14: P-wave velocity model (Refraction model with depth and velocity). It shows the depth of bedrock ranges from 118-122 feet (36-37.2 meter). The average P-wave velocity is about 17,000 ft/sec (5,182 m/sec) for limestone bedrock and is about 5,500 ft/sec (1,676 m/sec) for the glacial drift.

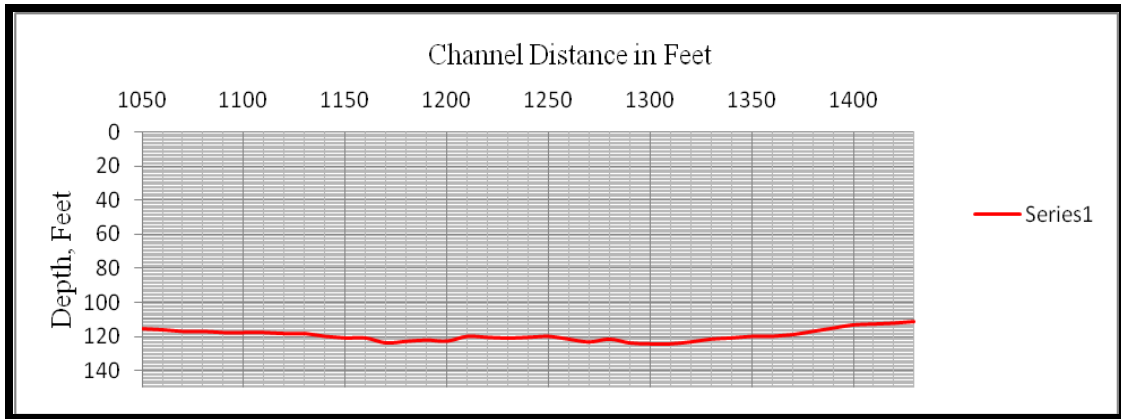


Figure 15: Refractor surface beneath the receivers obtained from the generalized reciprocal method indicating that the depth to bedrock is about 120 feet (36.6 m).



## CHAPTER 5

### Elastic Properties of the Glacial Drift Surface Layer

Poisson's ratio, an elastic property, is important for assessing the mechanical behavior of the earth materials. Poisson's ratio is defined as the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force, and can be determined from  $V_p$  and  $V_s$  of the materials. The average compressional and shear wave velocities ( $V_p$  and  $V_s$ , respectively) for the glacial surface layer (not for bedrock) obtained from the seismic refraction and MASW models of this study, were used to calculate Poisson's ratio using the following equation (Salem, 2000).

$$\text{poisson's ratio, } \sigma = \frac{0.5\left(\frac{V_p}{V_s}\right)^2 - 1}{\left(\frac{V_p}{V_s}\right)^2 - 1} \dots\dots\dots 1$$

Additionally, an empirical relationship (Equation 2 below) between  $V_p$  and porosity ( $\Phi$ ) for soils and shallow sediments of different lithologies has been described by Watkins et al. (1972).

$$\text{Porosity, } \Phi = -0.175 \ln (V_p) + 1.56 \dots\dots\dots 2$$

The calculated Poisson's ratio and porosity for the glacial drift of the present study using Equations 1 and 2 are shown in Table 3, and the resulting relationship between Poisson's ratio and porosity is shown in Figure 16. A review of studies regarding Poisson's ratio is given in Table 4. The values of Poisson's ratio and porosity for the clayey and saturated glacial drift of the present study are consistent with the results summarized by Stuempel et al. (1984), Meissner et al. (1985) for such material.

## Results and Calculation

Position	P-wave velocity(feet/sec)	S-wave velocity(feet/sec)	Poisson's ratio, $\sigma$ (Equation 1)	Porosity, $\Phi$ (Equation 2)
1180	5784	1330	0.472	25.19
1190	5772	1336	0.472	25.23
1200	5787	1354	0.471	25.18
1210	5784	1374	0.470	25.19
1220	5792	1302	0.473	25.17
1230	5790	1313	0.473	25.17
1240	5791	1394	0.470	25.17
1250	5793	1383	0.470	25.17
1260	5803	1336	0.472	25.13
1270	5807	1363	0.471	25.12
1280	5825	1378	0.470	25.07
1290	5825	1318	0.473	25.07
1300	5823	1340	0.472	25.08

Table 3: The estimated Poisson's ratio and porosity for the glacial drift of this study, calculated from equations 1 and 2.

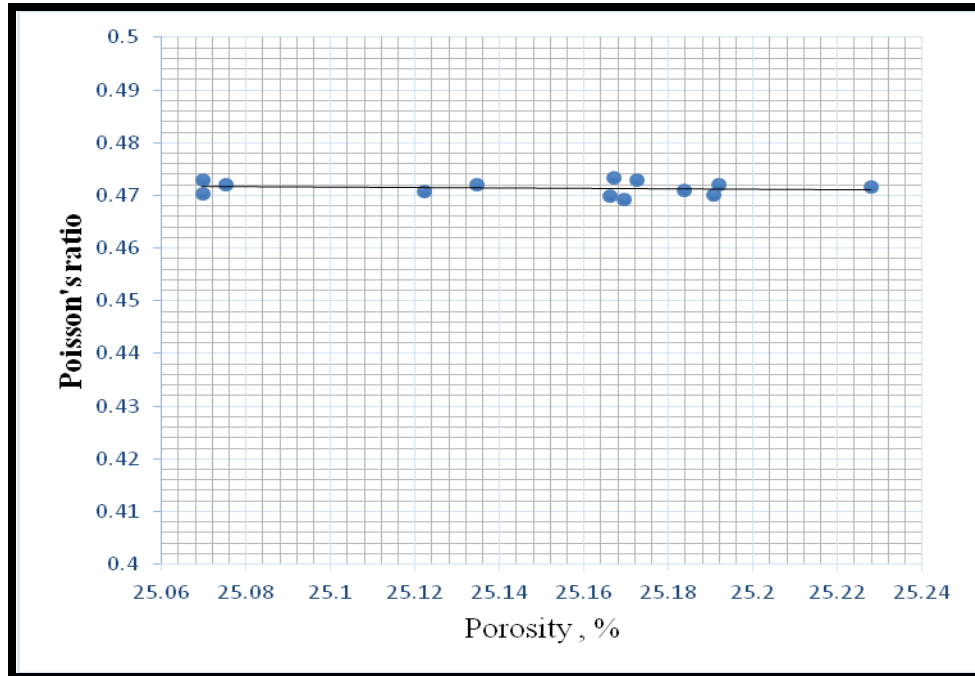


Figure 16: Poisson's ratio versus porosity obtained from compressional and shears wave velocities for surface soils, saturated sediments.

Study	Results, observations, remarks
Stuempel et al. (1984), Meissner et al. (1985)	Obtained $\sigma$ values of up to 0.49 for shallow, clayey, saturated sediments
Davis & Schultheiss (1980)	Obtained a $\sigma$ range of 0.4982-0.4997 for clays
Stoke & Woods (1972)	Obtained $\sigma = 0.31$ for unconsolidated, unsaturated sediments
Mann & Fatt (1960)	Pore aqueous solutions lead to an increase in $\sigma$ from negligible value to 0.5
Salem (1993)	Obtained a $\sigma$ range of 0.27-0.40 for shaly sandstone reservoirs saturated with multiphase fluids
Mann & Fatt (1960)	Pore aqueous solutions lead to an increase in $\sigma$ from a negligible value to 0.5
Tiab & Donaldson (1996)	Represented a $\sigma$ range of 0.14-0.41 for formations of different lithologies and saturates.
Koefoed et al. (1963)	Obvious relationship between the increase in $\sigma$ and the decrease in $\sigma$

Table 4: A review of studies related to Poisson's ratio (Salem, 2000).

## CHAPTER 6

### Summary and Conclusion

The purposes of this study were to determine, using a common data set, the  $V_p$ , and  $V_s$  velocity structure of glacial drift at a study site in Jay County, Indiana by using the MASW and seismic refraction methods. Those results were then used to calculate Poisson's ratio for the materials. SurfeSeis3 MASW software was used to process the data and produce 1D and 2D S-wave velocity profiles, by inverting the phase velocities of the surface waves. The high-velocity contrast in the MASW results suggest a bedrock depth of about 115 feet (35.1 m) with a bedrock shear wave velocity ranging from 2,400-2,700 ft/sec (732-823 m/sec), and the glacial drift having a shear wave velocity ranging from 1,200-2,000 ft/sec (366- 610 m/sec). P-wave seismic refraction analysis of the same data set suggests that the depth of bedrock ranges from 118-122 feet (36- 37.2 m/sec), with an average P-wave velocity of 5,500 ft/sec (1,676 m/sec) for the glacial drift and 17,000 ft/sec (5,182 m/sec) for the limestone bedrock. The water well closest to the survey area indicates a bedrock depth of 110 feet (33.6 m), which is in reasonable agreement with the seismic results. Other water wells farther away indicate a 122 feet (37.2 meter) depth to bedrock and another one at 140 feet (42.7 m) indicating that the bedrock depth in the area is somewhat variable but generally 110-120 feet (33.5- 36.6 m) depth near the study area and consistent with both the MASW and seismic refraction results. The estimated velocity structure using the MASW method and seismic refraction method is consistent with values suggested in the NEHRP site classification (FEMA 450-1/2003) for these glacial materials. For glacial drift (site class C),  $V_s$  should 1,200-1,800 ft/sec (366- 549 m/sec) (FEMA 450-1/2003). A consistent shear wave velocity of 2,400-2,700 ft/sec (732-

823 m/sec) for limestone bedrock was determined in the 1D and 2D MASW profiles and is consistent with site class B (FEMA 450-1/2003).

