Potential of MASW to Delineate Fractures in the Winterset Limestone at the Johnson County Landfill, Kansas

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Final Report to

Deffenbaugh Industries
Shawnee, Kansas

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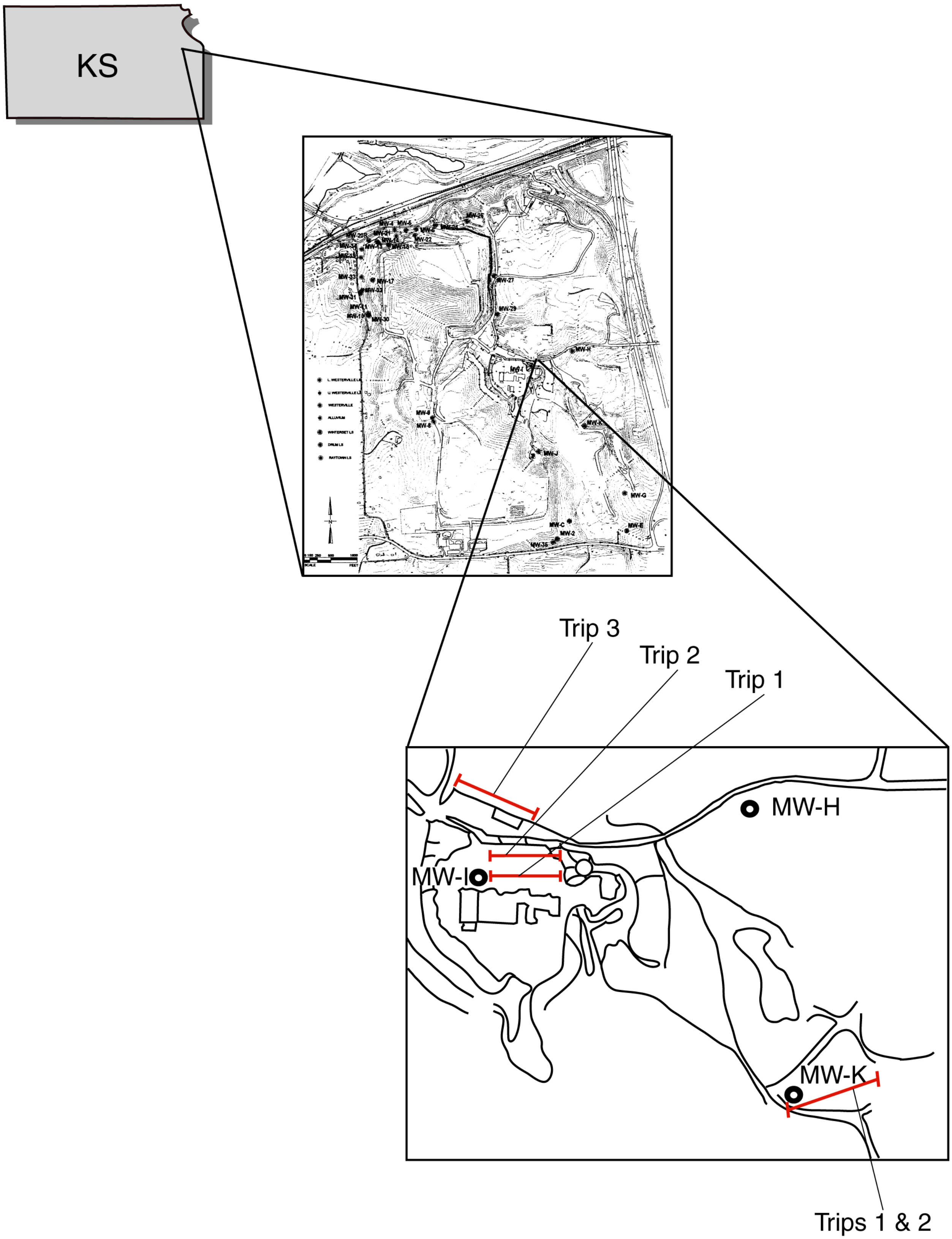
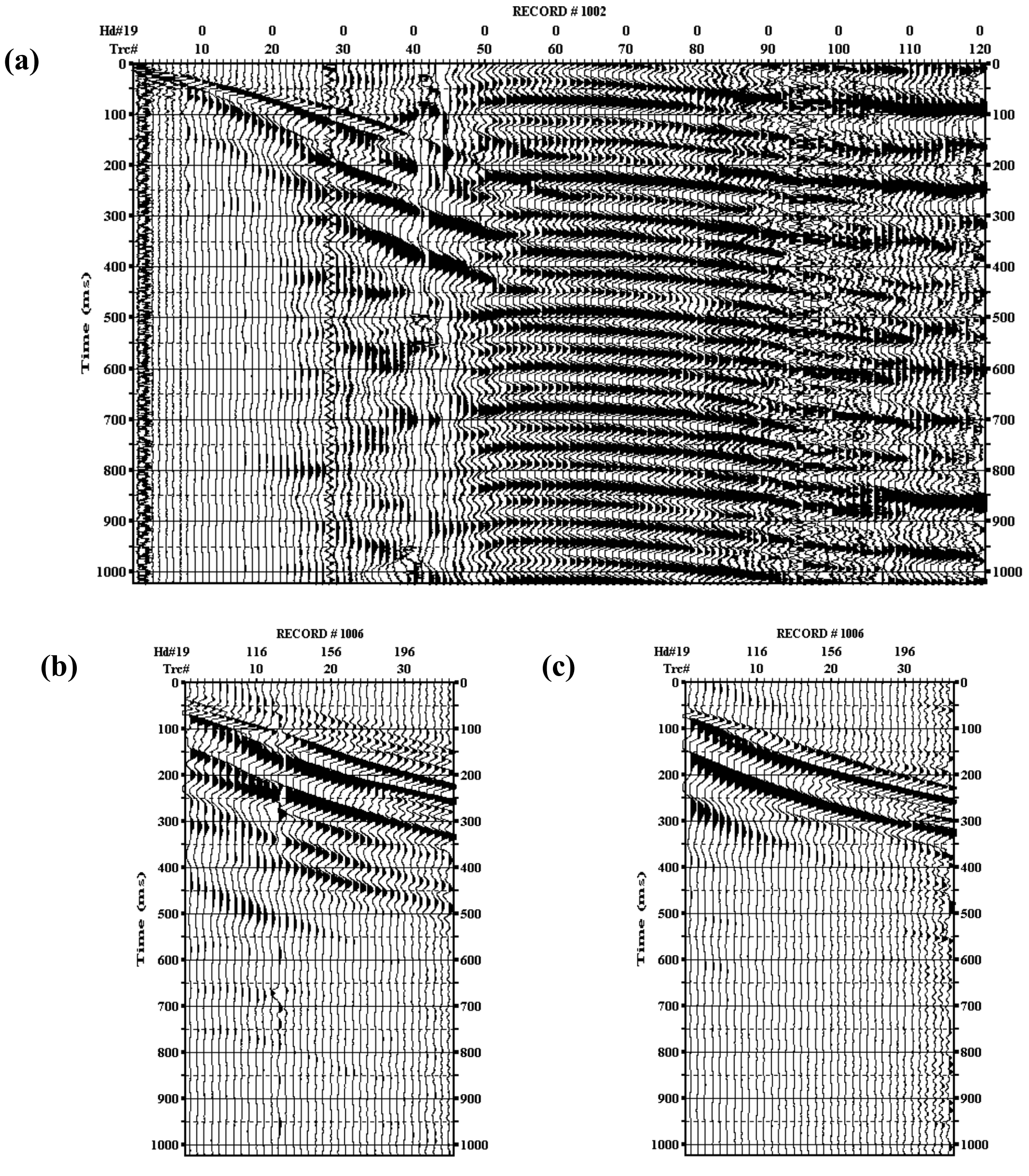


Figure 1. Site map of Johnson County Landfill area. Survey lines of all three trips are indicated.

