RECIPROCAL CHARACTERISTICS OF SURFACE WAVES: DETECTING NEAR SURFACE ANOMALIES

By

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RECIPROCAL CHARACTERISTICS OF SURFACE WAVES: DETECTING NEAR SURFACE ANOMALIES

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Abstract: The dispersive nature of surface waves (different frequencies traveling at different velocities) predominately depends on the subsurface shear-wave properties. The near-surface community takes advantage of this phenomenon through a technique known as Multi-Channel Analysis of Surface Waves (MASW), where the dispersion characteristics of surface waves are inverted to shear-wave velocity (V_S) profiles. Currently, the inversion is a one-dimensional averaging of the subsurface volume below a spread (source followed by a set of receivers). The greatest challenge lies in model assessment; short of a known embedded target, it is difficult to determine the reliability of the inverted profile. Here, we propose using reciprocity for assessing the inverted model. This simple and intuitive process tests for similarity by cross correlating the dispersion images acquired from two spreads moving in opposite direction and occupying a common profile on the surface. We demonstrate this idea using a 47 meter profile with known targets (two Transite pipes 15 centimeter inside diameter (6 inch I.D.) and buried roughly 1 meter deep). The best reciprocity and target resolution was obtained using a 12 meter spread length. The maximum depth of investigation was 6 meters. Results advocate the use of reciprocity as a viable method of analyzing and optimizing seismic surveys for near subsurface anomaly detection.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

II. SITE INFORMATION 4

III. DATA AND METHODOLOGY 6

IV. RESULTS 9

V. DISCUSSION 18

VI. CONCLUSION 20

REFERENCES 22

LIST OF FIGURES

Figure Page

1. Site Map 5
2. Dispersion Curve Images 10
3. Juenger-Pseudo Section 11
4. Vp Model 11
5. Vs Models 12
6. Vs Model Difference Plots 17

CHAPTER I

INTRODUCTION

Shear-wave velocity (Vs) characterization is utilized by many subsurface communities such as engineering and environmental science (Sheehan et al. 2005). Estimates of Vs are used to infer material properties (Santamarina et al. 2005) but the data are difficult to retrieve and reconstruct because the seismic record is dominated by P-waves. As such, both acquisition and processing of S-waves are highly challenging. S-wave wavefronts are low-amplitude and often have more complex shapes than their P-wave counterparts. As a result, when in the presence of background noise (natural or cultural)

S-wave processing becomes even more difficult. S-waves can be generated through a radial source or mode-conversion (P-to-S). Mode conversion requires appropriate changes in material properties across a formation boundary. Alam and Jaiswal (2017) showed that the point-explosive source can generate strong enough S-waves that can be recorded tangentially to the profile and the first-breaks could be inverted using an acoustic-type approach for generating the Vs structure of the shallow subsurface. Recording tangentially to a 2D profile such that the first breaks are exclusively S-waves poses additional challenges itself. Slightly misoriented horizontal geophones and near surface inhomogeneity can move the rays in-and-out of the profile plane causing P-waves, rather than S-waves, to be the first arriving energy.

An indirect way of estimating V_S is by inversion of surface waves (Park et. Al 1999) that are created by the excitation of the free surface by P-waves. The resulting retrograded elliptical motion of the free surface propagates in a dispersive manner, i.e., different frequencies propagate at different velocities. Park et al. (1999) developed a method called Multichannel Analysis of Surface Waves (MASW) to reconstruct V_S profiles from the surface wave dispersion characteristics recorded. The method assumes that surface waves comprise a series of mono-frequency plane waves, referred to as “phase,” each traveling at a characteristic velocity, referred to as “phase velocity.” The method assumes that over the spread length of the analysis, the subsurface is layer-cake and one dimensional (1D). While the inversion can be constrained by Vp information it assumes no horizontal variation. The method remains wildly popular for subsurface characterization despite the known limitations (Nolan et al. 2011).

One concern for the MASW approach draws from the subsurface resolution within the resulting Vs model. As mentioned above, for any given spread there is only one representative point of characterization located at the midpoint. This emphasizes the large impact that offset and linear spread geometry has on MASW results (Dikmen et al. 2010). Features have the potential to be overlooked or artifacts produced by the inversion process. This uncertainty emphasizes the need to determine an effective way of improving model reliability. To address this ambiguity, we suggest a reciprocal analysis of the dispersion images and Vs structures produced. Theoretically, two seismic surveys with the same field parameters over the same surface profile but propagating in different directions should produce nearly identical models. Thus, any significant disagreement between the two reciprocal models is a result of the inversion process reflecting a deviation in the one dimensionality of the subsurface, adjusting the confidence in the final interpretation for the subsurface. As many seismic processing programs make altering spread and offset possible, this suggested method provides a simple and intuitive way of determining the most effective geometry for the area of interest producing a more dependable characterization. This reciprocal approach allows the user to confirm that the features interpreted are not merely processing inversion artifacts, increasing the reliability of the final subsurface characterization.

CHAPTER II

SITE INFORMATION

The Oklahoma State University campus in Stillwater, Oklahoma is located in the north-central region of Payne County (Figure 1). The University has infrastructure located in the near subsurface in order to support operations of the institution. These utilities provide an excellent opportunity to explore the validity of this approach as the features are well documented and characterized. The survey location for this project is located in a lawn area north of the Noble Research Center building and contains two identifiable features perpendicular to the seismic profile utilized for this study. The two known intersected features are common moderately sized 15 centimeters inside diameter (6 inch I.D.) Transite (asbestos-cement) pipes buried roughly one meter deep. The furthest north feature is a capped and abandoned pipe while the other serves as an active irrigation pipe (Figure 1).

The project site is underlain by the Oscar Group which is characterized by red-brown to gray shales and orange-brown fine-grained sandstones with small interbedded limestone units. A 1984 geotechnical report conducted before the construction of the Noble Research Center, known as the 21st Century Building at that time, reported an average depth to bedrock of roughly 7 meters with very little variation between boreholes. In the boreholes closest to the survey profile the bedrock was characterized as a maroon mottled siltstone. The report noted that the rock is identified as siltstone instead of shale due to the lack of laminations observed. In a few boreholes, thin interbedded sandstone intervals were encountered. The 7 meters overlaying the bedrock is reported to contain a thin layer of topsoil (1.64 meters thick) with the rest characterized as a silty clay material. As this report was conducted before construction, the present conditions are expected to reflect the disturbances in the upper portion of the subsurface with the bedrock remaining intact as the depth of disturbance was noted as extending to a depth of 5 meters.