Poisson's ratio of the glacial drift of this study, calculated from seismic compressional and shear wave velocities, was found to range from 0.470 to 0.473, which is consistent with that of saturated clayey surface soils and sediment elsewhere (Stuempel et al., 1984; Meissner et al., 1985).

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## **Appendix A:**

### **Model 1: MASW 2D roll 24 through 48 channels pushed**

The following modeling parameters were entered into SurfeSeis3 for model 1.

- Survey type: MASW active survey and the seismic source is the impulsive source.
- Seismic survey geometry assignment: receiver array is not fixed, i.e., 24 rolls along through 48 with source pushing traces starting from channel 1 through 24, end at 25 through 48. Geophones 10 feet apart.
- Pushing seismic sources array: Files 1015-1039; Total number of the file are 25.
- Source location beginning from 95 to 119 and source offset distance is 60 feet.
- The mid-station is located ranging from 112 to 136.

### **Processing Step for Model 1**

The 48 geophones are located at stations 101-148, and a total of 25 seismic records were shot (acquired) with the source located at stations 95 through 119 for the records numbering from 1015 -1039.

SEG2 data files are converted to KGS format (*i.e., line1.dat*).

Applied geometry information (*i.e., field set up*) into the trace headers and

Then clicked on ‘display’ button, and then open the converted KGS data file (*i.e., line1.dat*). After that, one should have used the ‘scissors’ button located at the top-right corner of the window displaying the seismic data and specify to cut beginning

with traces 1 to 24 and increasing by 1 (Figure A1).

Next, one should have clicked on the "scissors" button to display a 'Cut Records' window comprising three tabs ('Record,' 'Trace,' and 'Time'). At the 'Record' tab selected the 'All Records' checkbox.

Next, clicked on 'Save Output As' button to specify the output file name (the default in this example would be *line1 (CUT).dat*). And at the 'Trace' tab selected the 'Begin' and 'End' trace numbers (i.e., 1 and 24). At both increments, boxes select 1 (this is because the source has moved with one geophone interval, i.e., 95, 96, etc.).

Finally, one should have clicked on the 'OK' button to extract (cut) the current set of records each including now only 24 traces and applied geometry setup (Figure A2). And then initiate the new file (e.g., *line1 (CUT).dat*) and proceeded through the records ([http://www.kgs.ku.edu/software/surfseis/how\\_to.html](http://www.kgs.ku.edu/software/surfseis/how_to.html)). Applying all the above steps to set up model 1, the geometry is shown in Figure A3.

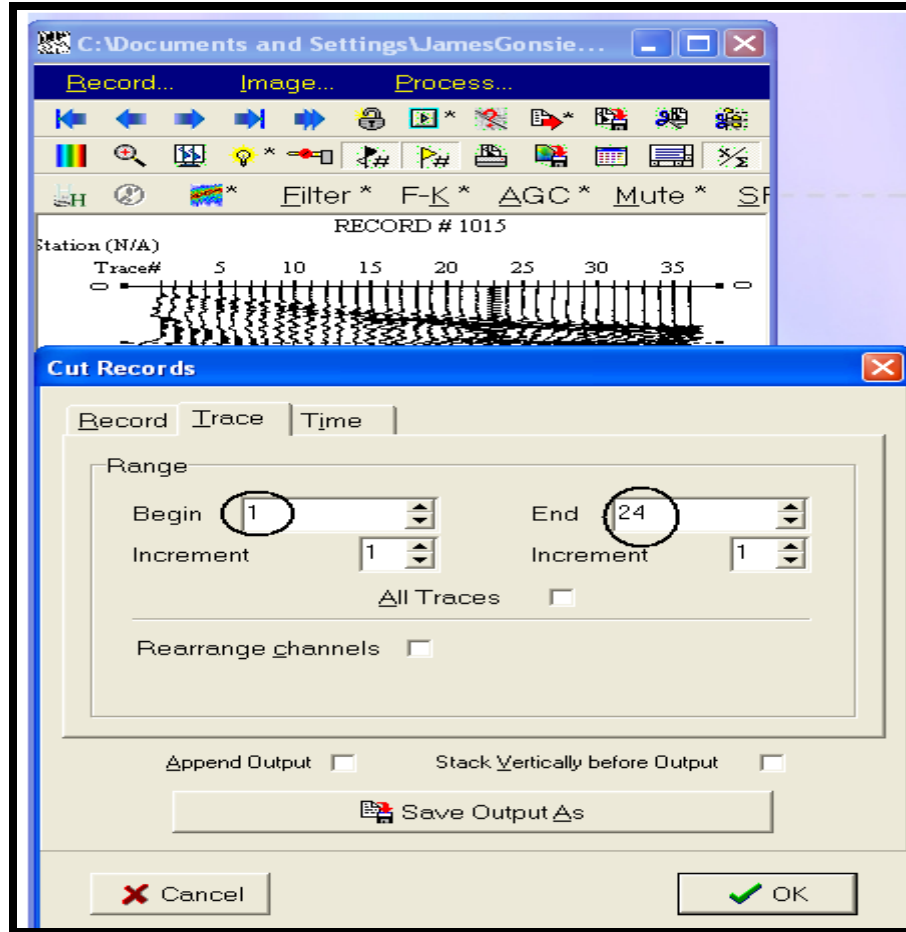


Figure A1: Roll along seismic data acquisition parameters selection. At the 'Trace' tab select the 'Begin' and 'End' trace numbers 1 and 24 respectively. At both increments, boxes select 1 (this is because source moved with one geophone intervals, i.e., 95, 96, etc.).

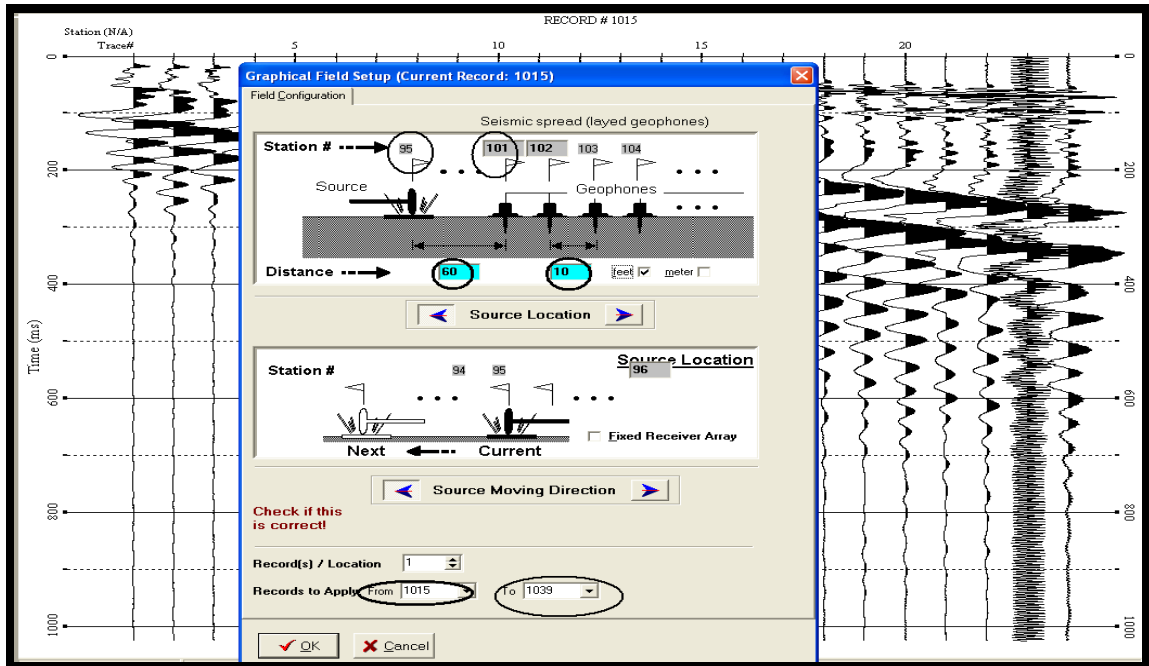


Figure A2: MASW seismic survey geometry assignment parameters selection. The figure shows 24 roll-along pushing traces, and offset distance is 60 feet (offset distance), and geophone spread is 10 feet.