1st Survey (Dec., 1999) – Line 1 (MW-I)



Single Shot (1006)

Stacked (1006-1012)

Figure 2. (a) A 120-channel shot gather collected using a weight-drop source that was designed and built at Kansas Geological Survey (KGS). Three vertical stacks were applied to produce one shot gather. This illustrates the noisy environment during the acquisition. Curved and repeated occurrence of strong surface waves at far-offset traces indicates the presence of noise that was possibly generated from vehicles moving around the survey area. (b) A shot gather made by taking some of near-offset traces that are fairly free of noise. (c) A shot gather made by stacking four adjacent shot gathers prepared in the same way as in (b). This illustrates how ambient noise can be further suppressed.

1st Survey (Dec., 1999) – Line 1 (MW-I)

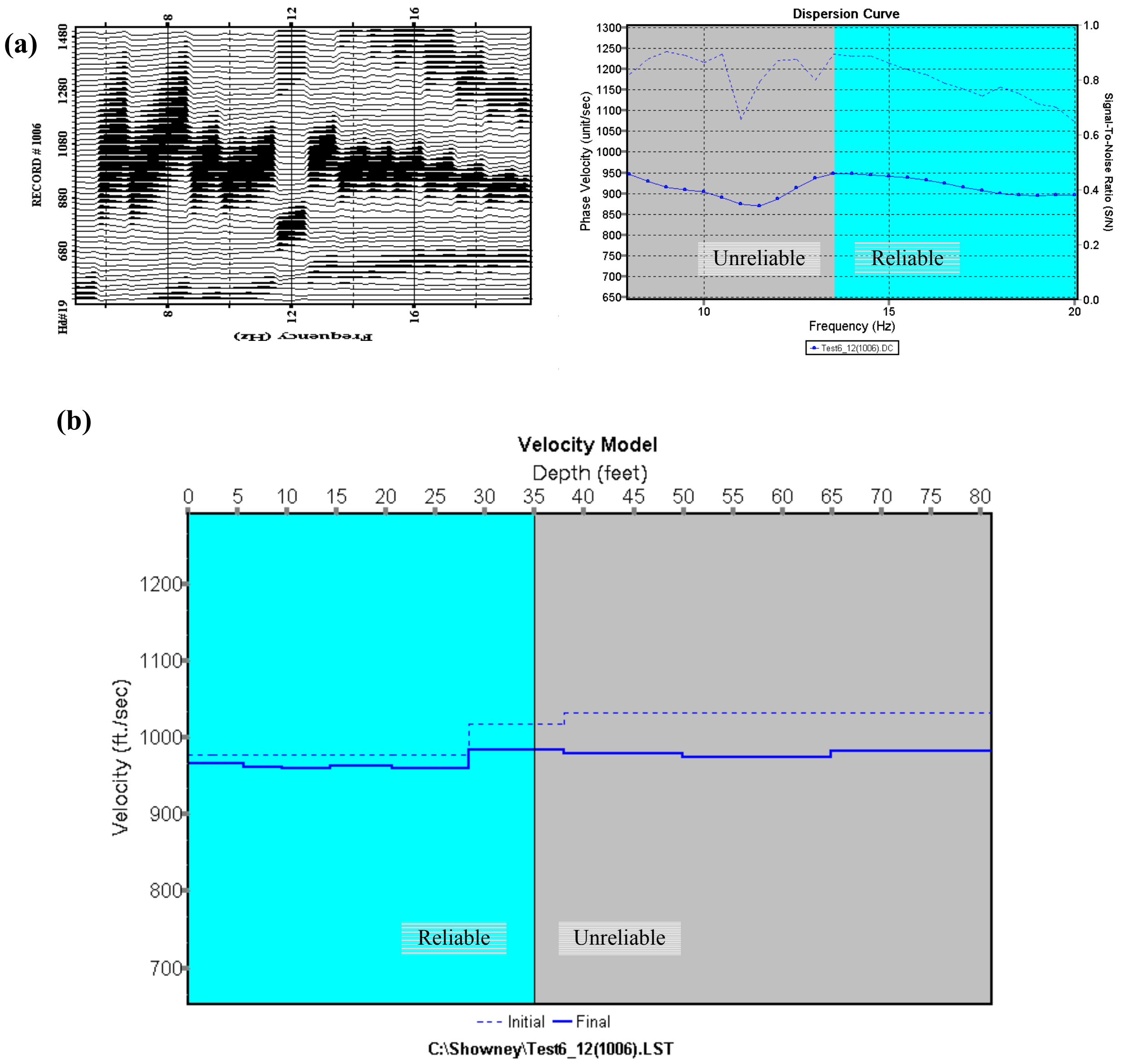


Figure 3. (a) An image of dispersion curve for a shot gather (# 1006) and corresponding curve extracted from this image. Unrealistic trend is found in the frequencies lower than 13 Hz and these frequencies are eliminated from the analysis. (b) An inversion result of S-velocity profile obtained from the extracted dispersion curve in (a). Reliable and unreliable ranges are indicated based upon the reliability of the dispersion curve.

2nd Survey (Jan., 2000) – MW-I

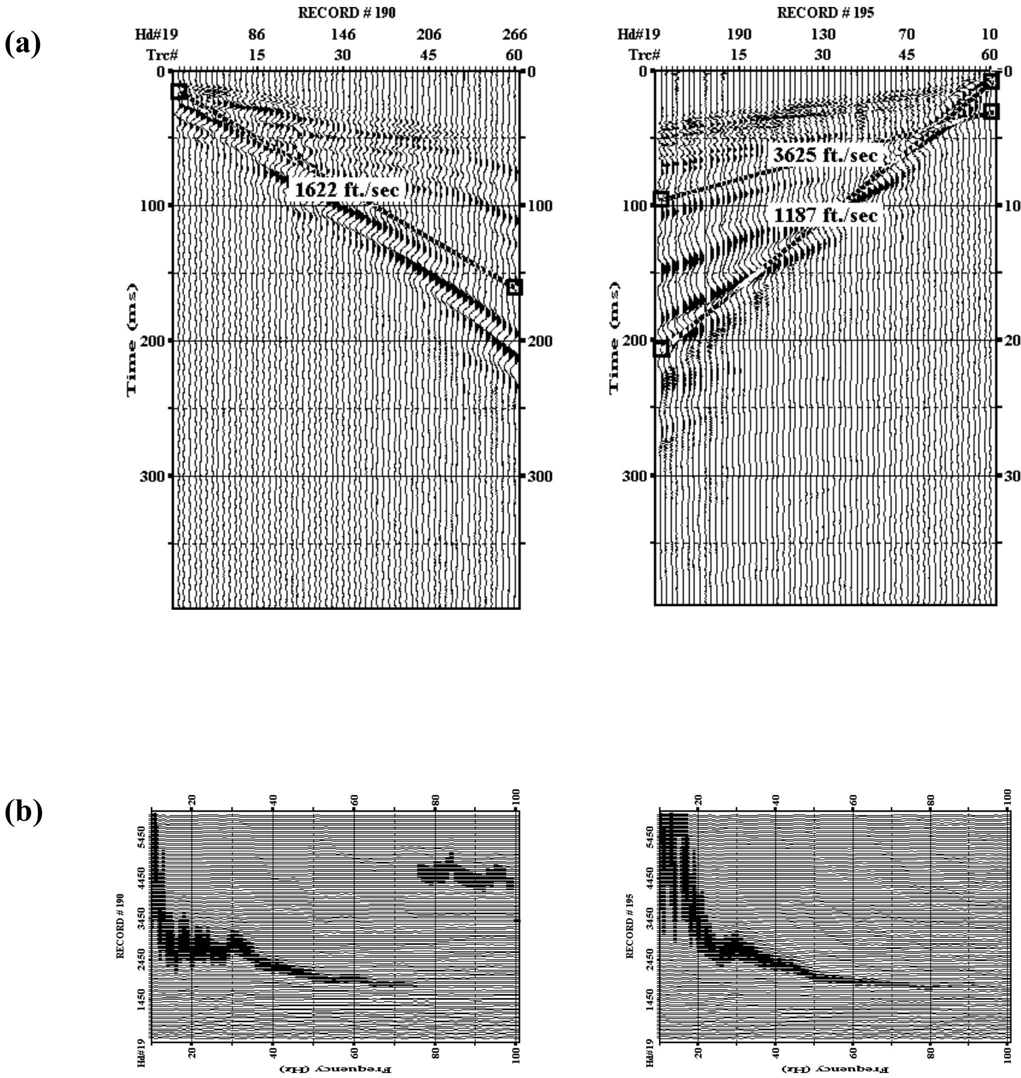
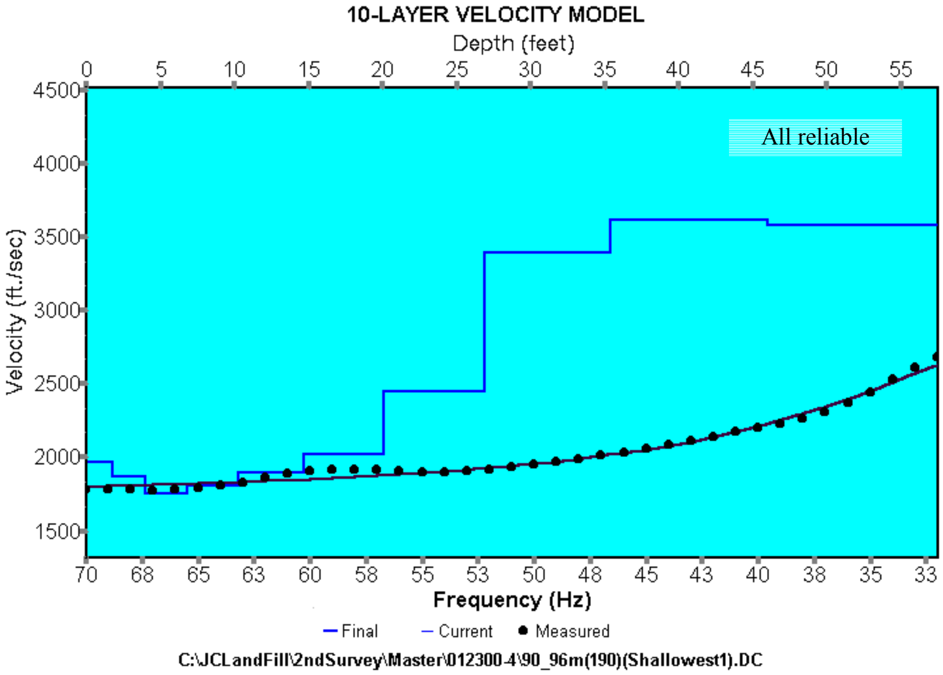


