Seismic Characterization of Geotechnical Sites By Multichannel Analysis of Surface Waves (MASW) Method

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ABSTRACT

Shear wave velocity (Vs) information of a soil site is one of the critical parameters in soil dynamics and earthquake engineering. Although it can be obtained from a shear-wave seismic survey either at the surface or through a borehole method, the surface-wave method is an excellent alternative. It utilizes the dispersion of Rayleigh waves that usually take more than two thirds of total seismic energy generated by an impact seismic source at the surface. This indicates a relative easiness in the field survey and sometimes also during the post-acquisition processing steps. Although because of this reason the method appears highly attractive, complications, however, may arise as with all other types of seismic method. Source-generated body waves (e.g., direct and refracted compressional waves), higher modes of Rayleigh waves, random ambient noise (e.g., cultural noise), and coherent arrivals scattered from surface objects (e.g., from building foundations) all interfere with the signal, the planar fundamental-mode Rayleigh waves propagating directly from source. A multichannel seismic method similar to the one long used in the oil industry provides a highly effective quality control during both acquisition and processing stages. In addition, a 2-D pattern-recognition processing technique has an extraordinary capability to differentiate signal from noise even under a severe noise contamination. This seismic method is applied to various soil-site projects to produce 1-D and 2-D Vs maps. Compressional wave velocity (Vp) is one of the valuable by-products obtainable from the same data set used for Vs analysis through a different processing step.

INTRODUCTION

A seismic method has often been used as a non destructive testing (NDT) method that can provide such key geotechnical parameters as shear and bulk moduli from the S-wave (Vs) and P-wave (Vp) velocities of near-surface materials. Surface wave has often been used to infer Vs variation with depth (a Vs profile) of near-surface materials from the measurement of Rayleigh-type surface waves. For the Vs profile is a key engineering parameter that can be associated with the stiffness profile in many geotechnical characterization of soil sites within the depth range of several tens of meters.

Conventional surface wave method (Stokoe et al., 1994; Nazarian et al., 1983) analyzes only one type of seismic waves (e.g., fundamental-mode Rayleigh waves) recorded at two separate surface locations, treating the recorded data being dominated by that specific type. When a seismic source generates seismic waves, however, various different types of seismic waves are generated simultaneously (Figure 1). In the broadest sense, these types of seismic waves can be grouped into two: body and surface waves. The former group includes direct, refracted, air-coupled, and reflected waves, whereas the latter group includes fundamental and higher modes of Rayleigh waves. Relative dominance of each type of seismic waves is a complicated function of earth (e.g., Vs, Vp, etc.), acquisition (e.g., source type, distance from source, receiver spacing, etc.), and cultural (e.g., traffic, surface objects, etc.) factors. It can only be controlled, to a certain degree, through an optimum field configuration that has to be established through a careful observation of all the types in their nature of velocity, attenuation, and interference with other types.

Multichannel analysis of surface waves (MASW) is a seismic method that can be used for geotechnical characterization of near-surface materials (Park et al., 1999a; Xia et al., 1999; Miller et al., 1999a). It identifies each type of seismic waves on a multichannel record based on the normal pattern recognition technique that has been used in oil exploration for several decades (Figure 1). The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (S/N) ever possible. Effectiveness in signal analysis is then further enhanced due to the diversity and flexibility in data processing step (e.g., Ivanov et al., 2001). The MASW method can generate a 2-D cross section of Vs from the analysis of surface waves in a fast manner. It can also generate a cross section of Vp from the analysis of refracted waves on the same data set used for the Vs cross section (Ivanov et al., 2000a).

SURFACE WAVE METHOD

In most surface seismic surveys that use a vertical seismic source like sledge hammer, more than two-thirds of total seismic energy generated is imparted into Rayleigh-type surface waves (Richart et al., 1970), the principal component of ground roll. Assuming vertical velocity variation, each frequency component (f) of the surface waves have different propagation velocity (called phase velocity, C_f), providing a different wavelength (λ_f) for each frequency propagated. This property is called dispersion. Although ground roll is considered noise on body-wave surveys (i.e., reflection or refraction profiling), its dispersive properties can be utilized to infer near-surface elastic properties. One of the most common ways to use the dispersive properties of surface waves is the construction of a shear (S)-wave velocity (Vs) profile through the analysis of plane-wave, fundamental mode Rayleigh waves (Stokoe et al., 1994; Bullen, 1963).