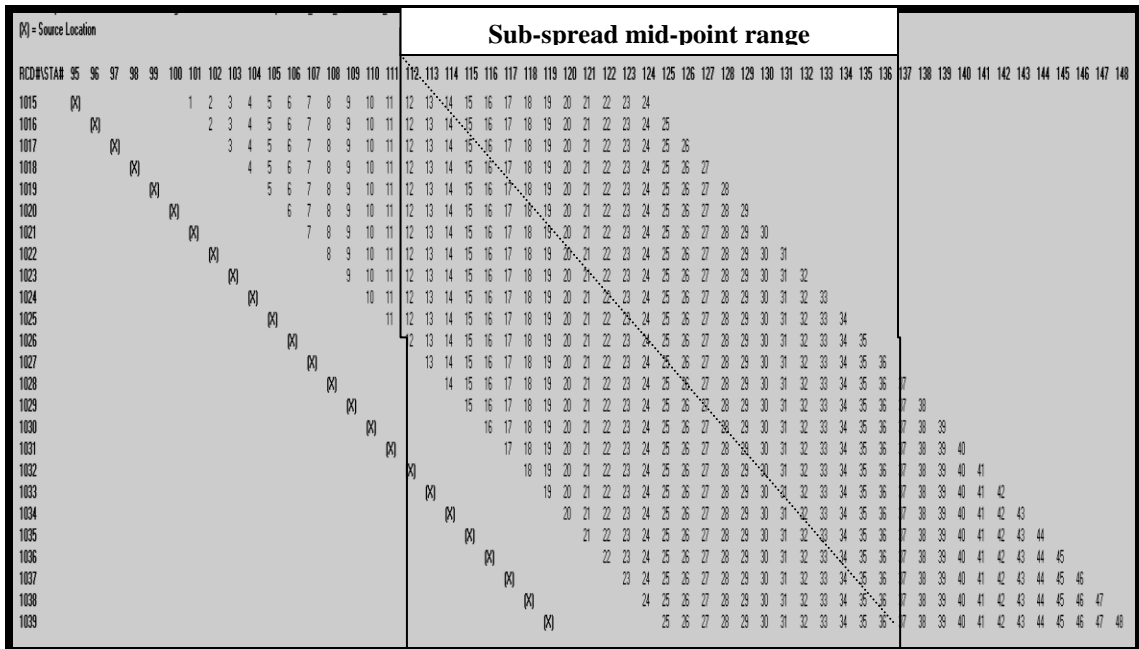


Figure A3: The figure shows receiver array is not fixed, i.e., 24 roll along pushing traces starting from 101 to 148 and source location (indicated by X) beginning from 95 to 119. The midpoints of each analyzed sub-spread are leveled as the mid station point and are distributed from stations 112 to 136.

## Data Processing

When geometry setup is done, the data is ready for further processing and interpretation. The steps are as follows:

- Single dispersion curves analysis
- Overtone analysis parameters
- Picking dispersion curve
- Inversion of dispersion curve

## Single Dispersion Curve Analysis

Preprocessing is required to get a primary idea about phase wave velocity and frequency range (Figure A4).

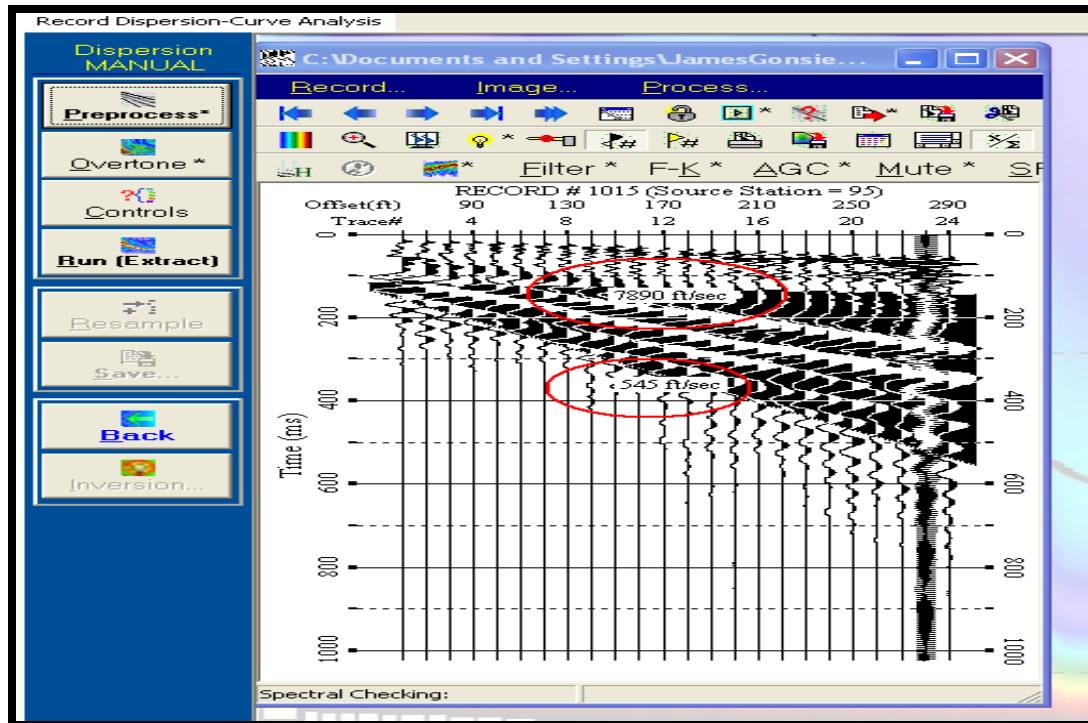


Figure A4: Single dispersion curve analysis for raw data file 1015 for the purposes of getting phase wave velocity ranges. According to this analysis, phase wave velocity range from 545-1100 feet/sec (166-335 m/sec).

## Overtone Analysis Parameters

Overtone analysis is required before picking the dispersion curve. Overtone analysis requires the input of the frequency and phase velocity ranges (Figure A5) to produce a dispersion curve (Figure A6).

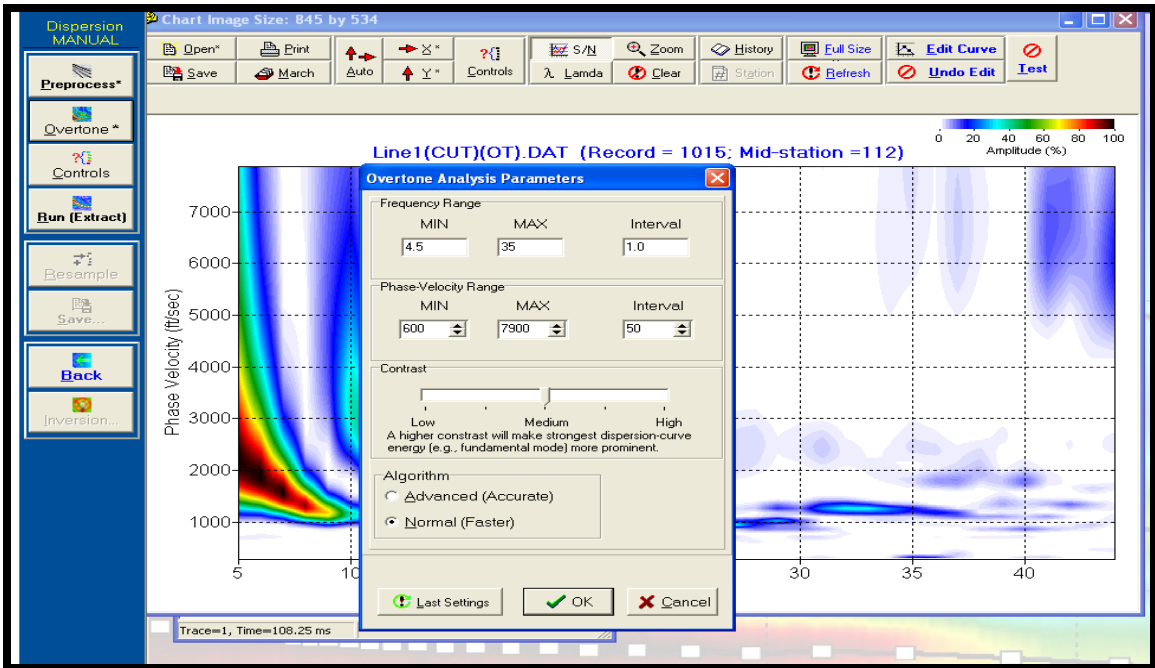


Figure A5: Overtone analysis parameter selection for model 1. Phase velocity range and frequency ranges are selected based on the seismic data.

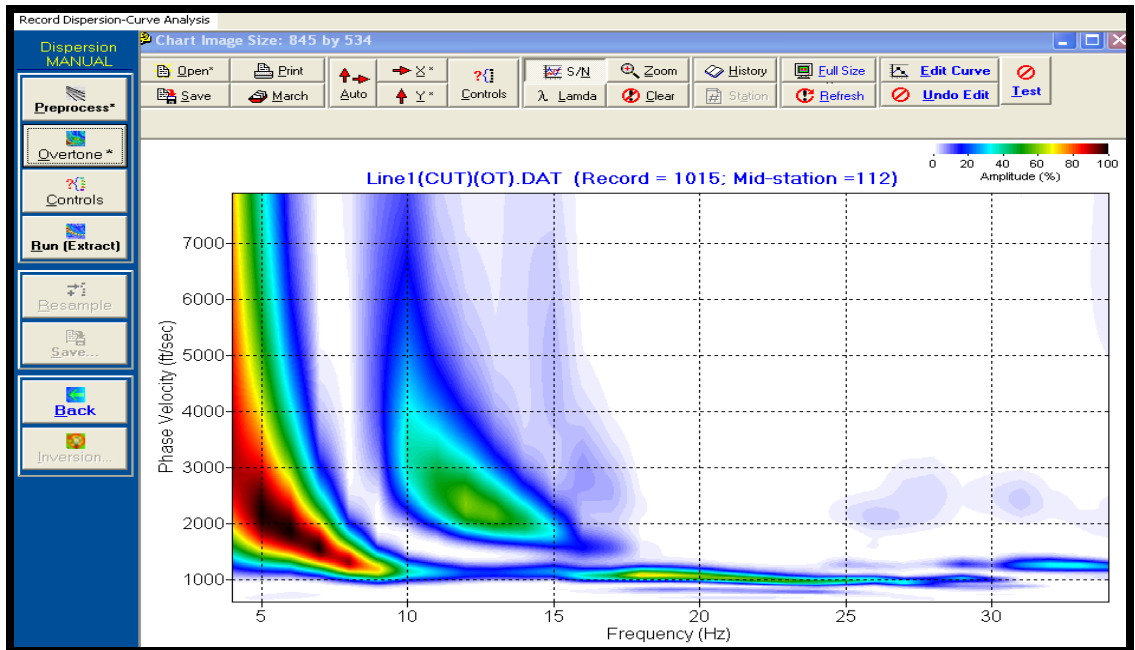


Figure A6: Applying phase velocity range and frequency range in all data to make a dispersion curve beneath the mid-station 112.