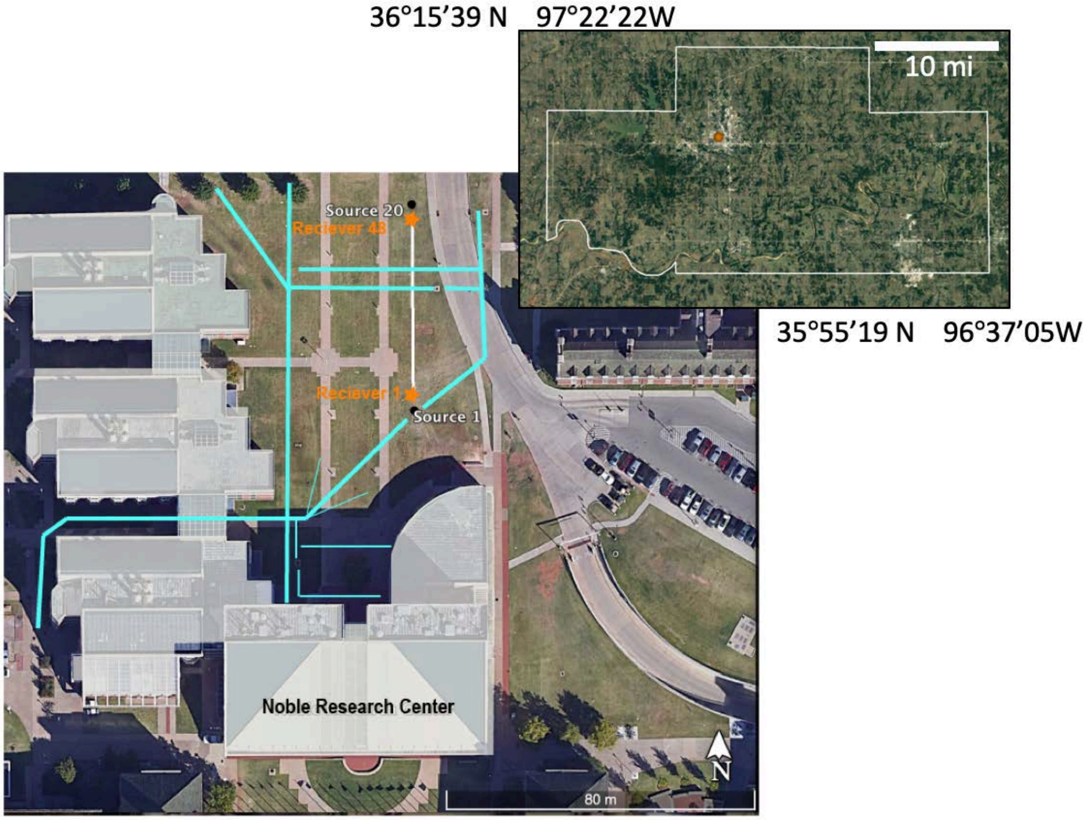


Figure 1. Site map with utility locations marked (blue) and the orientation of the survey profile (white). The receiver geometry is noted by the orange stars and the source configuration by the black circles. The inset image displays the location of the site within Payne County, Oklahoma

CHAPTER III

DATA AND METHODOLOGY

The seismic refraction survey was conducted using a 24-channel Geometrics-Geode Seismograph system and a static 48-10 Hertz geophone configuration using one meter spacing. There were 20-point sources generated using a 12-gauge Betsy Seisgun in augured holes drilled roughly 15 cm deep. The source was moved three meters after each shot along a 57-meter long profile with the first and last two shots extending beyond the receiver locations (Figure 1). Sampling was conducted at an interval of 0.250 milliseconds for roughly two seconds after each source was generated.

After data acquisition, the data set was imported into SeisSpace software to assign the geometry information from the field. To determine the optimal spread length for our study area, the acquired survey was exported using various offsets, which is a process supported by SeisSpace modules. Maximum offsets examined ranged from 3 to 45 meters in multiples of three. The resultant shot gathers were reviewed prior to export in order to determine which shots for the offset displayed contained a full seismic record. This was repeated for the simulated reverse propagating survey. Only shots that had a full record for both forward and 'reverse' surveys were included in order to ensure that both models would be representative of the same zone and would not be affected by amplitudes missing in incomplete records.

The standard MASW analysis procedures were followed for each set of the spread lengths. The first step being the conversion of the data to the SurfSeis compatible format. The next step was to assign the appropriate geometry parameters. The corresponding offset and propagation direction were selected and confirmed using the geometry spreadsheet generated. Next, a single dispersion curve was generated to ensure that the program parameters selected were appropriate for the dataset being analyzed. After satisfactory settings were achieved, dispersion curves were generated for all of the seismic records. A total of 240 dispersion curves were generated for this project. The same parameters were used for all offsets in attempt to minimize the possibility of introducing unwanted variability.

In order to indicate the most optimal spread length to visualize the subsurface characteristics for the site, the dispersion curves are subjected to correlation analyses. The dispersion curves produced for each offset and propagating direction were extracted as a numerical matrix and cross-correlated in MATLAB to provide a numerical representation of the degree of similarity. The dispersion curve semblance information was filtered to capture only the range which included the fundamental mode being analyzed. The resulting correlation information was then plotted with respect to midpoint location and spread length to identify the geometry that best indicates the dispersion characteristics of the subsurface in the plot identified as the Juenger pseudo-section. Based on this analysis, each dispersion curve was individually picked identifying the location along the fundamental mode curve within the image that corresponds to the trend depicted in the most dependable and informative spread length identified.