The entire process classically used to produce a Vs profile involves three steps: acquisition of ground roll, construction of dispersion curve (a plot of phase velocity vs. f), and backcalculation (inversion) of the Vs profile from the calculated dispersion curve. Broadband ground roll must be produced and recorded with minimal noise to allow accurate determination of the Vs profile. A variety of techniques can be used to calculate the dispersion curve (Park et al., 1998b; McMechan and Yedlin, 1981; Gabriels et al., 1987). Backcalculation of the Vs profile (inversion of the dispersion curve) is accomplished iteratively, using the measured dispersion curve as a reference for either forward modeling or a least-squares approach (Rix and Leipski, 1991). Usually values for Poisson's ratio and density are estimated during this step.

Although surface waves can be generated relatively easy and usually take the strongest energy, complications often arise due to inclusion of noise. Signal is defined as planar fundamental mode of Rayleigh wave, whereas everything else as noise. Noise may include random ambient noise (e.g., traffic and machinery noise), source-generated body waves (e.g., direct, refracted, scattered, and reflected compressional waves), and higher-mode surface waves. Effectiveness of a particular surface-wave method, therefore, is evaluated mainly in its capability to handle the noise inclusion during data acquisition and processing stages.

MULTICHANNEL METHOD

The multichannel seismic method (Dobrin and Savit, 1988) uses multiple number of receivers deployed in a linear pattern of equal receiver spacing with each receiver connected to an individual recording channel (Figure 2). One measurement (record) consists of multiple (usually more than twelve) recordings (traces) of seismic wavefields made at different distances (offsets) from the source. The main advantages exist in two aspects: pattern recognition capability and redundancy in measurements. The former allows a highly effective quality control during both data acquisition and processing steps. For example, surface and body waves can be identified separately on a record due to their unique arrival times and amplitude patterns resulting from the different seismic velocity and attenuation properties. This means that such critical acquisition parameters as offset and recording time can be optimized in a favorable way through a few iterations of noise analysis in the field. It also means that once data are collected, diverse multichannel processing techniques (Yilmaz, 1988) can be applied for an effective extraction of information (Ivanov et al., 2001). Redundancy in measurements allows the application of various types of noise-suppression techniques to further increase the signal-to-noise ratio (S/N). The basic field configuration and acquisition routine for MASW is the same as that used in conventional common-depth-point (CDP) reflection surveys (Dobrin and Savit, 1988). Because of this commonality, MASW can be applied to reflection (or refraction) data if low-frequency receivers were used and no analog lot-cut filter was applied during the data acquisition.

Various types of patterns can be analyzed with one multichannel record (shot gather). In general, they can be grouped into two: velocity and attenuation. Furthermore, with one specific type of pattern, the analysis can be focused into different types of seismic waves. For example, the velocity analysis can be applied either to reflection waves or surface waves by using different algorithm. The type used for surface wave method is the pattern recognition that reveals the variation of phase velocity with frequency (i.e., dispersion). While several different methods are available for this purpose, we use a wavefield transformation method by Park et al. (1998b; 1999c) that converts the seismic measurement in offset-time (x-t) domain directly into phase velocity-frequency (C_f-f) domain without any subjective pre-manipulation of data. Effectiveness of this method is illustrated by an synthetic experiment in Figure 3. A synthetic 48-channel shot gather in Figure 3a models multi-modal (fundamental and one higher mode) surface waves whose dispersion curves are displayed in Figure 3b. Figure 3c shows the result from the wavefield transformation in which patterns of the phase velocities for the two modes are accurately recovered by the image constructed from the re-distribution of seismic energy on shot gather. Robustness of the method is further illustrated in Figures 4a-b through another synthetic shot gather in which contamination by random ambient noise is so severe that presence of the surface waves is hardly noticeable. The investigated patterns of surface wave dispersion, however, are recovered fairly intact by the transformation method (Figure 4b). The last synthetic experiment shown in Figures 4c-d illustrates that the pattern recognition becomes more effective with more number of channels used during the survey.