## Picking Dispersion Curve

The lowest velocity for any given frequency is named the fundamental mode velocity. The next phase velocity higher than the fundamental mode phase velocity is named the higher order mode velocity. Xia et al. (1999) stated that the phase velocity of Rayleigh waves of a layered earth model is a function of frequency and four groups of earth parameters such as compressional wave velocity ( $V_p$ ), shear wave velocity ( $V_s$ ), density, and thickness of layers. For the fundamental mode of Rayleigh waves, analysis of the Jacobian matrix for high frequencies (2–40 Hz) gives a measure of dispersion curve sensitivity to earth model parameters. Fundamental mode and higher order mode are extracted simultaneously considering signal-noise ratio and continued until the last dispersion curve. Here, however, only three example dispersion curves are shown which are the 24 channels pushed spreads centered at stations 112 (Figure A7), 113 (Figure A8) and 136 (Figure A9).

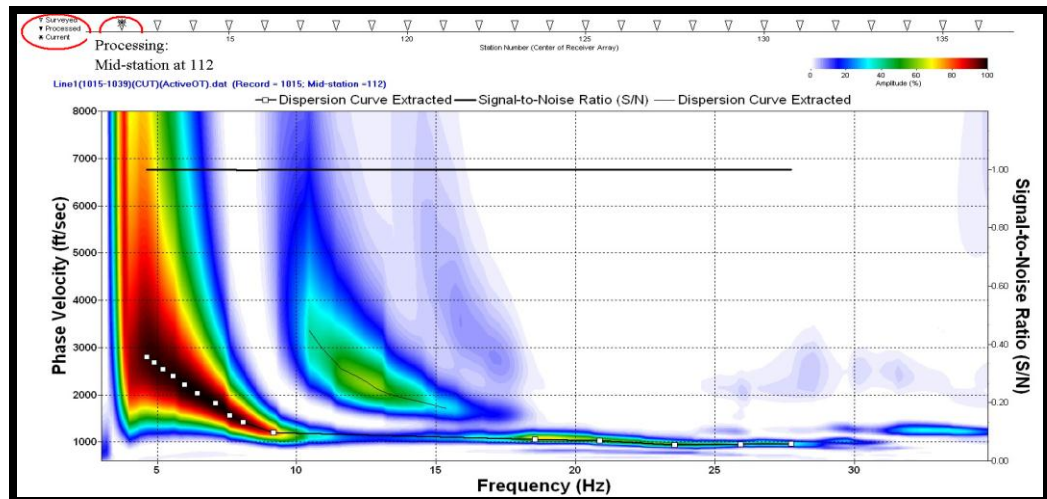


Figure A7: Dispersion curve (the function of phase velocity and frequency) is extracted for the fundamental mode and higher order mode simultaneously at mid-station 112 for this pushed 24-channel spread. The white dots indicate the extracted dispersion curve.



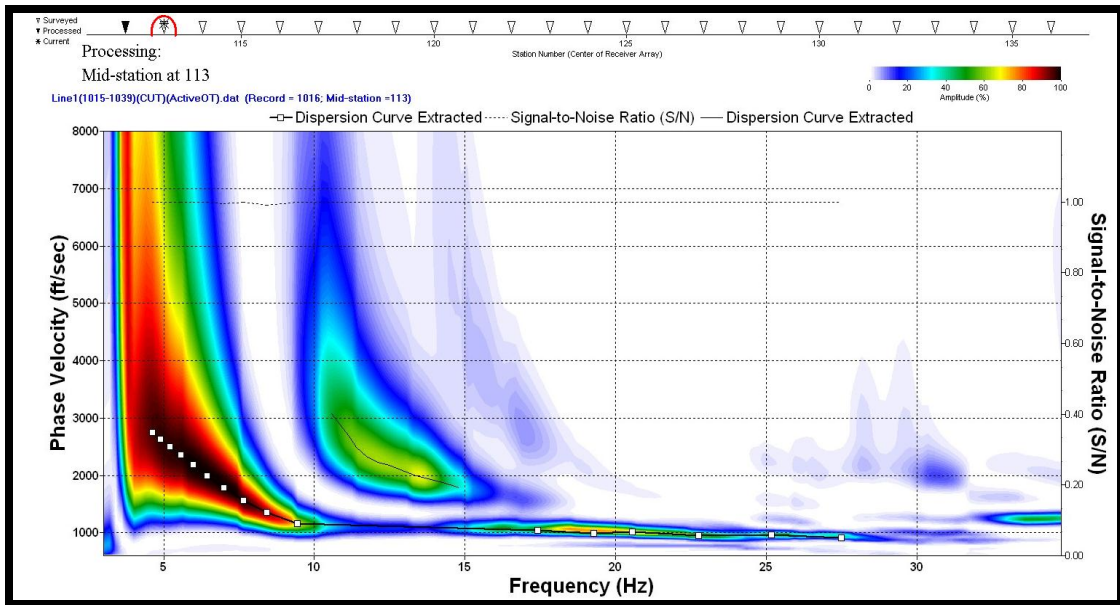


Figure A8: Dispersion curve (the function of phase velocity and frequency) is extracted for the fundamental mode and higher order mode simultaneously at mid-station 113 for this pushed 24-channel spread. The white dots indicate the extracted dispersion curve.

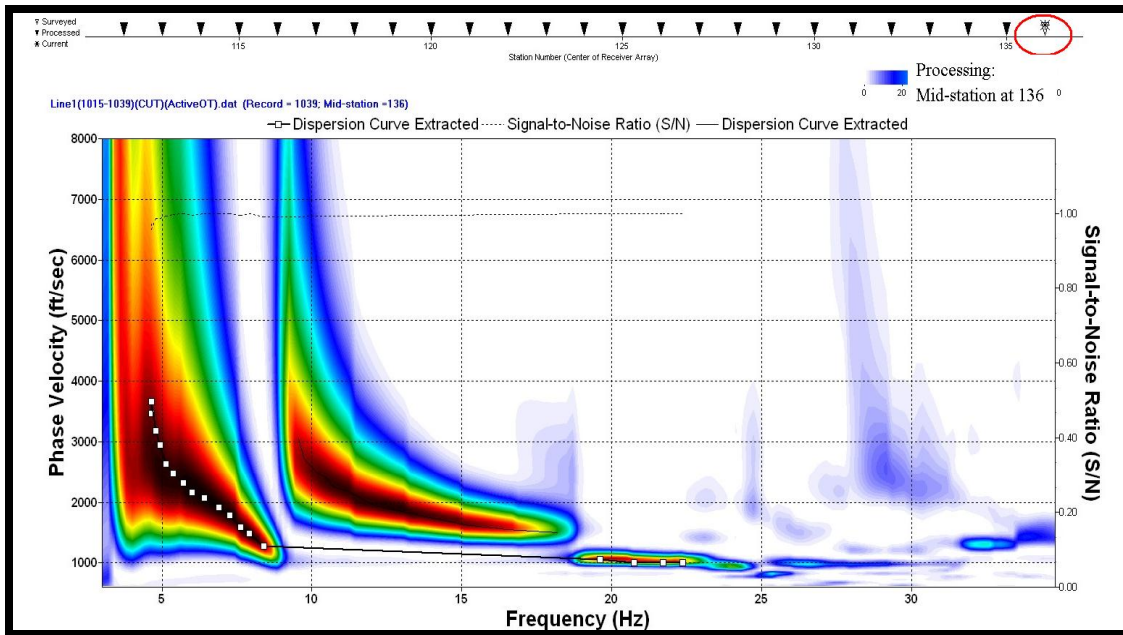


Figure A9: Dispersion curve (the function of phase velocity and frequency) is extracted for the fundamental mode and higher order mode simultaneously at mid-station 136 for this pushed 24-channel spread. The white dots indicate the extracted dispersion curve. The Signal to Noise ratio is a measure of high amplitude wave energy at a given frequency, which assists in dispersion curve picking.

## Inversion of Dispersion Curve

After picking the fundamental mode and higher order mode from all the dispersion curves, the dispersion data are inverted to produce an S-wave velocity profile (Xia, et al., 1999, 2002). The resulting 2D shear wave velocity profile (Figure A10) represents the series of 1D Vs functions produced for each 24-channel sub spread rolled through the stationary 48 channel spread with the series of 1D velocity functions plotted at each sub-spread midpoint (i.e., stations 112 through 136).