Before the picks from the dispersion curves are subjected to the inversion process, a fixed layer model providing compressional velocity (Vp) constraints was generated. The first step in producing the Vp model was to pick the first breaks for each trace for every shot within SeisSpace, totaling 960 first break picks due to the acquisition parameters. This information was then imported into the travel-time inversion software, FAST. Here the first arrival times and starting velocity information was processed to yield a final Vp model. Using this model as a guide, average velocities were obtained for a specified number of layers at determined depths for the survey profile collected. Once converted to a compatible file format, the model was imported into the SurfSeis program and the inversion process was initiated.

Once the inversion process was complete a total of 30 Vs models were produced. All of the Vs pairs were then exported and analyzed in order to determine which best captured the anomalous zone. To do so, the reverse model was subtracted from the forward model and plotted with respect to the model location to identify areas that indicated a zone of interest. The resultant models were then visually examined to determine the feature resolution capability of each spread length studied. The models that reliably identified the region that contains the features both qualitatively and quantitatively indicate the optimal offset for the study area leading to a defendable subsurface characterization.

CHAPTER IV

RESULTS

The dispersion curves generated demonstrate the effect of spread length on the frequency bandwidth best defined; the shorter spread lengths resulted in the higher frequency displaying the highest amplitudes while the larger spread lengths best captured lower frequencies (Figure 2). This is also reflected in the average correlation ratios of the dispersion curve images (Figure 3). The Juenger pseudo-section of the correlation ratios of each dispersion curve with respect to spread length and the relative surface location of the midpoints identified the 9 and 12 meter offsets as remaining the most 1-D for a majority of the spread with a zone at roughly 24 and 30 meter surface distance deviating significantly from the trend (Figure 3). This anomalous zone corresponds to the location of the two pipes that intersect the survey profile. The picks that were made for each dispersion curve were made with the understanding that these two offsets offered the best capture of the dispersion characteristics of the subsurface and better-informed picks for all of the spread lengths analyzed, as these characteristics do not change with respect to spread length.

The Shear-wave velocity models produced displayed the same general velocity structure and characterization reflecting the subsurface materials documented within the research area. The 3 to 24 meter spread lengths indicated the presence of an anomalous zone which corresponded to the relative location of the pipes at roughly 24 and 30 meter lateral distance in the figure (Figure 5). The model difference analysis performed supported the observations as the same region was identified as being an area of interest (Figure 6).

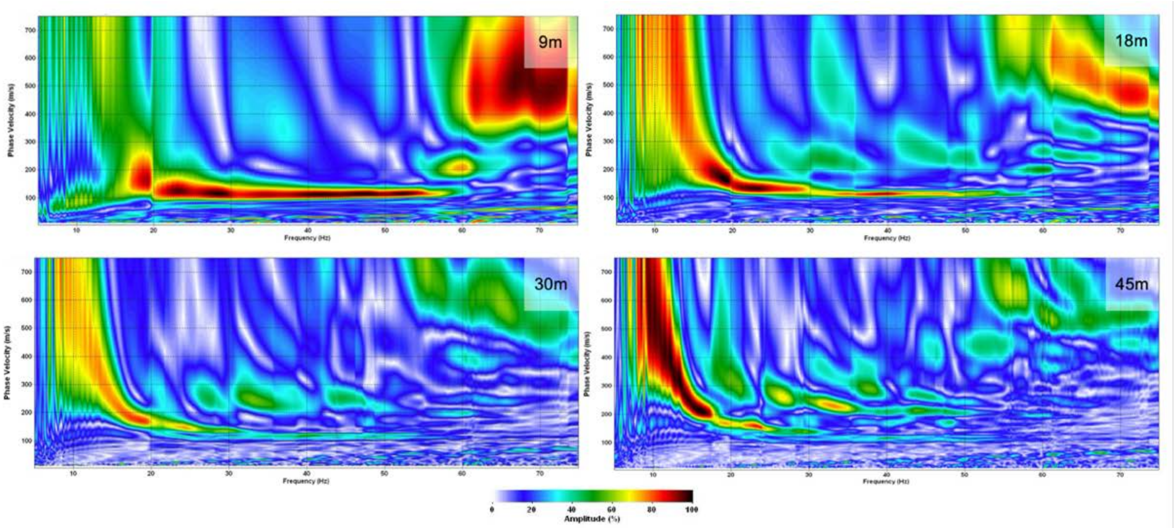


Figure 2. A sample of the dispersion curve images generated within the SurfSeis program for the spread lengths examined during the project.

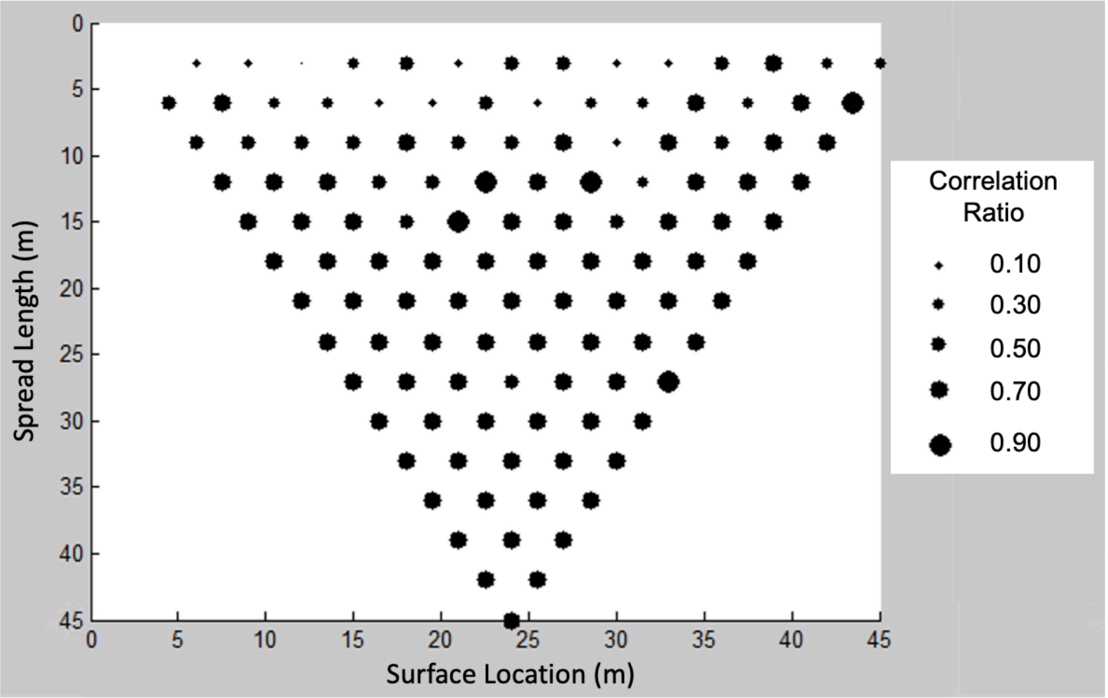


Figure 3. Juenger pseudo-section diagram displaying the correlation of the dispersion curve images with respect to the spread length and the relative surface location of the spread midpoints. The relative size of the points is representative of the degree of correlation as indicated by the legend.