MASW—FIELD EXAMPLE

During last several years, the MASW method has been successfully applied to various types of geotechnical and geophysical projects. These projects include mapping 2-D bedrock surface and shear properties of overburden materials (Miller et al., 1999a), weak spots (Miller et al., 1999b), Poisson's ratio distribution (Ivanov et al., 2000a), generation of shear-wave velocity (Vs) profiles (Xia et al., 2000a), detection of voids (Park et al., 1998a), seismic evaluation of pavements (Ryden et al., 2001; Park et al., 2001a; 2001b), and seismic characterization of sea-bottom sediments (Park et al., 2000a; Ivanov et al., 2000b). On this paper are presented some data sets obtained from one of the recent projects performed at the Kansas Geological Survey (KGS).

Soil Site Field Data Near Yuma, Arizona

Figure 5a is a shot gather collected over a dry soil site within the Basin and Range Province near Yuma, Arizona. A weight-drop source (RAWD) built at KGS was used as seismic source and 10-Hz geophones were used as receiver. Among many other shot gathers of different sizes and offsets collected at the site is shown here the one that has thirty traces, simulating a 30-channel acquisition, recorded over the offset range of 5 - 40 m with 1.2-m receiver spacing. Near-surface materials at the site consist of thick (> 30 m) accumulation of alluvial and colluvial sediments eroded from the topographically high ridges (Block, 2001). A preliminary identification of seismic events is made according to packets of seismic waves that have fairly common coherency in velocity and frequency (Figure 5b). The events are interpreted as refracted (and possibly guided) compressional wave event (A), higher-mode (B), and fundamental-mode (C) surface-wave events as marked on the figure. The body-wave event (A) has much a higher apparent frequency (about 100 Hz) than those of surface waves (about 40 Hz). Apparent phase velocity (i.e., horizontally travelling velocity) of each event is marked on the interpretation schematic of Figure 5b.

Multichannel Analysis

Figure 5c shows the wavefield transformation of the shot gather. According to their apparent frequencies and velocities identified on the shot gather, events (A, B, and C) are correlated to the corresponding dispersion images on the figure. The fastest body-wave event (A) is shown to have a slight dispersion. This indicates the possible inclusion of guided waves (Sheriff and Geldart, 1989). It is shown that the higher mode (B) and the fundamental mode (C) have frequency ranges of approximately 35-90 Hz and 10-35 Hz, respectively, but both modes have almost common range of phase velocities (approximately 300-600 m/sec). This means that the preliminary interpretation in offset-time (*x-t*) scope of each mode (Figure 5b) was not quite correct because both modes exist as a mixture fanning through the both zones of B and C. Because of this reason, the conventional 2-D velocity filtering (*f-k* filtering) can not be used to filter out the higher mode and extend the bandwidth of the fundamental mode to the higher (> 35 Hz) frequencies (if any detectable energy exists). A special 2-D filtering scheme (Park et al., 2001d) was developed that applies the "cut" and "pass" operations of filtering within the frequency- phase velocity (f - C_f) domain instead of frequency-wave number (*f-k*) domain. Figure 6 shows the shot gather (left) and its wavefield transformation (right) before (Figure 6a) and after (Figure 6b) this filtering. A fundamental mode of 10-60 Hz was extracted from the transformation of the filtered shot gather and Figure 7 show the Vs profile inverted from this dispersion curve by using an automated algorithm by Xia et al. (1999).

Swept-Frequency Decompostion

Shot gather in Figure 5a is decomposed into a swept-frequency format (Park et al., 1999a) in which individual frequency of seismic waves is separately displayed in a continuous manner from low (10 Hz) to high (125 Hz) frequencies. The decomposed record is displayed in Figure 7 in 30 Hz increment. Phase velocities are marked at two arbitrary frequencies in each displayed segment for reference purpose. This type of decomposed display is quite useful to examine various aspects of seismic characteristics that may not be obvious in the normal shot gather. For example, the lowest frequencies (around 10 Hz) of surface waves show somewhat irregular (or broken) coherency as well as relatively weak energy. This is due to the near-field effect (Stokoe et al., 1994; Park et al., 1999a), indicating that the longest wavelengths (about 40 m) were not completely stabilized within the offset range to become well-developed plane waves. A gradual reduction of linear slope (i.e., increase of phase velocity) is observed at far-offset traces for the frequencies around 30 Hz. This represents the start of energy dominance by the faster higher mode that always begins at the far-offset traces and spreads into the near-offset traces at the higher frequencies (Park et al., 2000b). The apparent back-scattering feature observed around 35 Hz is actually a wave-interference phenomenon between the slower fundamental mode and the faster higher mode whose dominance spreads into the near-offset traces as the frequency becomes higher. Complete dominance by the higher mode is seen at the frequencies higher than about 40 Hz. The higher mode then shows a normal dispersion (i.e., decrease of phase velocity with frequency) up to around 90 Hz at which a fairly abrupt reduction of the slope occurs due to the dominance by the faster body waves (i.e., refraction and guided waves). A lot more aspects of the seismic phenomenon can be examined from this decomposed shot gather than those discussed above.