Figure 4. (a) Two shot gathers obtained at the same surface location with different source locations. This illustrates that ambient noise was dynamically changing and of low-frequency nature. (b) Images of the dispersion curves obtained from each shot gather in (a) illustrating that the phase-velocity information for the frequencies lower than 30 Hz is not reliable due to the noise problem.

2nd Survey (Jan., 2000) – MW-I


10-LAYER VELOCITY MODEL

C:\JCLandFill\2ndSurvey\Master\012300-4\90_96m(190)(Shallowest1).DC

Figure 5. An inversion result of S-velocity profile obtained from a shot gather collected at a site near well MW-I from the second trip.

3rd Survey (June, 2000) – MW-I

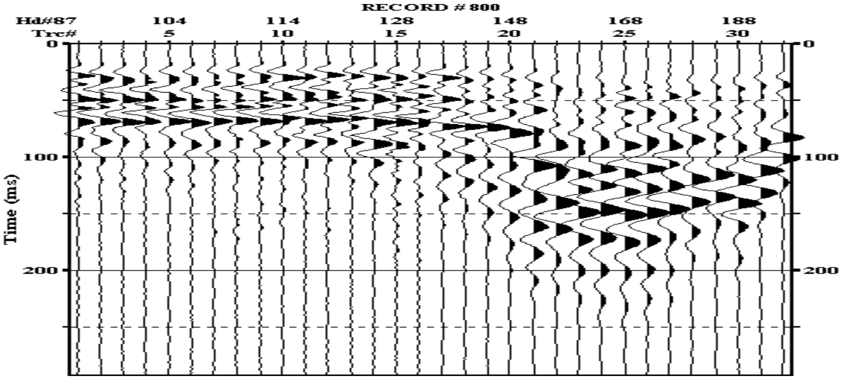


Figure 6. A common-offset section acquired from the third trip at a site near the well MW-I. This illustrates how the near-surface condition changes horizontally.

3rd Survey (June, 2000) – MW-I

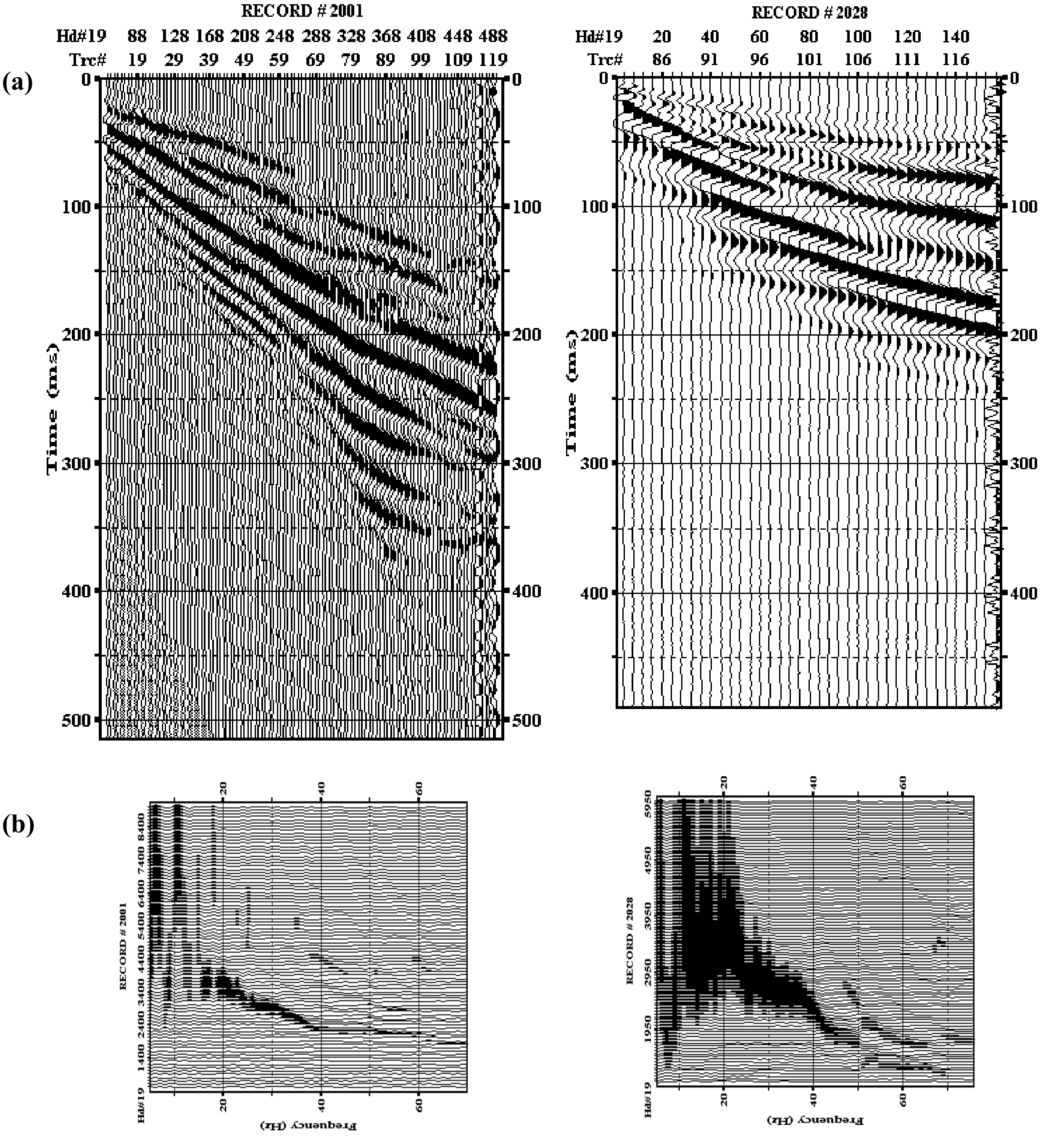
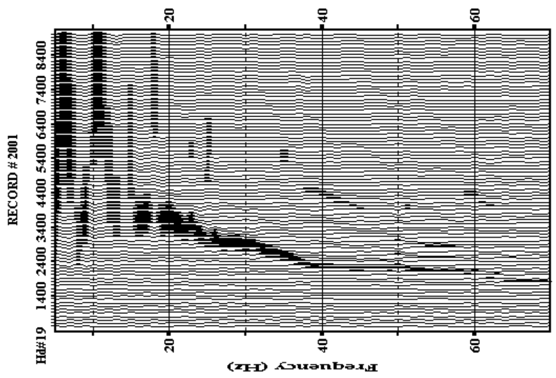
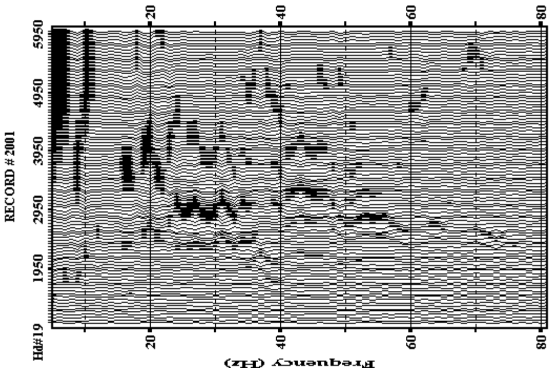