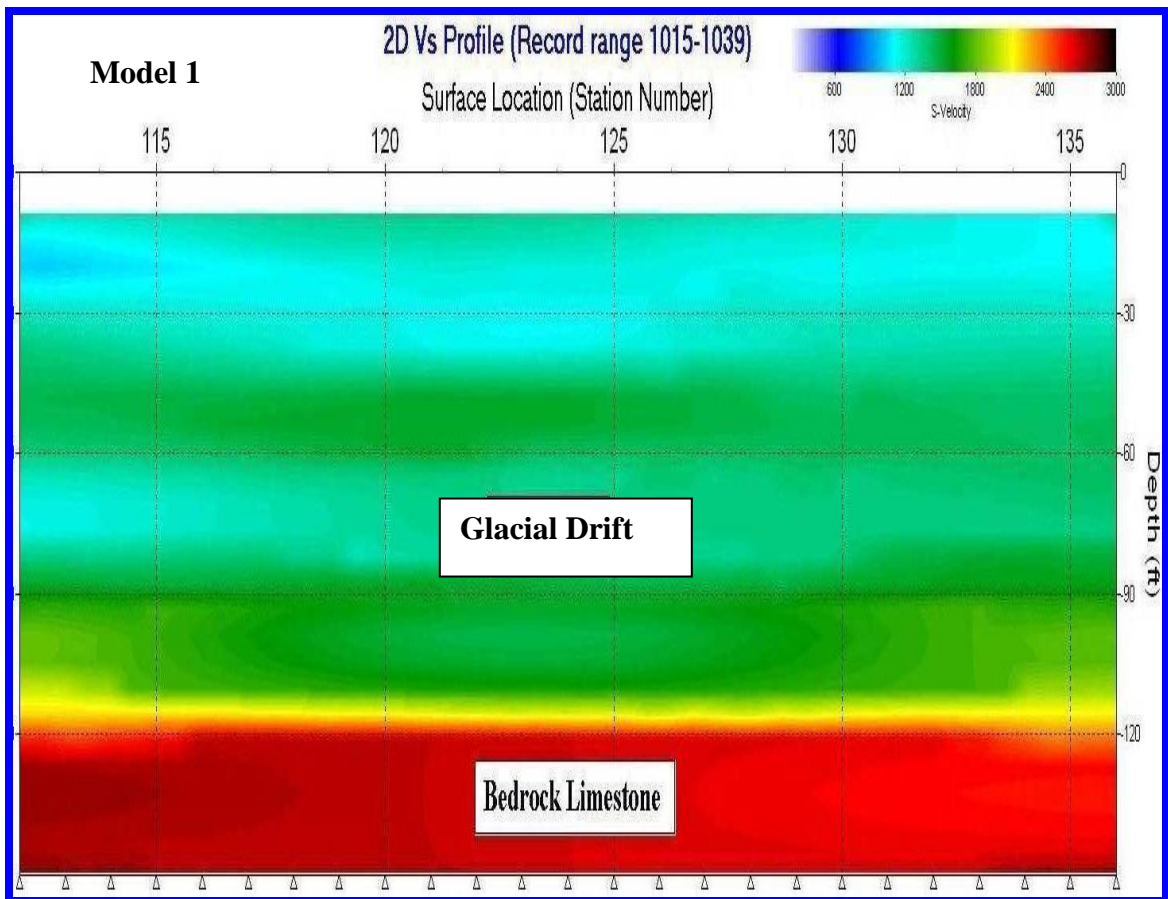


Figure A10: 2D (surface and depth) shear wave velocity ( $V_s$ ) profile obtained from the active source MASW survey using a 24 channel sub-spread pushed through the stationary 48 channel spread. High-velocity contrast inferred to define the depth to bedrock, and it is approximately 113 feet. The Average velocity is 1,800 feet/sec and 2,700 feet/sec for glacial drift and bedrock limestone respectively.

## **Interpretation of model 1**

In figure A10, the vertical axis is depth, and the horizontal axis is station location where a shear wave velocity function is plotted at the midpoint location of each 24 channel sub spread. The color of this 2D profile represents the variation of  $V_s$ .

In Figure A10, the different colors indicate velocities ranging from 400-3,000 feet/sec (121-914) m/sec. The velocities are in a range from about 1,200-2,000 feet/sec to about 115 feet or 35 meters at which depth the velocity increases abruptly to about 2,600-2,700 feet/sec (792-822 m/sec).

## **Appendix B:**

### **Model 2: MASW 2D roll 24 through 48 Channels Pulled**

The 48 geophones are located at stations 101-148, and a total of 25 seismic records were shot (acquired) with the source located at stations 130 through 154 for the records numbered from 1050-1075 with the stations at the middle of the sub-spread ranging from 112 to 136. The process for defining the geometry followed that of model 1 and produced the geometry profile for model 2 (Figure B1). The velocity function for each 24-channel record is plotted at the midpoint of the 24 channel sub-spread (Figure B1), so the locations labeled as 'Mid-station' are the location of the resulting series of 1D  $V_s$  functions. After completing the entire processes such as preprocessing and overtone analysis as previously described for model 1, the dispersion curves were picked (Figure B2) and inverted to produce the 2D shear wave profile shown in Figure B3.



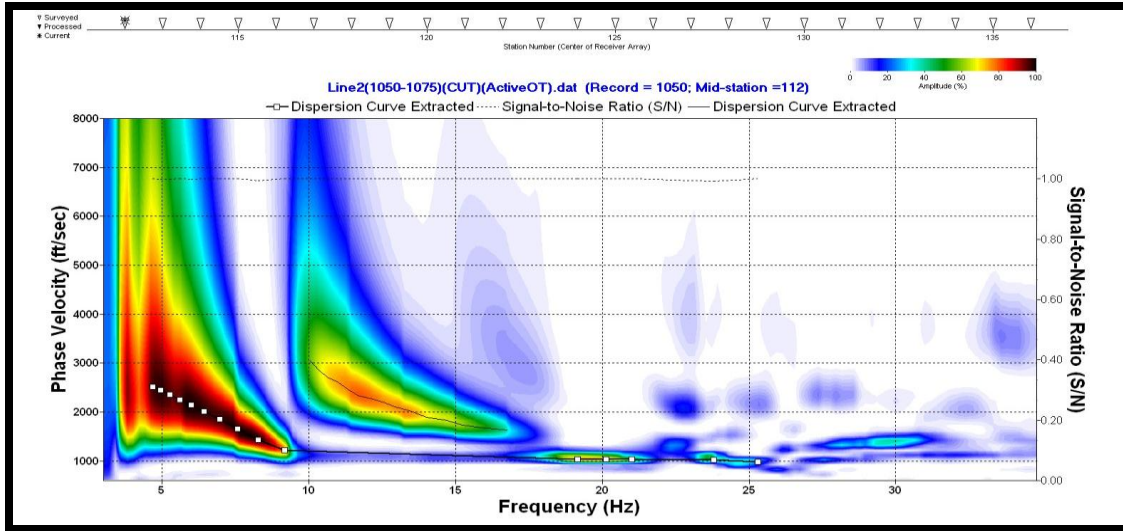


Figure B2: Dispersion curve is extracted for the fundamental mode and higher order mode simultaneously at mid station 112 for 24 roll-along pulled sub-spread.

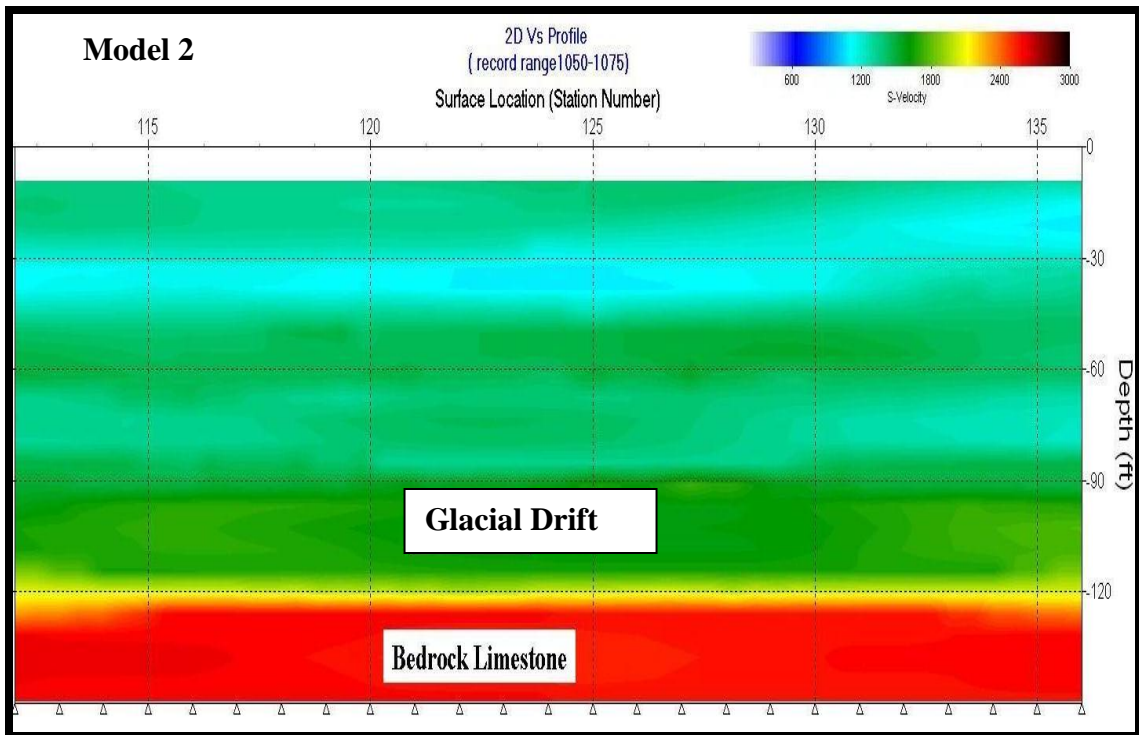


Figure B3: 2D (surface and depth) shear wave velocity (Vs) profile obtained from the active source MASW survey using a 24 channel sub-spread pulled through the stationary 48 channel spread. High-velocity contrast inferred to define the depth to bedrock, and it is approximately 118 feet. The average velocity is 1800 feet/sec and 2700 feet/sec for glacial drift and bedrock respectively.

## **Appendix C:**

### **Model 3: MASW 2D roll 36 through 48 Channels Pushed**

Modeling parameters were entered into the SurfeSeis3 for model 3.