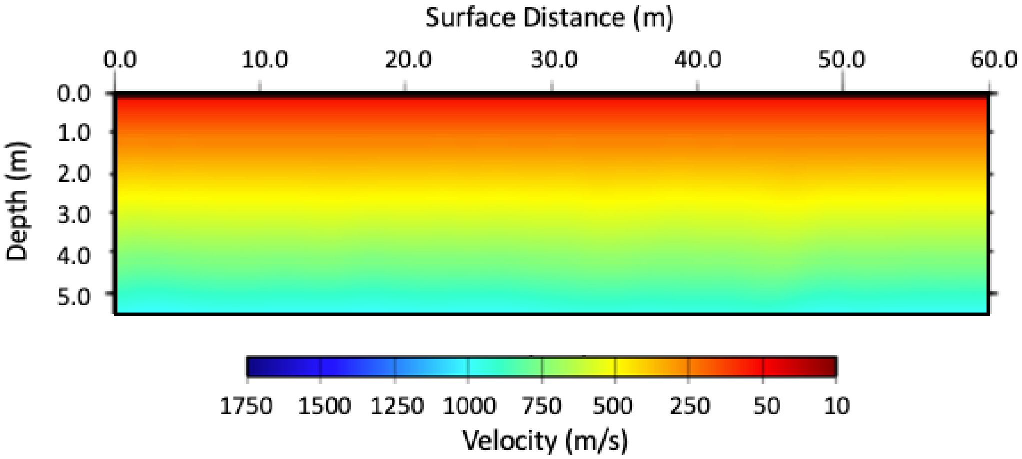
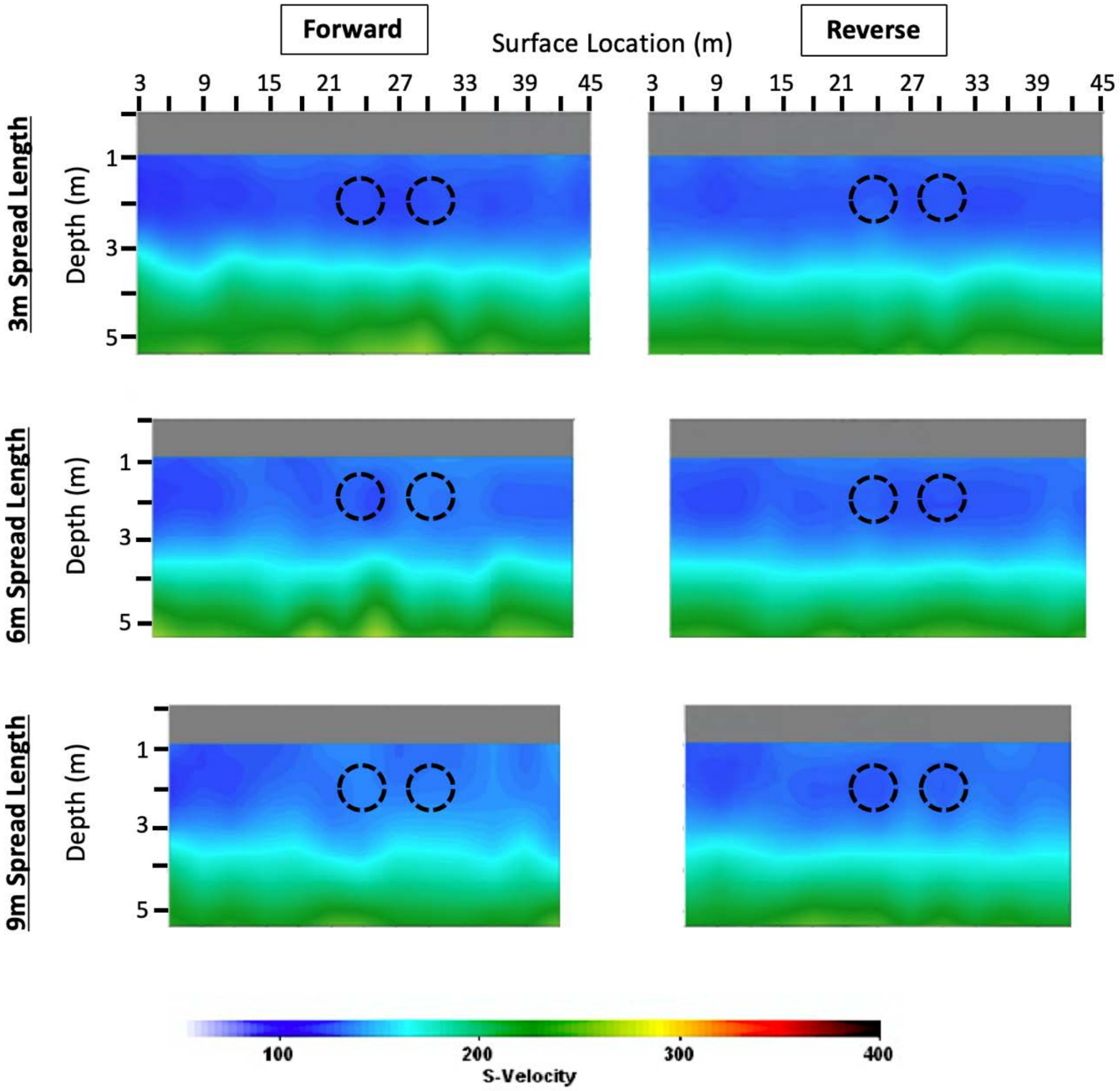