Figure 7. (a) Two shot gathers acquired from the third trip at a site near the well MW-I. One (record # 2001) of the two was obtained near the start of the survey line and the other (record #2028) from a place in the middle of the line. These two apparently different shot gathers generate basically the same dispersion curve images in the high-frequency range (> 25 Hz) indicating that the ambient noise played a major role in making them look different significantly.

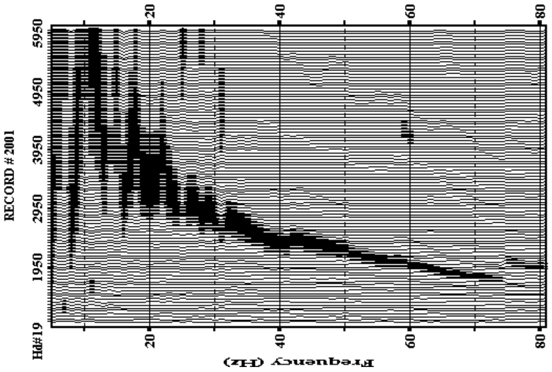
3rd Survey (June, 2000) – MW-I



Full Offset (60 Traces)



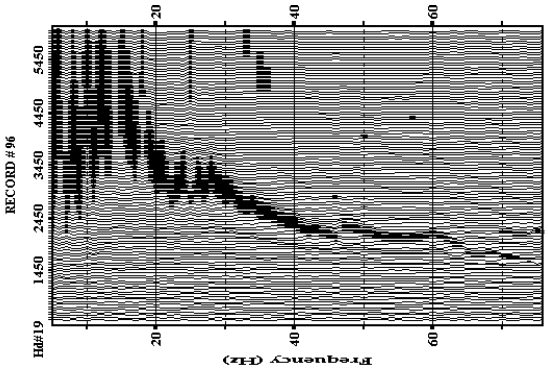
Far Offset (30 Traces)



Near Offset (30 Traces)

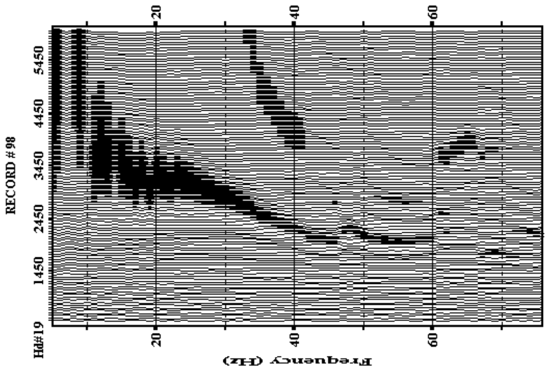
Figure 8. Dispersion curve images analyzed from a shot gather acquired from the third trip at a site near the well MW-I. This illustrates that the far-offset traces were contaminated with ambient noise and affects adversely during the dispersion-curve analysis.

3rd Survey (June, 2000) – MW-I



HM(96).bmp

One Shot Gather



HM(sum96_02).bmp

Stack of 4 Shot Gathers

Figure 9. Dispersion curve images analyzed from two different types of shot gathers: the one from a raw shot gather and the other prepared by stacking four of those raw shot gathers together. This illustrates that the adverse effect of ambient noise, especially at low frequencies, can be reduced by the stacking.

3rd Survey (June, 2000) – MW-I

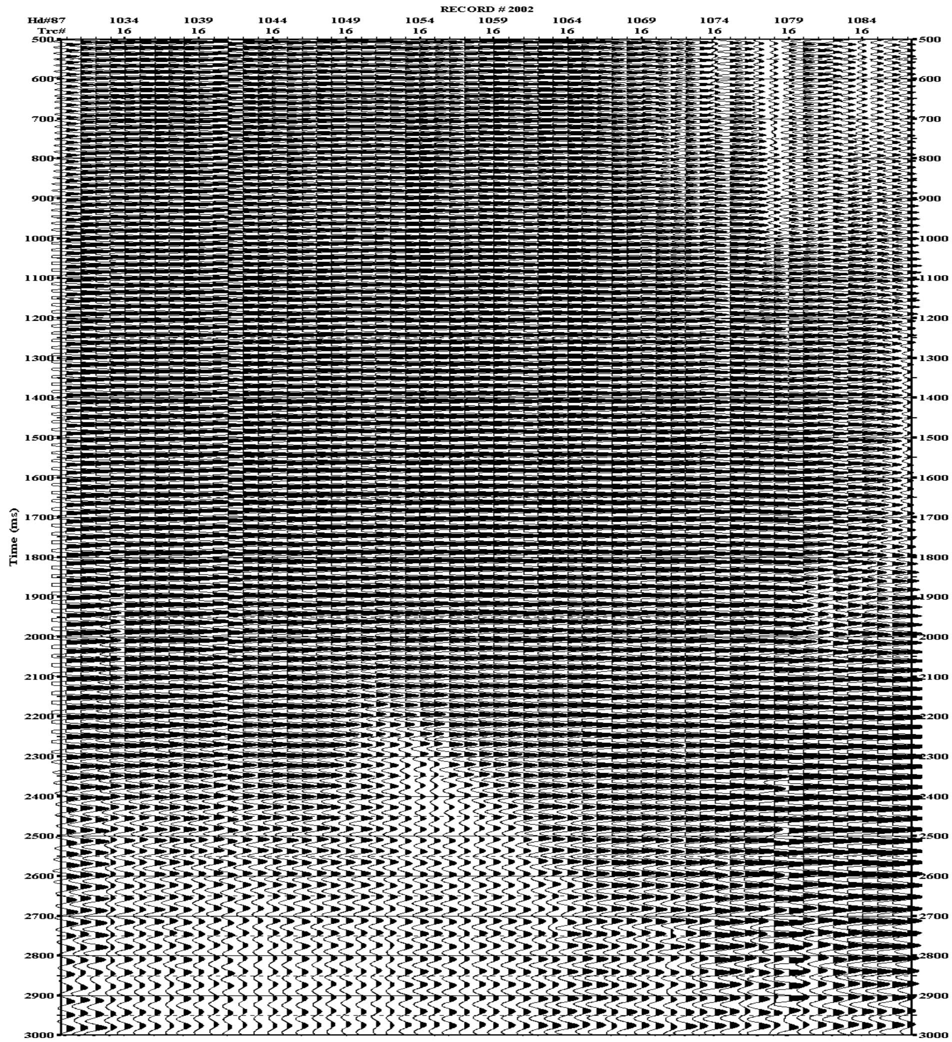


Figure 10. A stacked section of the swept-frequency-decomposition (SFD) records from the third trip. This section basically illustrates that there is a minor heterogeneity at deep and shallow part of the earth near the start and ending locations, respectively, of the survey line.