2-D Vs and Vp Maps

Multiple number (more than fifty) of shot gathers were collected along a linear survey line by moving both source and the receiver spread in a similar manner to the conventional roll-along mode (Dobrin and Savit, 1988). Although diverse analyses are possible with respect to velocity and attenuation of all the seismic events on the shot gather, we focused into the analysis of the fundamental mode surface waves and the first arrivals (refracted waves) of compressional waves to extract Vs and Vp information, respectively. Detailed description of the Vp analysis can be found from Ivanov et al. (2000a). Each shot gather consisting of thirty traces was analyzed to generate one Vs profile, and then a 2-D Vs map was constructed from the multiples of 1-D profiles (Figure 8a). In addition, they were also analyzed for the Vp files in a joint manner (Ivanov et al., 2000a) and the resultant 2-D Vp map is shown in Figure 8b. Details on this project will be available in the near future.

DISCUSSIONS

As its name may imply, it appears that the MASW method requires a multichannel (e.g., 24-channel) recording device, so-many receivers, and long cables with multiple hookups. All these specifications are often expensive (and bulky) enough for the engineers to pull out the method at the early stage of project planning. However, these specifications are not always required. For example, a simulated 48-channel shot gather can be obtained with a single-channel device (or two-channel device such as digital spectral analyzer), one geophone, and a sledge hammer by repeating the single-channel measurement 48 times at 48 different offsets (Ryden et al., 2001). That is, the traditional walkaway method used in the exploration seismic survey can be applied to this single-channel case. This approach is especially economical for the small-scale projects.

Advantages with MASW method were described with a focus to soil application. Since the authors' main purpose was to introduce a seismic method from which various projects in soil dynamics and earthquake engineering can benefit, detailed description on the field logistics was omitted on this paper, but can be found from Park et al. (1999a). Further description on the optimum acquisition parameters (e.g., number of channels, source offset, receiver spacing, etc.) in association with the accuracy in the dispersion curves can be found from Park et al. (2001c).

Higher modes of surface waves were treated here as noise. However, they are also surface waves of the same generation mechanism governed by the same elastic properties of near-surface materials as the fundamental mode. In fact, higher modes are more sensitive (in dispersion and attenuation) to the elastic properties than the fundamental mode (Xia et al., 2000b; Xia et al., 2001). This means the inversion of a higher-mode dispersion curve can achieve a higher resolution as well as the deeper depth of analysis than that of the fundamental mode. Currently, we are investigating the possibility of the simultaneous inversion of multi-modal dispersion curves in a joint manner.

CONCLUSIONS

Multichannel analysis of surface waves (MASW) method is an effective alternative to the shear-wave method to evaluate stiffness of soil. It is a non-destructive method robust in its quality control during acquisition and processing stages. It makes field procedure extremely simple and the post-acquisition steps to generate dispersion curves highly objective and accurate. All these advantages come from the pattern-recognition capability of the multichannel seismic method that can delineate different types of seismic events in their velocity and attenuation properties through the coherency examination along the offset-time (x-t) axes.

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FIGURE CAPTIONS

Figure 1. A schematic showing various different types of seismic events generated simultaneously on an impact applied to surface of the earth. An example field multichannel record (shot gather) is displayed with identified events marked on it.

Figure 2. A schematic showing field configuration of instruments used during a multichannel seismic survey.

Figure 3. (a) A synthetic 48-channel record that contains multi-modal surface waves (no other types of waves) whose dispersion curves are displayed in (b), and (c) the dispersion curve images constructed from a direct wavefield transformation of (a).

Figure 4. (a) The synthetic shot gather of Figure 3a after strong and random ambient noise has been added, and (b) its wavefield transformation that shows almost hidden pattern of the dispersion. (c) Same type of shot gather but simulating a use of more number of channels (96 channels) during acquisition, and (b) its wavefield transformation.