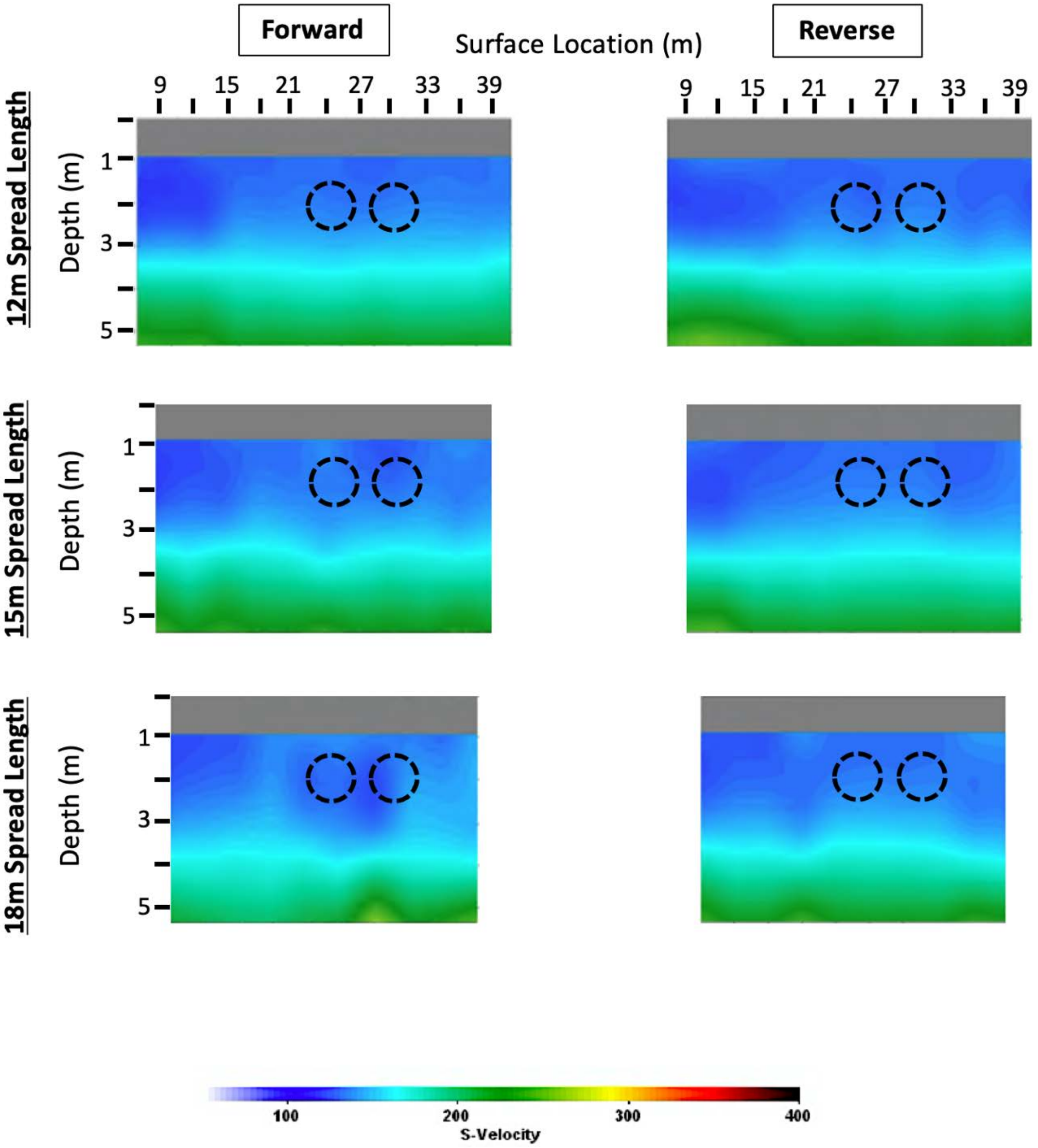