3rd Survey (June, 2000) – MW-I

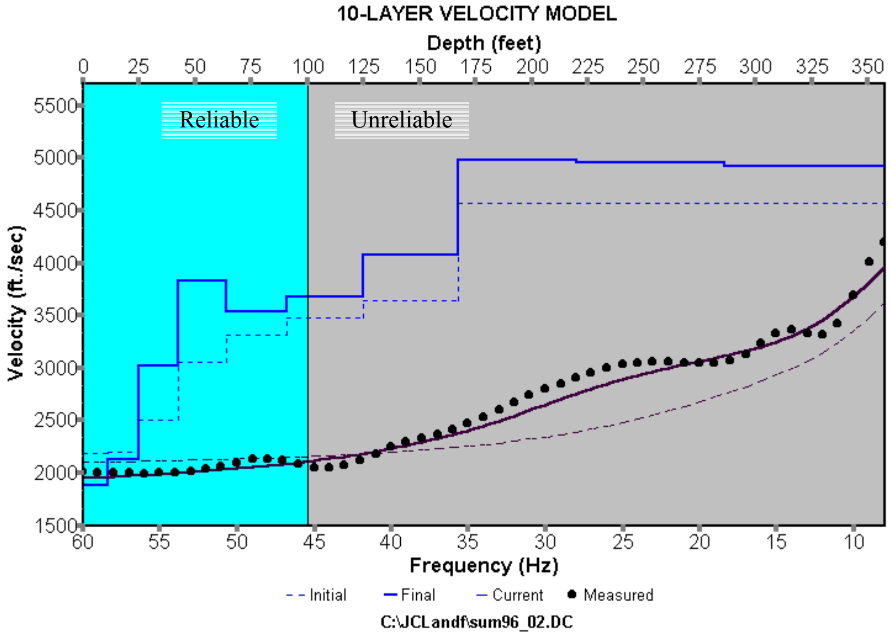


Figure 11. The inversion result of a shot gather from the third trip illustrating how closely the theoretical and measured dispersion curves match each other and the reliable depth range for the result.

1st Survey (Dec., 1999) – Line 2 (MW-K)

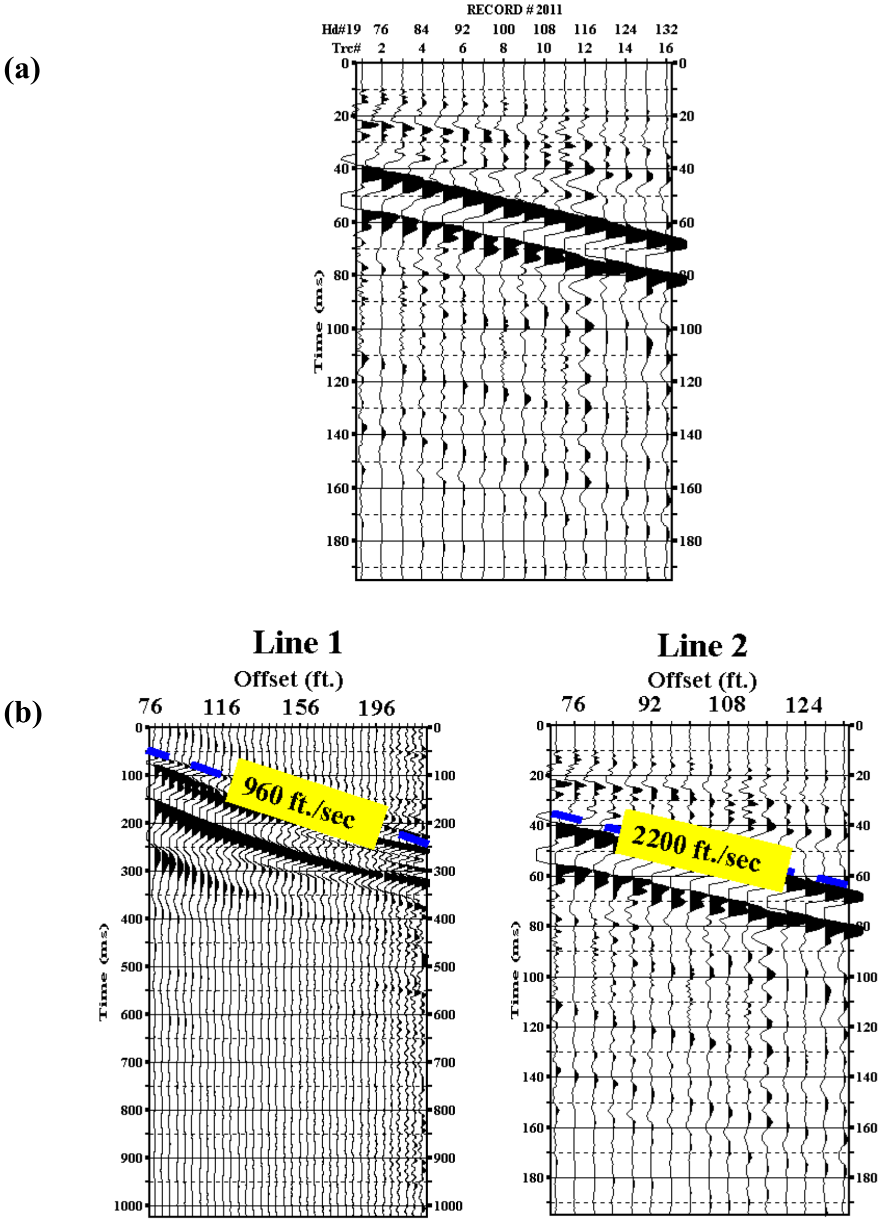


Figure 12. (a) A shot gather acquired from the first trip at a site (Line 2) near the well MW-K. Surface waves are basically non-dispersive. (b) The shot gather in (a) is compared with a shot gather acquired from the same trip at a site (Line 1) near the well MW-I. Characteristics of the surface waves are quite different due to the difference in the near-surface materials between the two sites.

1st Survey (Dec., 1999) – Line 2 (MW-K)