- Survey Type: MASW Active survey and the seismic source is the impulsive source.
- Seismic survey geometry assignment: receiver array is not fixed, i.e., 36 rolls along pushing traces starting from station 101 to 148. Geophones are 10 feet apart.
- Pushing seismic sources array: record range 1015-1027 and total number of file are 13
- Source location beginning from 95 to 107 and source offset distance is 60 feet.
- The mid-station is located ranging from 118 to 130.

The process of defining the geometry followed that of model 1 and produced the geometry profile for model 3 (Figure C1). The velocity function for each 36-channel sub-spread (Figure C1), so the locations labeled as 'Mid-station' are the location of the resulting series of 1D Vs functions. After completing all processes such as preprocessing, overtone analysis and dispersion curve analysis as previously described for model 1, the dispersion curves were picked and inverted to produce the 2D shear wave profile shown in Figure C2.

(X) = Source Location																	<b>Sub-spread mid-point</b>																																																	
RCO#	STAB	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148											
1015	(X)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36																												
1016	(X)		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37																												
1017	(X)		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38																												
1018	(X)		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39																												
1019	(X)		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40																												
1020	(X)		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41																												
1021	(X)		7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42																												
1022	(X)		8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43																												
1023	(X)		9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44																												
1024	(X)		10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45																												
1025	(X)		11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46																												
1026	(X)		12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47																												
1027	(X)		13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48																												

Figure C1: Receiver array is not fixed, i.e., a sub-spread of 36 channels were pushed rolled behind a series of shot points (pushed). Roll along pushing traces starting from station 101 to 148 and source location (indicating by (X)) beginning from station 95 to 107. The midpoints of each analyzed sub-spread are labeled as the mid station point and are distributed from station 118 to 130.



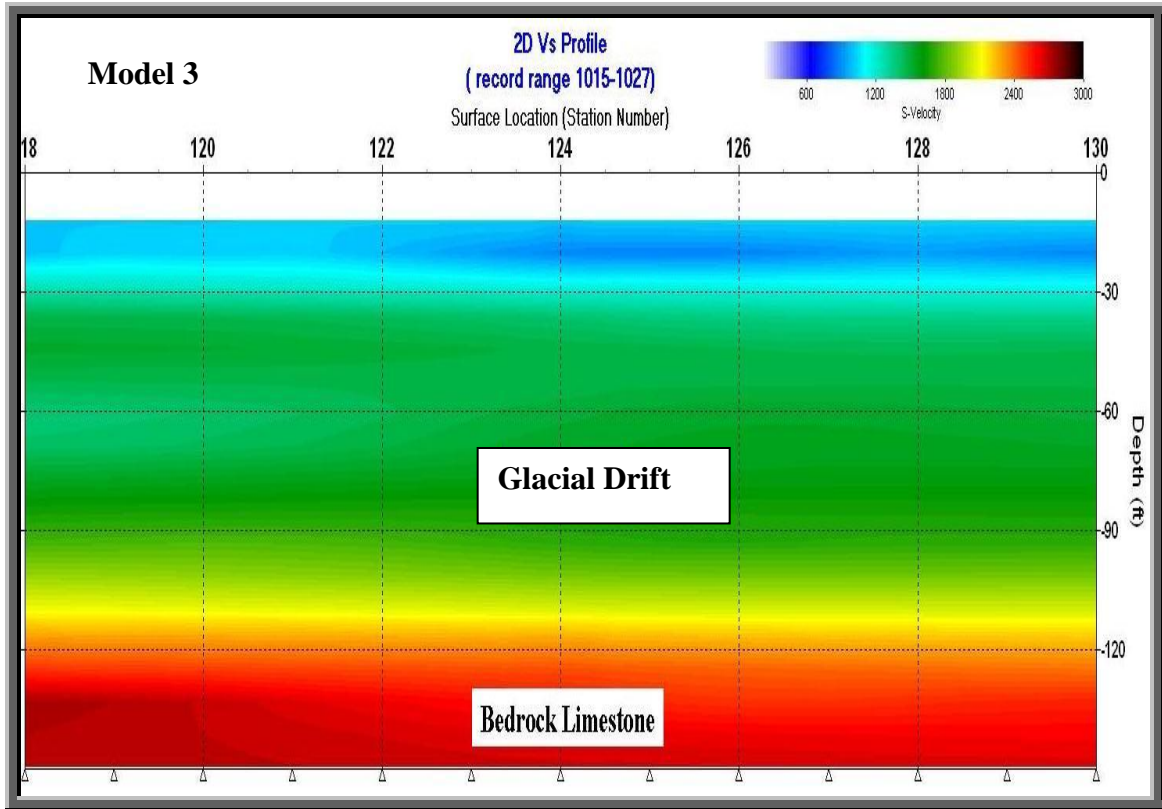


Figure C2: 2D (surface and depth) shear wave velocity ( $V_s$ ) profile obtained from the active source MASW survey using a 36 channel sub-spread pushed through the stationary 48 channel spread. High-velocity contrast inferred to define the depth to bedrock, and it is approximately 113 feet. The average velocity is about 1800 feet/sec and 2700 feet/sec for glacial drift and bedrock respectively.

### Interpretation of model 3

In figure C2, the vertical axis is depth, and the horizontal axis is station location where a shear wave velocity function is plotted at the mid-point location of each 24-channel sub spread. The color of this 2D profile represents the variation of  $V_s$ . In Figure C2, the different colors indicate velocities ranging from 400-3000 feet/sec (121-914 m/sec). The velocities are in a range from about 1200-1800 feet/sec to about 113 feet (34 meters) at which depth the velocity increases abruptly to about 2700 feet/sec (822 m/sec).



## **Appendix D:**

### **Model 4: MASW 2D roll 36 through 48 channels Pulled**

The 48 geophones are found on stations 101-148, and a total of 13 seismic records were shot (acquired) with the source placed at stations 142 through 154 for the records numbered from 1062 -1075. The following parameters were entered into the SurfeSeis3.

- Survey Type: MASW Active survey and seismic sources are impulsive sources.
- Seismic survey geometry assignment: receiver array is not fixed, i.e., 36 rolls along pulling traces starting from station 101 to 148. Geophones are 10 feet apart.
- Pulling seismic sources array: record range 1062-1075 (i.e., total file 13).
- The source location is beginning from 142 to 154 and offset distance is 60 ft.
- The mid-station is located ranging from 118 to 130.

The process of defining the geometry followed that of model 1 and produced the geometry profile for model 4 (Figure D1). The velocity function for each 36-channel sub-spread (Figure D1), so the locations labeled as ‘Mid-station’ are the location of the resulting series of 1D Vs functions. After completing all processes such as preprocessing, overtone analysis and dispersion curve analysis as previously described for model 1, the dispersion curves were picked and inverted to produce the 2D shear wave profile shown in Figure D2.



## **Appendix E:**

### **Model 5: MASW 1D 1 through 48 Stationary Channels**

The 48 geophones are placed on stations 1001-1048, and a total of 48 seismic records were shot (acquired) with the source set at stations 95 through 153 for the records numbered from 1015 -1075. The following parameters entered into the SurfeSeis3.

- Survey Type: MASW Active survey and the seismic source is the impulsive source.
- Seismic survey geometry assignment: receiver array is fixed, i.e., 48 geophones starting from station 101 to 148. Geophones are 10 feet apart.
- Source location beginning from 142 to 154 (source offset distance is 60 feet) and mid station are located at 124.

The process of defining the geometry followed that of model 1 and produced the geometry profile for model 5 (Figure E1). The velocity function for 48-channel record is plotted at the midpoint of the 48 channel (Figure E2), so the locations labeled as ‘Mid-station’ are the location of the resulting Vs profile. After completing all processes such as preprocessing, overtone analysis and dispersion curve analysis as previously described for model 1, the dispersion curves were picked (Figure E2) and inverted to produce the 2D shear wave profile shown in Figure E3.



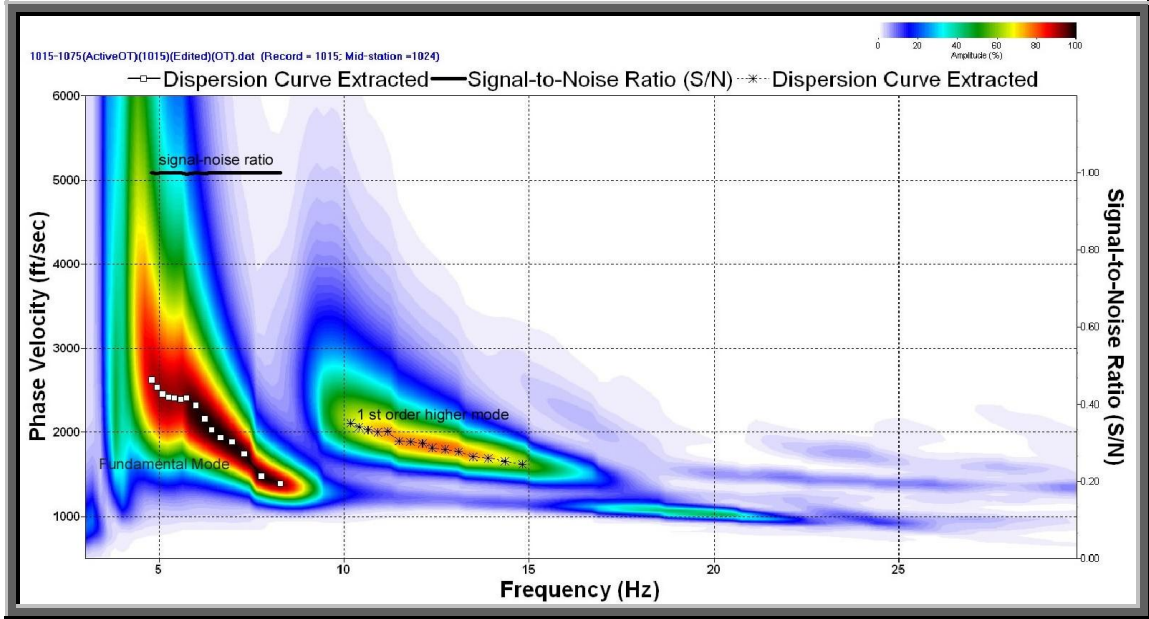


Figure E2: Dispersion curve is extracted for the fundamental mode and higher order mode simultaneously at mid station 124 for 48 fixed traces.