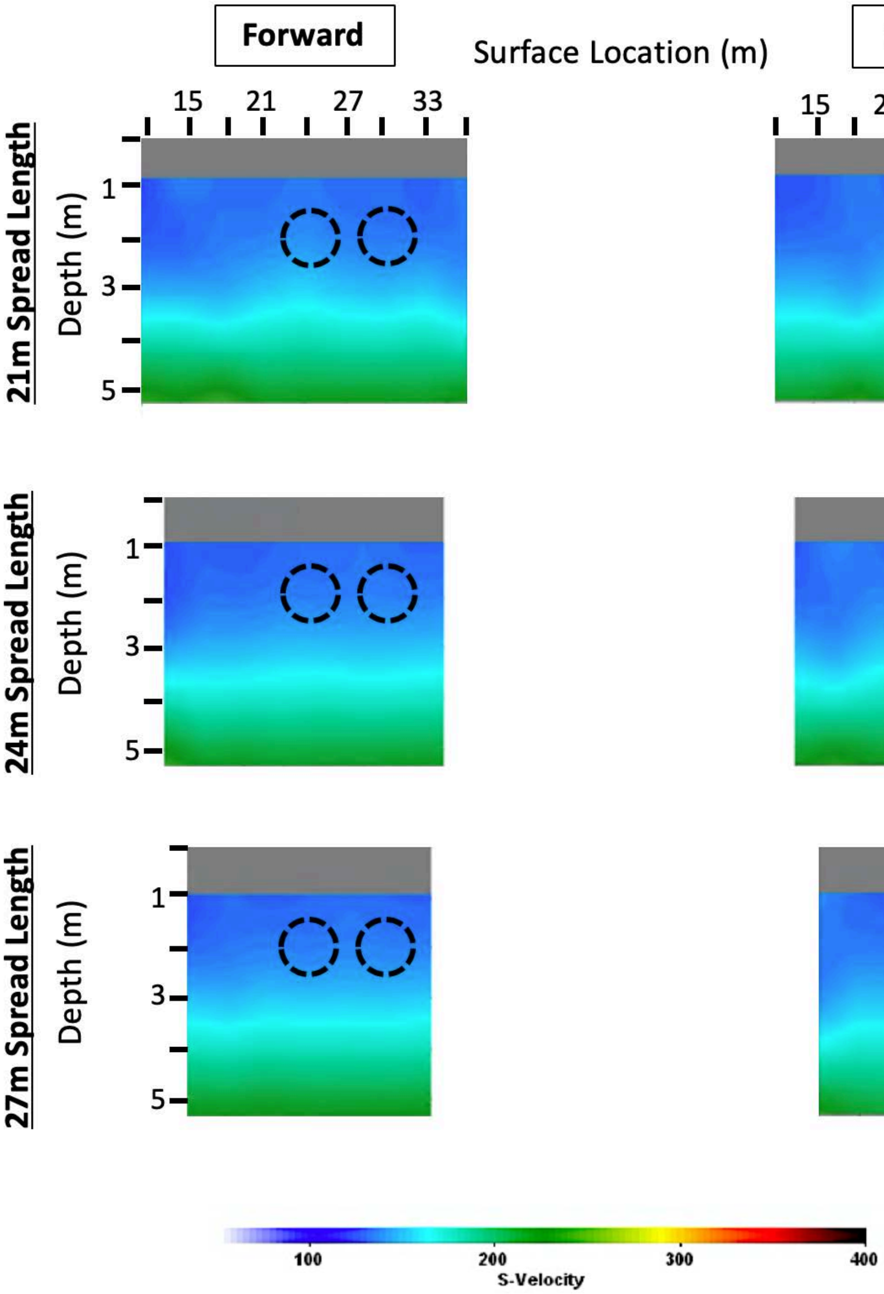
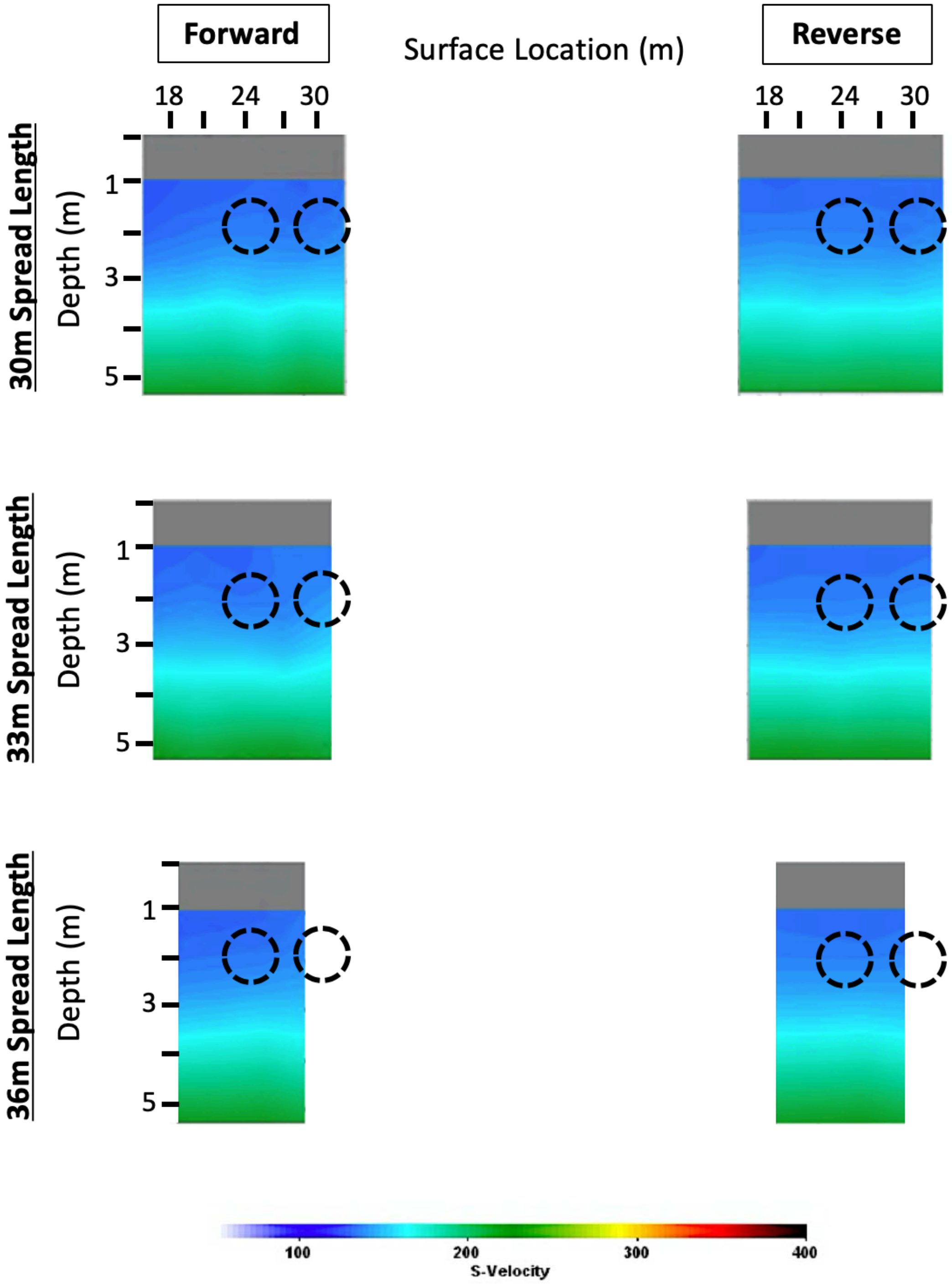