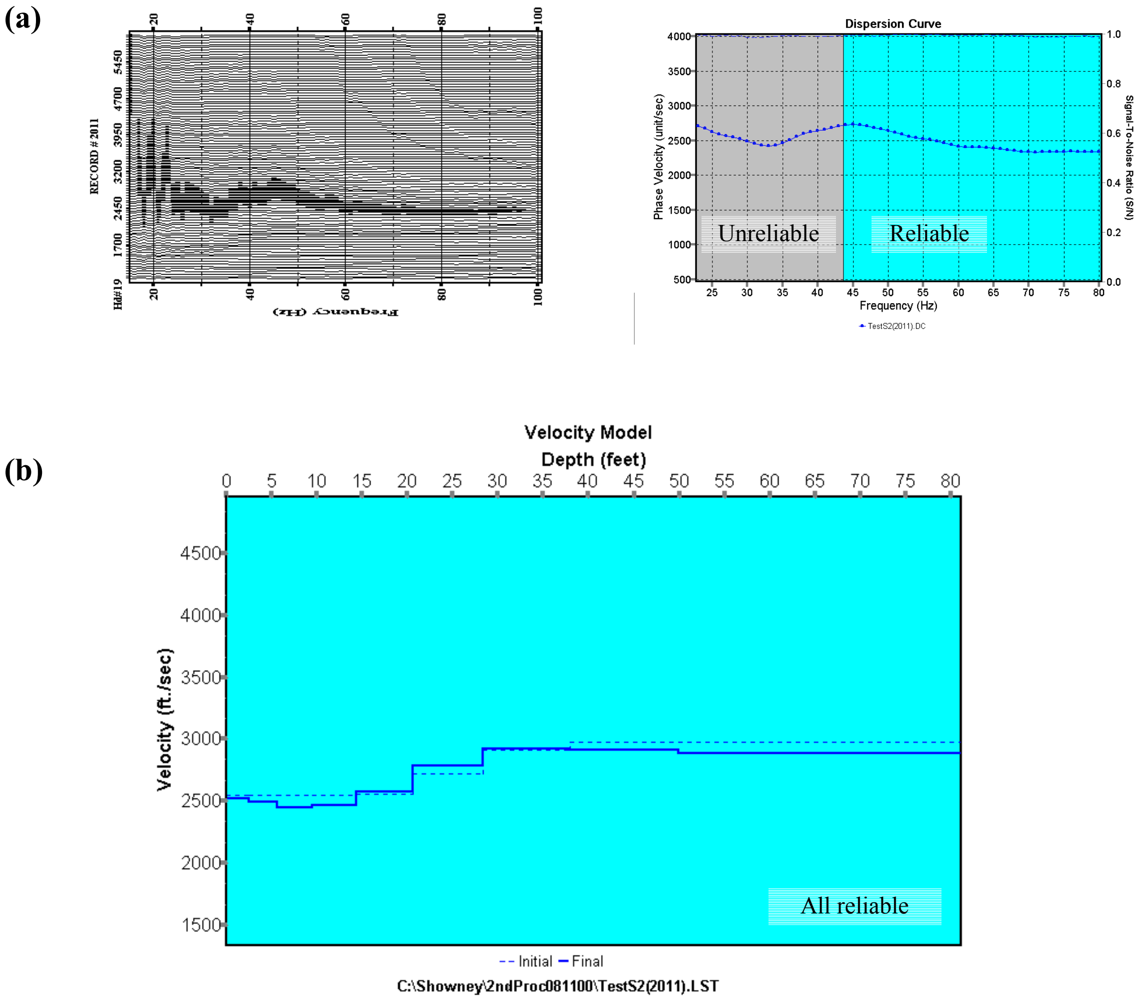


Figure 13. (a) Dispersion-curve analysis of a shot gather acquired from the first trip at a site (Line 2) near the well MW-K. Low frequencies (< 45 Hz) are not reliable due to the presence of ambient noise. (b) The inversion result of the dispersion curve obtained from the analysis shown in (a).

2nd Survey (Jan., 2000) – MW-K

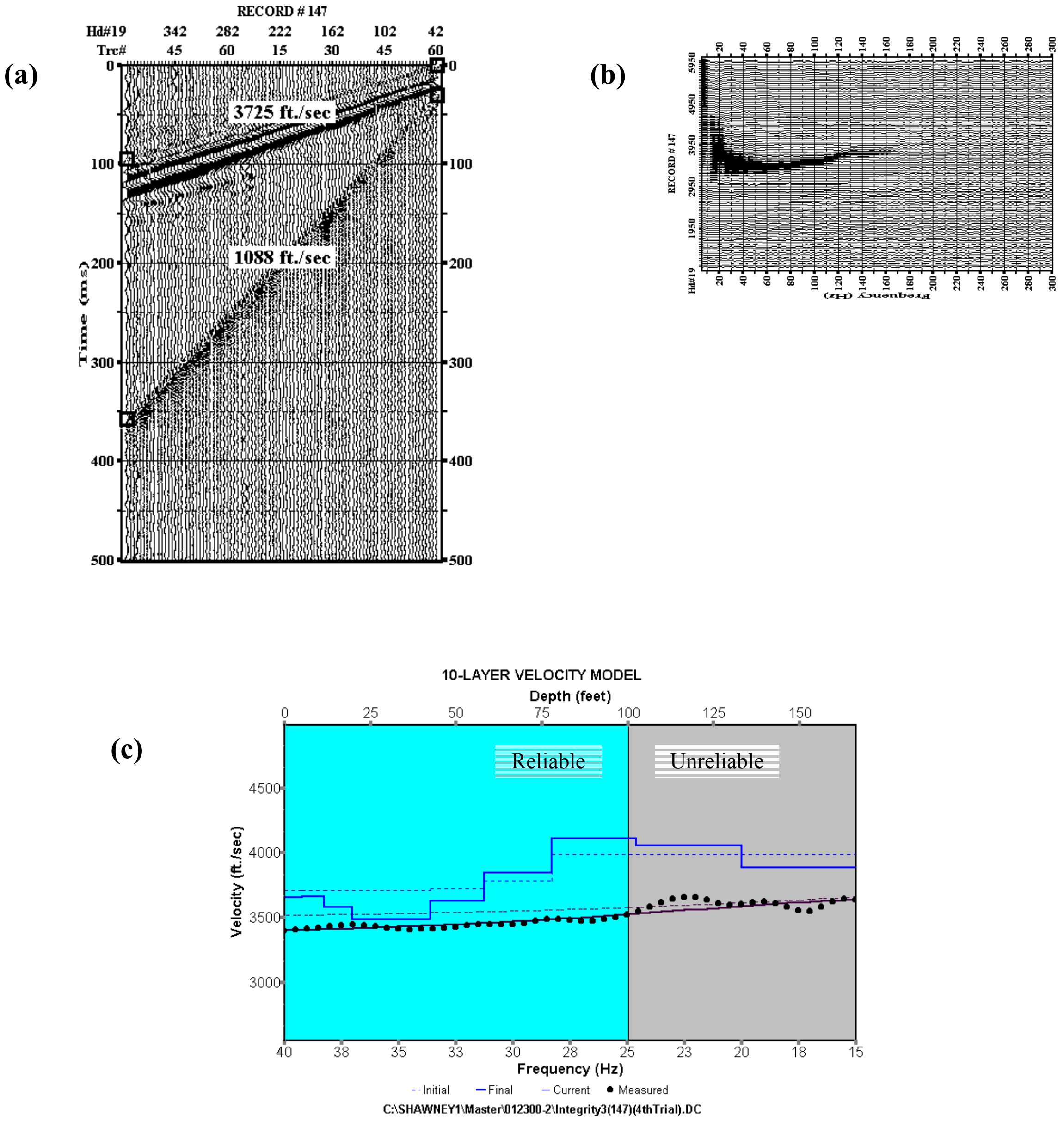


Figure 14. (a) A shot gather acquired from the second trip at a site near the well MW-K. The higher velocity (3725 ft./sec) event represents the surface-wave event, whereas the lower velocity (1088 ft./sec) event is the air-wave event. (b) A dispersion-curve image analyzed from the shot gather in (a) illustrating a good quality over a wide (20 Hz – 150 Hz) range of frequency. (c) The inversion result of the dispersion curve extracted from the analysis in (b).

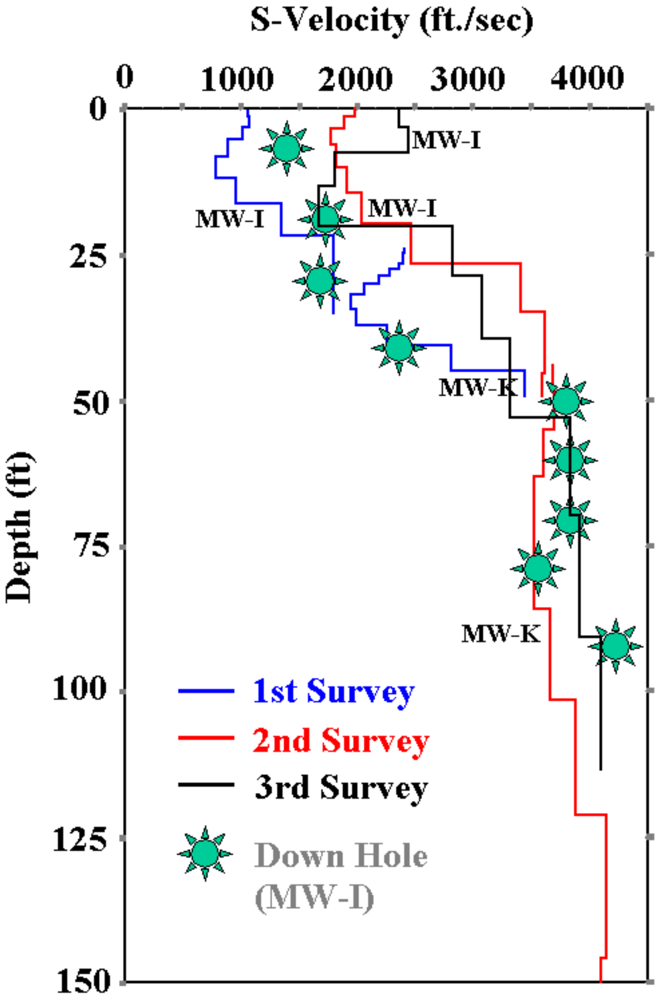


Figure 15. S-velocity profiles obtained from all three trips displayed after an appropriate depth adjustment due to the difference in elevations for the two sites (MW-K and MW-I). S-velocities calculated from the down-hole survey performed during the third trip are marked as well.