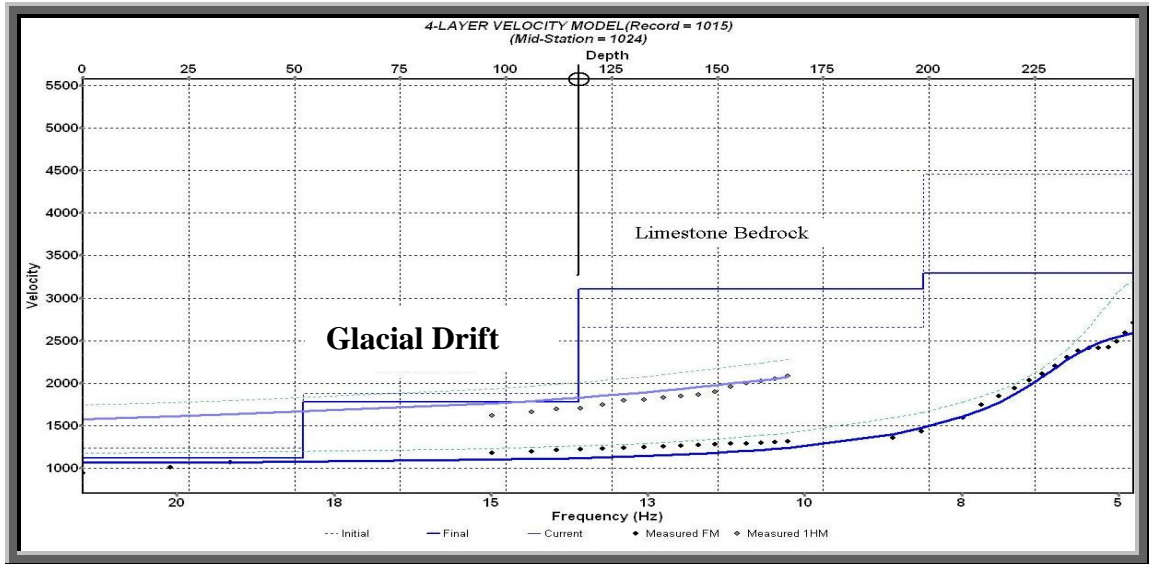


Figure E3: 1D shear wave velocity ( $V_s$ ) profile obtained from active MASW survey using 48 fixed receivers with the same sources-receiver configuration beneath the mid-station at 124. The blue line indicates the calculated 1D  $V_s$  structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dot). High-velocity contrast inferred to define the depth to bedrock, and it is approximately 120 feet (36 meters). The estimated average S-wave velocities are 1,800 feet/sec (548 m/sec) and 3,100 feet/sec (944 m/sec) for glacial drift and bedrock respectively.

## **Interpretation of model 5**

Four layer velocity models give the minimum RMS errors with the fit best of the data compared to other models. 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). Figure E3 displays a 1D depth vs. shear wave velocity structure at mid station 124. The significant increase in velocity at a depth of 120 feet (36 meters) is interpreted as the boundary between glacial drift and limestone bedrock. According to this velocity model, the bedrock velocity is about 3,100 feet/sec (944 m/sec) and the overlying glacial drift velocity is around 1,700 feet/sec (518 m/sec). The abrupt Vs change is interpreted as glacial drift over limestone bedrock at 112 feet (34 meters).

## **Appendix F:**

### **Model 6: MASW 1D 13 through 36 Stationary Channels**

The 24 geophones are located on stations 113 through 136, and a total of 24 seismic records were shot (acquired) with the source located at stations 113 through 136 for the records numbered from 1027 to 1063. The following parameters were entered into the SurfeSeis3.

- Survey Type: MASW Active survey and seismic sources are impulsive sources.
- Seismic survey geometry assignment: receiver array is fixed, i.e., 24 geophones starting from station 113 to 136. Geophones are located at 10 feet apart.
- Source location beginning from station 107 to 142 and source offset distance is 60 ft.
- The mid-station is located at 124.

The process of defining the geometry followed that of model 1 and produced the geometry profile for model 6 (Figure F1). The velocity function for 24-channel record is plotted at the midpoint between 113 and 136 (Figure F1), so the locations labeled as ‘Mid-station’ are the location of the resulting Vs profile. After completing all processes such as preprocessing, overtone analysis and dispersion curve analysis as previously described for model 1, the dispersion curves were picked (Figure F2) and inverted to produce the 1D shear wave profile shown in Figure F3.

RCID#STA#	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142			
1027	(X)						13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1028		(X)					13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1029			(X)				13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1030				(X)			13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1031					(X)		13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1032						(X)	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1033							13(X)	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1034							13	14(X)	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1035							13	14	15(X)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1036							13	14	15	16(X)	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1037							13	14	15	16	17(X)	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1038							13	14	15	16	17	18(X)	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1039							13	14	15	16	17	18	19(X)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1040							13	14	15	16	17	18	19	20(X)	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1041							13	14	15	16	17	18	19	20	21(X)	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1042							13	14	15	16	17	18	19	20	21	22(X)	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
1043							13	14	15	16	17	18	19	20	21	22	23(X)	24	25	26	27	28	29	30	31	32	33	34	35	36									
1044							13	14	15	16	17	18	19	20	21	22	23	24(X)	25	26	27	28	29	30	31	32	33	34	35	36									
1045							13	14	15	16	17	18	19	20	21	22	23	24	25(X)	26	27	28	29	30	31	32	33	34	35	36									
1046							13	14	15	16	17	18	19	20	21	22	23	24	25	26(X)	27	28	29	30	31	32	33	34	35	36									
1047							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27(X)	28	29	30	31	32	33	34	35	36									
1048							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28(X)	29	30	31	32	33	34	35	36									
1049							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29(X)	30	31	32	33	34	35	36									
1050							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30(X)	31	32	33	34	35	36									
1051							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31(X)	32	33	34	35	36									
1052							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32(X)	33	34	35	36									
1053							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33(X)	34	35	36									
1054							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34(X)	35	36									
1055							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35(X)	36									
1056							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36(X)									
1057							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36								(X)	
1058							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36								(X)	
1059							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									(X)
1061							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									(X)
1062							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									(X)
1063							13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									(X)

Figure F1: Receiver array is fixed, i.e., 13-36 traces starting from station 113 to station 136 and source location (indicating by (X)) beginning from 107 to 142. And, the mid station is located at 124.

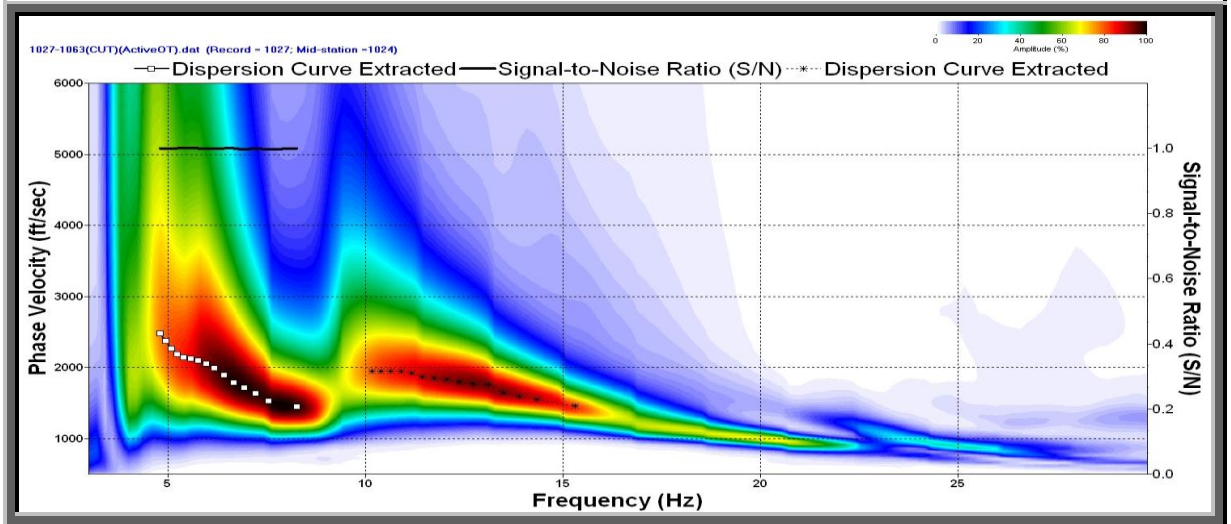


Figure F2: Dispersion curve is extracted for the fundamental mode and higher order mode simultaneously at mid station 124 for 24 fixed traces. The white dots indicate the extracted dispersion curve.