Figure 4. Vp model produced which was used to constrain the inversion process.


Forward
Surface Location (m)
Reverse
3
9
15
21
27
33
39
45
3m Spread Length
6m Spread Length
9m Spread Length
Depth (m)
1
3
5
100
200
300
400
S-Velocity


Forward
Surface Location (m)
Reverse
9
15
21
27
33
39
12m Spread Length
15m Spread Length
18m Spread Length
Depth (m)
1
3
5
100
200
300
400
S-Velocity


Forward
Surface Location (m)
Reverse
15
21
27
33
15
21
27
33
21m Spread Length
Depth (m)
1
3
5
24m Spread Length
Depth (m)
1
3
5
27m Spread Length
Depth (m)
1
3
5
100
200
300
400
S-Velocity


Forward
Surface Location (m)
Reverse
18
24
30
18
24
30
30m Spread Length
Depth (m)
1
3
5
33m Spread Length
Depth (m)
1
3
5
36m Spread Length
Depth (m)
1
3
5
100
200
300
400
S-Velocity

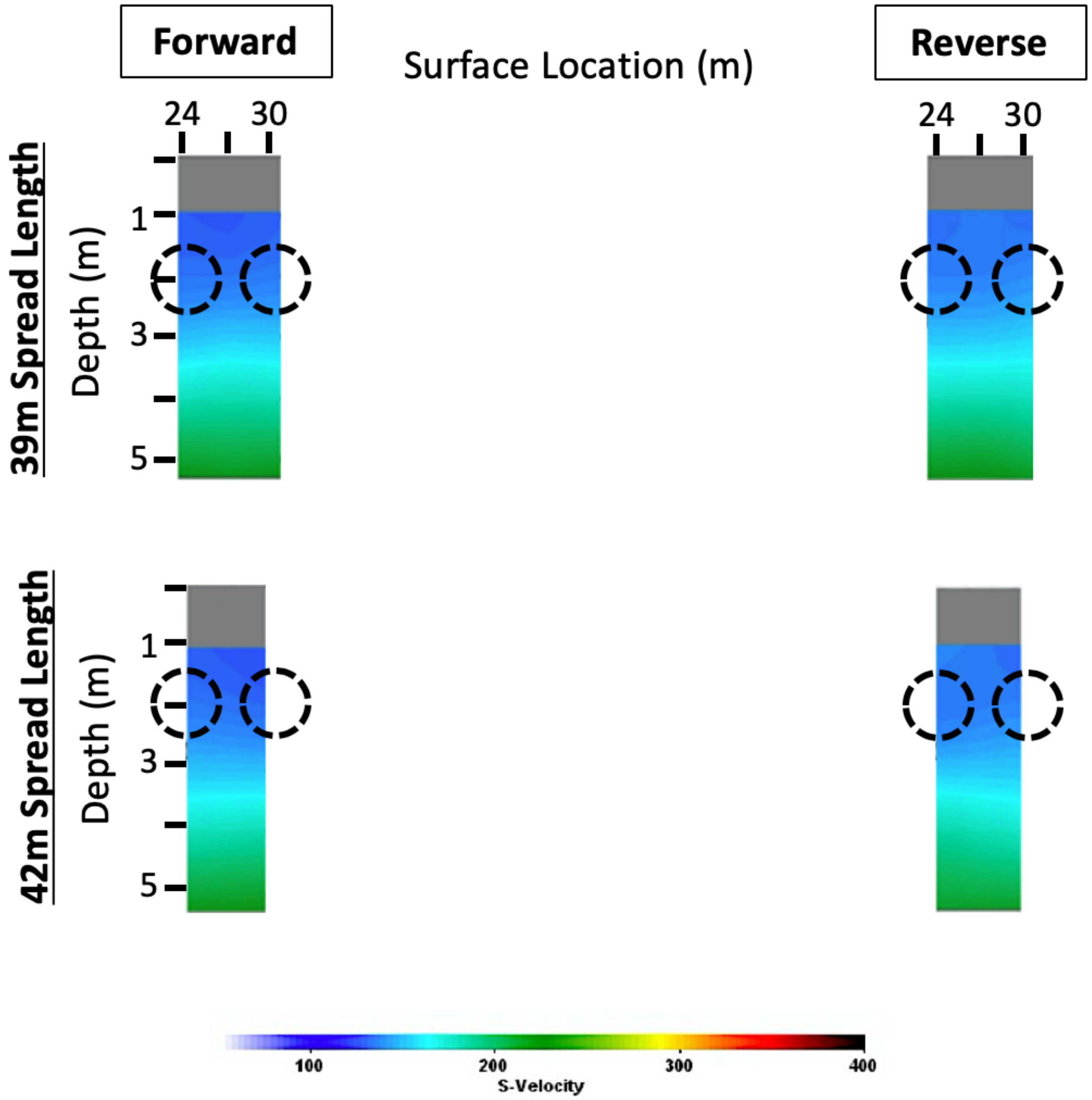


Figure 5. Vs models produced by the spread lengths examined for the project. Forward simulated rolls are located on the left and the right Vs models are the reciprocal counterparts, with the black circles representative of the feature locations with respect to model depth. The smaller spread lengths display a great deal of heterogeneity and the larger spread lengths lose essentially all resolution capabilities due to the greater effect of averaging as well as midpoint distribution in relation to the location of the features.