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Summary

The shear wave velocity as a function of depth, calculated using the Multi-channel Analysis of Surface Waves (MASW) method (Park et al., 1999; Xia et al., 1999), provided a reliable measure of shear wave velocity well within the empirically determined level of accuracy the method possesses (Xia et al., 2000). Tests designed specifically to evaluate the potential of MASW to discriminate moderate changes in fracture permeability at the Johnson County Landfill (JCL) suggest moderate differences in yield such as observed between MW-I and MW-K cannot be confidently detected using this method (Figure 1). Depths of investigation on the five profiles acquired during phase 1 testing on this study ranged from a few feet below ground surface (BGS) to as much as 100 ft BGS in some cases. Discrepancies between shear-wave velocity profiles measured at these two sites are attributable to localized changes in near-surface conditions, differences in near-surface material, and variability of surface noise sources, but not as a result of changes in rock properties in this very uniform, cyclic limestone/shale geologic setting. Considering the characteristics of these two test sites, the MASW method provided representative measurements, consistent with ground truth and well within the expected accuracy and repeatability range.

Drilling has provided evidence of differences in permeability but no measurable differences in rock properties. With the subtle difference expected at this site, based on the drill data, it is not surprising MASW did not provide the necessary resolution to be used as a reconnaissance tool for locating high permeability fracture lineaments at this site. When comparing this study to previous investigations using this surface wave imaging technology at sites across the country (Miller and Xia, 1999a; Miller and Xia, 1999b, Miller et al., 1999), the inability to detect or discern a unique velocity pattern consistent with the proposed fracture patterns is not surprising. It also brings up the possibility that they do not exist. There are a variety of reasons that could explain the small difference in yield at these two monitor wells, fractures is only one.

Calculating the shear wave velocity field from surface wave arrivals can generally be accomplished with a high degree of accuracy regardless of cultural noise or obstacles. Data for this study were acquired in and around areas with significant amounts of high amplitude, low

frequency noise. Care was taken to insure no data carried artifacts related to surface features and all data were acquired with special attention placed on the spread location relative to surface materials and structures. Comparisons of data characteristics recorded from geophones with steel baseplates to those with spikes revealed no significant difference in wavetrain properties or calculated dispersion curves. Of particular concern during data acquisition was geophone placement in the parking lot, where coupling of the steel plates would vary significantly from station to station. Unlike recording concerns prominent when using other types of acoustic waves, surface waves seem to have only limited dependence on changes in receiver coupling. Non-source noise recorded on surface wave data reduces the quality of the dispersion curve but does not usually prevent an accurate and robust inversion unless the noise is excessive (i.e., equivalent in amplitude and with the same seismic source-to-receiver orientation).

MASW provides shear wave velocity profiles accurately (15%) representing average shear wave velocities for a particular subsurface volume (Xia et al., 2000). Velocities measured during this study ranged from just over 900 ft/sec to around 4000 ft/sec. A localized change of over 1100 ft/sec (100%) in the very near-surface material was observed at site 1 between the parking lot site and the shale site behind the Johnny on the Spot warehouse. This change has been correlated to the fill material present beneath the parking lot not behind the warehouse. General differences of around 15 to 20% were observed between site 1 and site 2 at the depth of the Winterset Limestone (around 100 or so ft). These differences are not sufficiently above the accuracy of the method to be interpreted to represent changes in geology. There does not seem to be a characteristic or property of the shear wave velocity field uniquely distinguishable or diagnostic of fractures in at the depth of the Winterset Limestone. If these fractures really exist, the apparent lack of sensitivity could be related to their size or lateral extent relative to the wavelength of the groundroll (horizontal resolution) or it could be related to size of the fractures and density (vertical resolution). With the limited evidence supporting fracturing as the source of the increased permeability and the extremely small differences in yield, it is unlikely, based on the seismic data in conjunction with supporting borehole data that has been incorporated into the seismic study, that significant differences in fracture permeability exist between MW-I and MW-K.

Interpreting changes in lithology with this technique has routinely involved correlating high velocity gradients and measured velocities to ground truth. Velocity fields at these two sites have not provided distinct enough changes in velocity at a vertical resolution sufficient to allow correlation to the borehole-defined geology. Only at a depth BGS of around 25 to 30 ft does a strong change in velocity occur at both sites. This is likely related to lithology, but due to the cyclic nature of the rocks at this site it is beyond the vertical resolution of these data to determine exactly which unit this change correlates to. There are strong indications that the borehole lithology can be grossly correlated to the shear wave velocity profile. The gradational nature of the shear wave velocity field makes interpreting and correlating unique layers to borehole geology a bit speculative at these two sites.

Introduction

Surface waves traditionally have been viewed as noise on multichannel seismic data designed to image environmental, engineering, and groundwater targets (Steeples and Miller, 1990). A recent development incorporating concepts from spectral analysis of surface waves (SASW) developed for civil engineering applications (Nazarian et al., 1983) with multi-trace seismic acquisition methods commonly used for petroleum applications (Glover, 1959) shows great potential for detecting, and in some cases delineating, anomalous subsurface materials. Extending the common use of surface wave analysis techniques from estimating 1-D shear wave velocities to detection and/or imaging required a multichannel approach to data acquisition and processing. Integrating the MASW method with CMP-style data acquisition permits the generation of a laterally continuous 2-D shear wave velocity field cross-section (Park et al., 1996; Xia et al., 1997; Xia et al., 1998; Park et al., 1999; Xia, et al., 1999). The MASW method as used here requires minimal processing and is relatively insensitive to cultural interference. Mating MASW with the redundant sampling approach used in CMP data acquisition provides a non-invasive method of delineating horizontal and vertical variations in near-surface material properties.

Continuous acquisition of multichannel surface wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels (Park et al., 1998), mapping the bedrock surface (Xia et al., 1998; Miller and Xia, 1999a), locating remnants of underground mines (Park et al., 1999), and delineating fracture systems (Park et al., 1997; Miller and Xia, 1999b). Extending this technology from sporadic sampling to continuous imaging required the incorporation of MASW with concepts from the CDP method (Mayne, 1962). Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross-section of the shear wave velocity field. Cross-sections generated in this fashion contain specific information about the horizontal and vertical continuity and physical properties of materials as shallow as a few inches to over 300 ft BGS in some settings.

Several key characteristics of surface waves and surface wave imaging make application of this technique possible in areas and at sites where other geophysical tools have failed or provided inadequate results. First and probably foremost is the ease with which surface waves can be generated. The relative high amplitude nature of surface waves (in comparison to body waves) makes possible their application in areas with elevated levels of mechanic/acoustic noise. A layer over half space is all that is necessary to propagate surface waves. It is one of the few acoustic methods that does not require velocity to increase with depth and/or a contrast (i.e., velocity, density, or combination [acoustic impedance]). Conductivity of soils, electrical noise, conductive structures, and buried utilities all represent significant problems or at least important considerations for electrical or EM methods. These have little or no impact on the generation or propagation and generally have no influence on the processing or interpretation of surface wave data. This flexibility in acquisition and insensitivity to environmental noise allows successful use of shear wave velocity profiling in areas where other geophysical methods might be limited.

Data Acquisition

Data were acquired along five unique profiles (Figure 1). Three were over or around MW-I and two were coincident in map view and separated by about 20 ft vertically near MW-K. The two profiles at MW-K were acquired before and after the removal of 20 ft of material during the quarrying process. All five lines ranged in length from around 300 ft to as much as 600 ft. Standard CMP roll-along techniques were used to record nominal 48-channel shot records along each line. Asphalt and concrete surfaces necessitated the outfitting of geophones with metal baseplates. Geophones planted in loose dirt areas employed traditional 3” steel spikes to obtain direct coupling. A 60-channel Geometrics StrataView seismograph recorded three vertically stacked impacts from a rubber band assisted weight drop transported on a Case Uniloader at each shot station. Single 4.5 Hz Geospace GS-11D geophones spaced 4 ft apart along the profile lines and responded to frequencies from 20 Hz to 60 Hz. The source-to-nearest-receiver offset was nominally 24 ft and source-to-farthest-receiver offset was around 200 ft. This recording geometry and frequency range provided the optimum spread and data characteristics for examining earth materials between about 5 and 120 ft of depth along most lines.