Figure 5. (a) One of the multichannel (30-channel) records collected over a dry, thick soil site near Yuma, Arizona. Three different types of events identified are refracted (and possibly guided) body waves (A), a higher-mode (B), and fundamental-mode (C) surface waves. (b) An interpretation schematic indicating apparent velocities and approximate scopes of the identified events in their offset-time (x-t) space. (c) Wavefield transformation of (a) in which identified events in x-t space are correlated with corresponding images in phase velocity-frequency (C_f-f) space.

Figure 6. Shot gather of Figure 5a (left) and its wavefield transformation (right) (a) before and (b) after a special 2-D filter has been applied to filter out the higher-mode energy. Dominance of the higher mode disappeared completely and the fundamental mode is now extended up to 60 Hz.

Figure 7. Vs profile obtained from the inversion of the fundamental mode dispersion curve extracted from the wavefield transformation of Figure 6b. Vs values from the crosshole survey near the seismic survey line are also marked. (The crosshole data at depths shallower than 10 m are not available.)

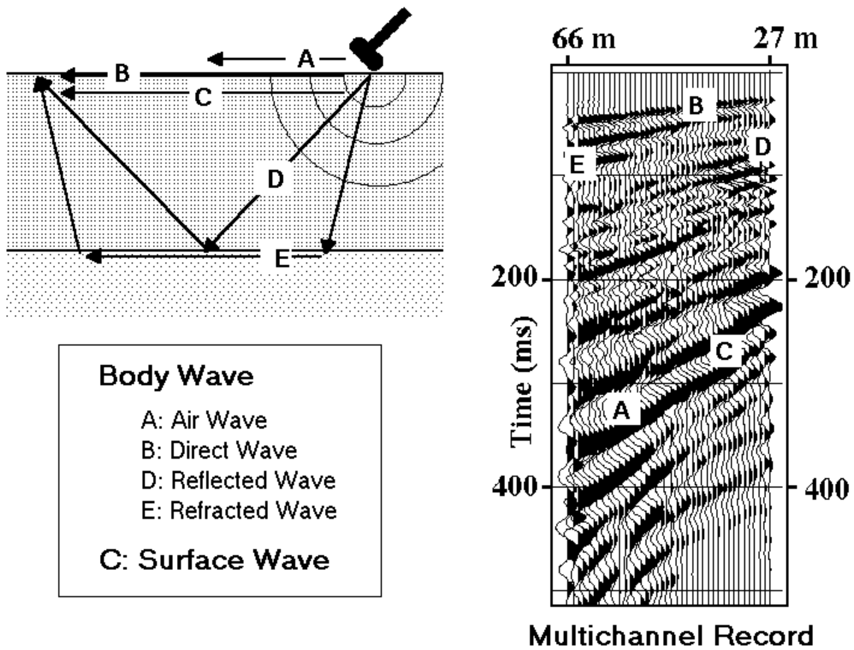
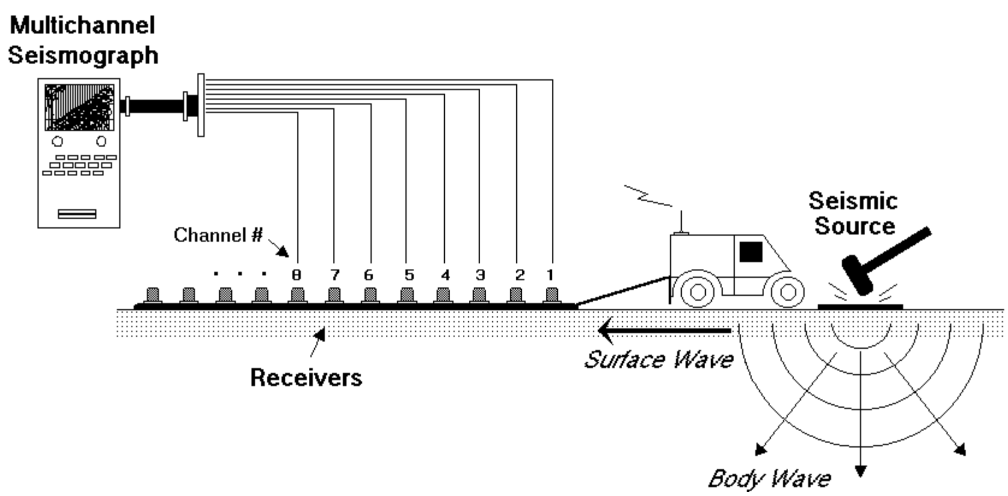

A
B
C
D
E
Body Wave
A: Air Wave
B: Direct Wave
D: Reflected Wave
E: Refracted Wave
C: Surface Wave
66 m
27 m
200
400
Time (ms)
Multichannel Record

Figure 1.