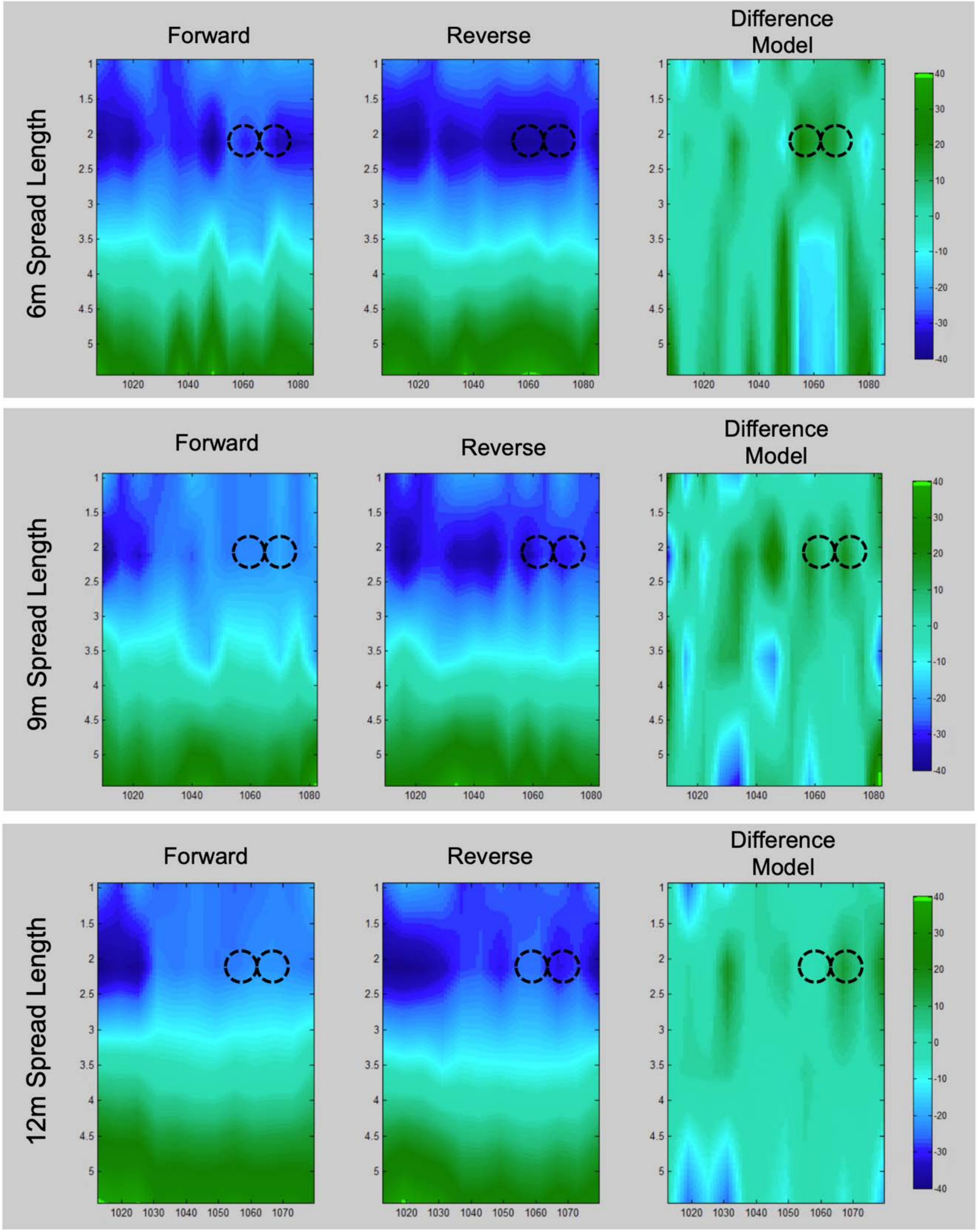


Figure 6. Displays the forward and reverse Vs models for 6, 9 and 12 meter spread lengths as well as the difference model locating anomalous zones within the reciprocal models. The spread lengths included capture the anomalous zones which correspond to the feature locations with respect to model depth.

CHAPTER V

DISCUSSION

Another study, Steinel et al. (2014), implemented a reciprocal analysis approach to investigate the dependability of the products produced by SurfSeis. Their study focused on the reproducibility of the Shear-wave velocity structures produced, with the results exhibiting a great deal of vertical variation between corresponding models. Due to the fact that the inversion is directed by the picks made along the dispersion curve which are chosen according to the operator's interpretations, it is here that a lot of uncertainty and inconsistency can be introduced into the modeling process. It is this reason that determination of an optimal spread length as outlined within this project allows you to determine the most dependable dispersion characteristics of the subsurface within your area of interest and eliminate some of the uncertainty introduced by human dependent interpretations that the inversion heavily relies on.

The reciprocal analysis of the dispersion curve images is solely based on the data extracted from the seismic records which allows for greater confidence to be placed in the results produced. Once the most optimal spread length is identified you can then capture the most accurate dispersion curve trends and better guide the inversion process having this increase in dependability of the dispersion curve picks allows you to resolve smaller features or anomalous zones within the survey area as demonstrated within this study. It is this finer resolution and the ability to determine the best characteristics possible that make a roll-along survey more favorable when utilizing MASW. A fixed spread ultimately has only one midpoint location, however the degree of correlation between the dispersion curve images had a maximum correlation ratio at the zero-lag location of 1.00 and therefore suggests that if a general Vs structure is the goal it would provide the most one-dimensional depiction of the Earth.

While many of the spread length Vs models displayed anomalous zones, which correspond to the location of the features within the survey, there is an offset between where the anomalies present themselves within the model and their physical location. The features included in the seismic survey for this study appear to present themselves at a depth of 2 meters within the models, despite the features being located at roughly 1 meter depth in reality. It is likely that in Figures 5 and 6, 1 meter model depth is actually the ground surface. This offset is due to the fact that the depths which are iteratively updated during the inversion process are approximated values based on the frequency and velocity of the picks along the dispersion curves. Therefore, the depths presented within the final Vs models are a model depth and should be considered as such when making interpretations.

CHAPTER VI

CONCLUSION

The reciprocal analysis of the dispersion curve images along with the pseudo section of the correlation ratios identified the 9 and 12 meter spread lengths as the most optimal for characterizing the dispersion characteristics of the subsurface materials. This produced picks for all of the spread lengths that best captured the true properties. As a result, the Vs models more reliably reflected the subsurface materials, with the 3 through 24 meter spread lengths indicating the zone of interest. Based on the resultant models and the model difference analysis the 9 and 12 meter spread lengths detected the zone of interest displaying the strongest deviation zone correlating to the location of the features. The consistent identification of the zone of interest in both model assessments assures that the spread lengths identified are the most dependable for the site conditions.

This study demonstrates that reciprocal analysis of the dispersion curve images is an effective tool in determining the spread length that produces the most reliable dispersion characteristics. The Juenger pseudo section generated as a result of these correlation suggests a method of detecting possible areas of interest within a survey early in the processing procedures. These analyses provide a way of ensuring that the Vs models produced are as dependable as possible reducing the uncertainties introduced by human interpretations. The reciprocal analyses of the Vs models themselves allows more confidence to be placed in the interpretation of anomalous features as the repeated presence of the anomalies affirms the objects while any disagreement in the images reduces the confidence as well as the likelihood of interpreting artifacts as true features. The results of this study demonstrate the effectiveness of the proposed reciprocal analysis approach as an optimal offset analysis tool, producing the most optimal and reliable subsurface characterization results.

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