Data Processing

Each 48-trace shot gather was recorded with live receivers in the optimum recording window. Multichannel records were analyzed with *SurfSeis* (a proprietary software package of the Kansas Geological Survey), facilitating the use of MASW with continuous profiling techniques. Each shot gather generated one dispersion curve. Care was taken to insure the spectral properties of the t-x data (shot gathers) were consistent with the maximum and minimum f-v_c values (v_c is phase velocities of surface waves) contained in the dispersion curve. Each dispersion curve was individually inverted into an x-v_s trace. The shear wave velocity field generated in this fashion does "smear" gradational velocity anomalies to a limited extent and requires an understanding of the overall resolution. The processing flow generally included the following steps:

SEG-2 to KGS-modified SEG-Y
Calculate the dispersion curve from phase velocity as function of frequency
Estimate initial model (20 Hz to 60 Hz—15 to 250 ft wavelength)
Invert to solve for shear wave velocity

SITE MW-I

Seismic data for site MW-I were collected along three unique lines all trending east/west in general (Figure 1). The three profiles were collected during three distinctly different trips and weather/soil conditions. The first survey line was acquired through the employee parking lot immediately east of the scale house near Johnny on the Spot and was acquired during December 1999. The second was acquired on a Sunday (to avoid some of the truck noise) during January 2000, and the third was collected during June of 2000. These three profiles were acquired at uniquely different places and times to avoid problems encountered during previous surveys.

The December 1999 survey was acquired in the parking lot for convenience and to be in close proximity to MW-I. Data from that section were strongly contaminated with noise from haul trucks and possessed a near-surface velocity unrealistically below expectations and comparable data acquired at the same time near well MW-K (Figure 2). Dispersion curves calculated from the first profile were very unreliable and did not extend to primary depths of interest (Figure 3). Examination of site records revealed that this site was part of the landfill before it was converted to a parking lot and the upper 20 to 30 ft would most likely be fill and waste materials. Since the objective of this initial test was to look for subtle differences at depth with the assumption the near-surface conditions (i.e., ability to generate and propagate low frequencies) were close enough to the same at both sites to be considered identical, it was deemed necessary to collect another set of data from the site in an area less likely to be influenced or to have fill material in the near-surface.

A second survey conducted during January of 2000 was designed to correct for two sources of error. The line was moved closer to the outcrop, thereby reducing the amount of fill present beneath the profile, and it was acquired on a Sunday to minimize the amount of recorded surface noise. The resulting data were of much higher quality and more consistent with both expectation and data from MW-K, but it still was influenced by the fill material in the near-surface sufficiently to negate direct comparisons with data from MW-K. As well, the fill material attenuated the low frequencies necessary to achieve penetration depths in excess of 120 ft (Figure 4). Dispersion curve data provided reliable velocity information from a few feet BGS to depths in excess of 60 ft (Figure 5).

A third profile was acquired behind Johnny on the Spot in an area freshly stripped of the upper 20 to 30 ft of rock (Figure 1). A drainage area near the east end of the profile shows the effects of a variable near-surface on the general character of the surface wave (Figure 6). It is also possible this anomaly is related to deeper features that control the observed surface drainage area. In particular, faults or fractures could produce such a marked change in wavelet properties. Shot gathers from this third profile are much more consistent with expectations and data previously acquired at the MW-K site (Figure 7). Source-to-receiver offset has a significant impact on the interpretability of the dispersion curve and on the robustness of the inversion process (Figure 8). Here as well the effects of stacking several shots in hopes of enhancing signal is evident on the dispersion curves (Figure 9). Another way of studying the properties of dispersive ground roll is to separate the surface wave into each of its individual frequency components (Figure 10). Resulting wiggle trace displays provide as measure of lateral consistency in the amplitude character of the signal. Changes in the amplitude due to attenuation or lack of attenuation are indicative of changes in layer rigidity or stiffness. The overall consistency in the near surface between site MW-I #3 and MW-K provided dispersion curves that could be directly compared (Figure 11). Even with this much improved data set the reliable depth range was still a bit less than anticipated, with maximum reliable depths of penetration just over 100 ft.

SITE MW-K

Site MW-K was selected based on its apparent lower permeability from borehole tests within the Winterset Limestone (Figure 1). Neither site (MW-K nor MW-I) provided physical test results or samples that could confirm the presence of or even a measurable change in fracture density or permeability. Therefore, changes observed in fluid yield between the two sites may or may not be related to changes in the physical properties of the limestone and hence show no observable change in the shear wave velocity. This low permeability site was selected to be reasonably close to MW-I and penetrating as close as possible to the same geologic interval from ground surface to the Winterset in this area.

The initial survey conducted as part of phase 1 provided excellent results that were quite reliable, considering the environment. Shot gathers have dominant surface waves with little or no noticeable body waves or industrial noise (Figure 12). A distinct difference in the lowest surface wave velocity is clearly noticeable when comparing records from the MW-I and MW-K sites. This difference is related to the fill present beneath the parking lot at MW-I, whereas MW-K is in an area with only natural materials. This velocity difference was initially suggested to be related to possible differences in permeability. However, with very minimal study it was clear this difference was related to bulk material differences (i.e., fill at MW-I) rather than the subtle changes modeled to possibly be evident as a result of the proposed fractures. Dispersion curve calculations provided shear wave velocity profiles that were very reliable and representative of actual shear wave velocities at this site (Figure 13). It was these data that turned the attention to MW-I as the anomalous data set, with a calculated shear wave velocity unreliable below about 30 ft.

A second trip during January of 2000 was undertaken to narrow down the source of the erroneous and very limited shear wave velocity profiles calculated during the December trip. During this second trip to the site, data collected at the MW-K site were consistent with the previous trip (Figure 14). Slight differences were observed as a result of the more than 20 ft of shale that had been stripped off between the two site visits. This difference could be directly correlated to the velocity profiles since the lines were coincident with each other with the only difference being the stripped-off shale.

The shear wave profiles generated at MW-K were consistent with each other and provide measured shear wave traces that are less than 15% different, after correction for the change in elevation due to removal of the shale layer. Based on data from this site, it appears the surface wave has effectively penetrated depths in excess of 200 ft, providing a reliable measure of shear wave velocity down to just over 100 ft. This depth of penetration is not as deep as had been hoped, but at the MW-K site this should have been deep enough on the second trip to sample the Winterset Limestone.

CONCLUSIONS

Based on the combined results of all five surveys conducted during the 7 months this program was active, it is clear that the very marginal difference in fluid production between observation well MW-I and MW-K are not the result of fractures with sufficient expression to effect the shear wave velocity in the limestone more than 15%. This observation is based on both borehole and surface wave data.

Combining all five profiles and the uphole survey conducted in MW-I into a single depth versus shear wave velocity graph provides an extremely instructive view of the subsurface, limitations of this method, and a general idea of the scatter in these data (Figure 15). The borehole data clearly tell the story of MW-I. Measured velocities of 1500 to 1750 ft/sec down to 30 ft BGS is not representative of the hard rock (limestone/shale) environment depicted by most geologic cross-sections in this area. Velocity this low is a natural fill or compacted man-placed fill. Clearly after about 40 ft the velocity increases dramatically (3 times) and assumes a range consistent with a limestone/shale setting. Comparing the borehole and various velocity traces from the five different surveys shows all data representing depths greater than 50 ft are within a 500 ft/sec scatter around 3750 ft/sec. This scatter represents an error in measurement of about 13%. Unfortunately, the depth of interest is at the very limit of the reliable data set. If anything, the slightly higher average velocity observed on the third survey at MW-I is opposite what would be expected if this area were more fractured relative to the area around MW-K.

The source of all the confusion and difficulties encountered during the initial 3 months of this research program are for the most part related to the fill material under the parking lot. Unfortunately, this fill material limited the depth of penetration and significantly increased the confusion as to the source of such an extreme difference. By design this test was developed and executed to evaluate two areas identical except the measured difference in the apparent increased permeability, unfortunately the differences unrelated to the proposed fractures were much more significant than the test was designed to allow. Near-surface velocity profiles tell the story quite effectively. The initial survey was conducted in a thicker area of the fill and closer to the edge of the fill and hence the velocities observed were the lowest anywhere else studied. As the survey was moved to ever more competent and less disturbed near-surface materials, the velocity increased until it was consistent with a hard rock, competent near-surface environment directly behind the Johnny on the Spot warehouse.

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