Multichannel
Seismograph
Channel #
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Seismic
Source
Receivers
Surface Wave
Body Wave

Figure 2.

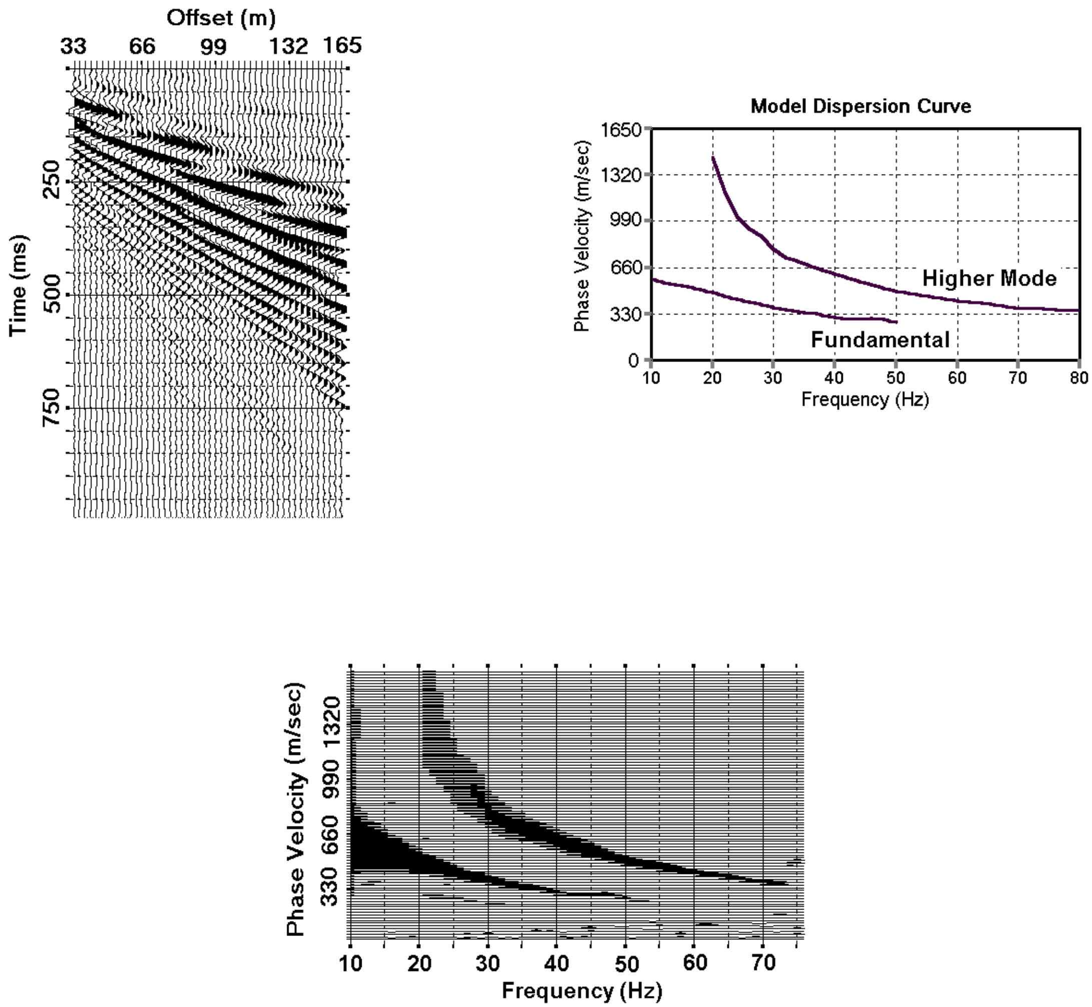

Offset (m)
33 66 99 132 165
Time (ms)
250
500
750
Model Dispersion Curve
Phase Velocity (m/sec)
1650
1320
990
660
330
0
Higher Mode
Fundamental
10 20 30 40 50 60 70 80
Frequency (Hz)
Phase Velocity (m/sec)
330 660 990 1320
10 20 30 40 50 60 70
Frequency (Hz)

Figure 3.