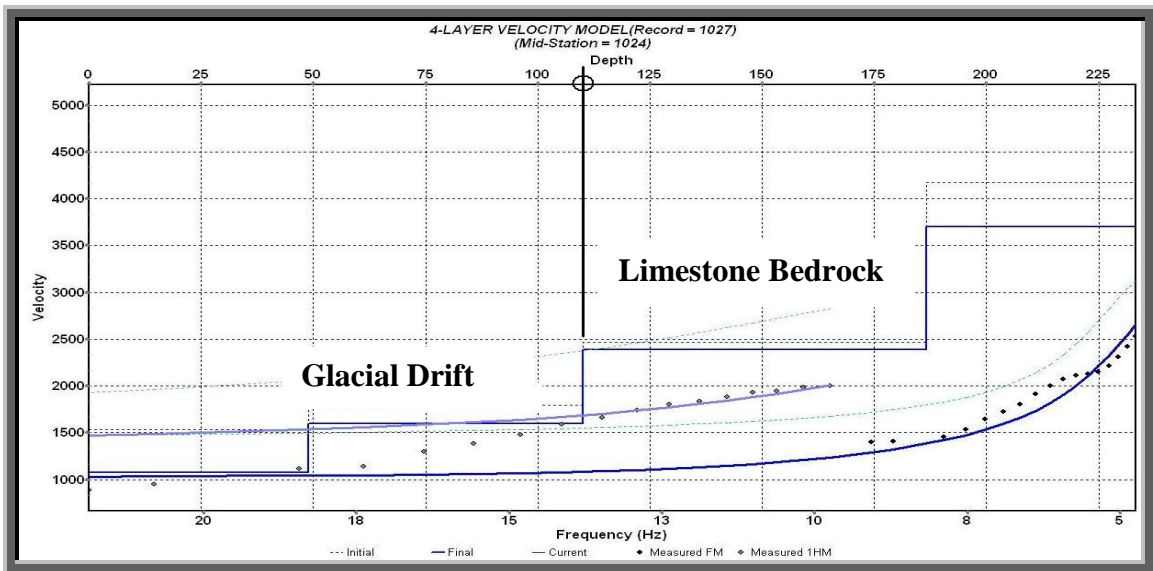


Figure F3: 1D shear wave velocity ( $V_s$ ) profile obtained from active MASW survey using 24 fixed receivers with the same sources-receiver configuration beneath the mid-station at 124. The blue line indicates the calculated 1D  $V_s$  structure from an initial earth based model, which is compared to a current model calculated from the picked dispersion curve (black dot). High-velocity contrast inferred to define the depth to bedrock, and it is approximately 113 feet (34 meters). The average S wave velocities are 1,800 feet/sec (548 m/sec) and 2,700 feet/sec (822 m/sec) for glacial drift and bedrock respectively.



## Interpretation of model 6

Four layer velocity models give the minimum RMS errors with the fit best of the data compared to other models. 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). Figure F3 displays a 1D depth vs. shear wave velocity structure beneath the mid station 124. The significant increase in velocity at a depth of 113 feet (34 meters) is interpreted as the boundary between glacial drift and limestone bedrock. According to this velocity model, bedrock is about 2,700 feet/sec (822 m/sec) and the overlying glacial drift is around 1,800 feet/sec (548 m/sec).

## Appendix G:

### Flat Layer Interpretation

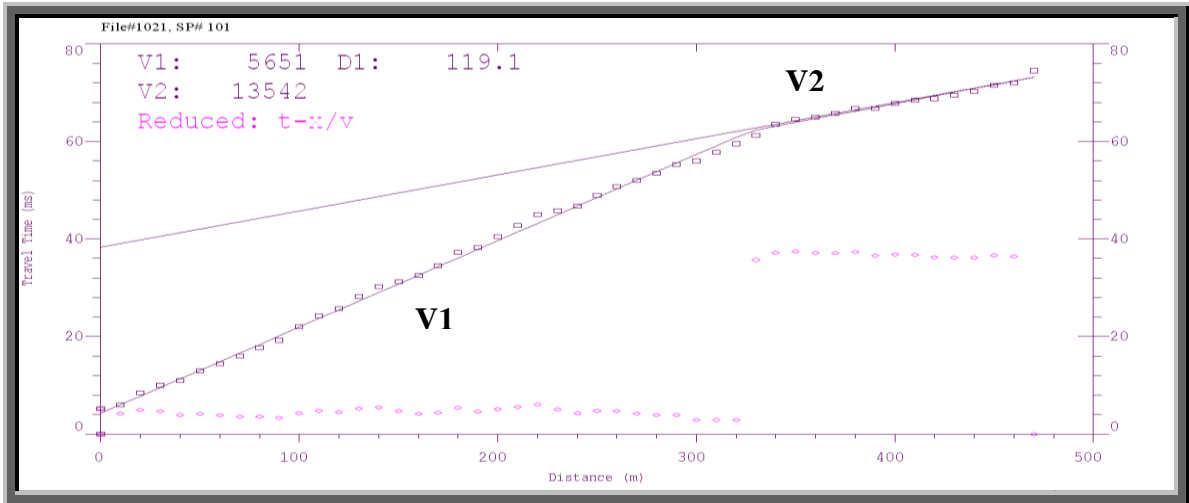


Figure G1: Flat layer interpretation for forward shot (for two layers).

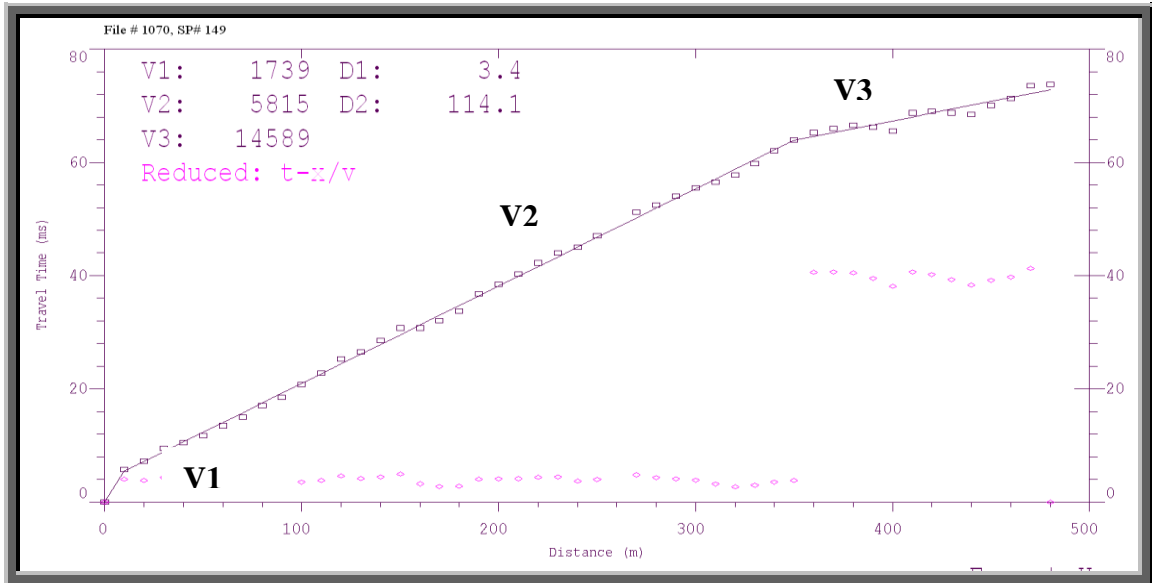


Figure G2: Flat layer interpretation for forward shot (for three layers).

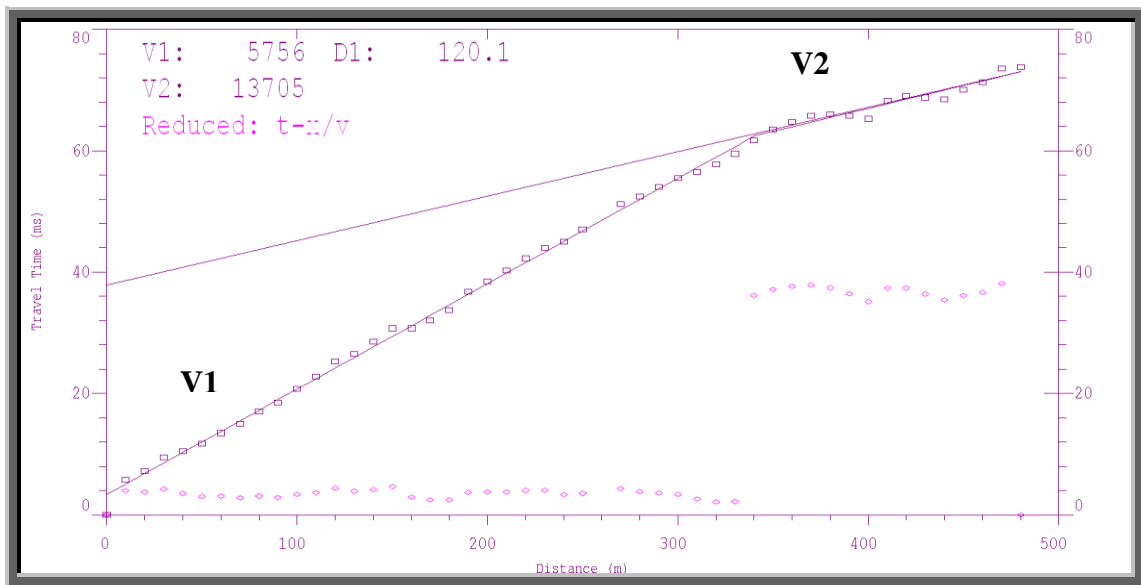


Figure G3: Flat layer interpretation for reverse shot (for two layers)