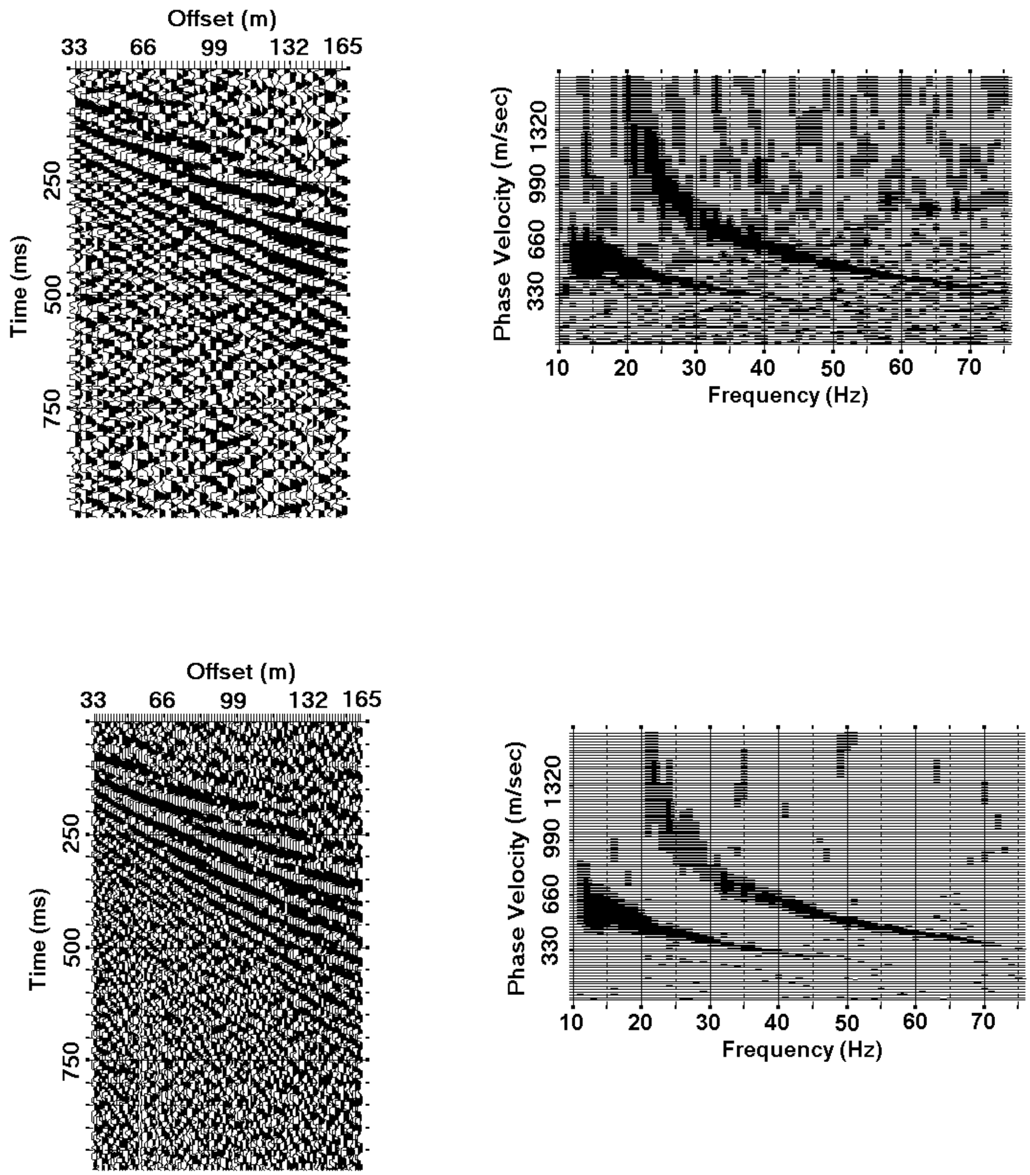
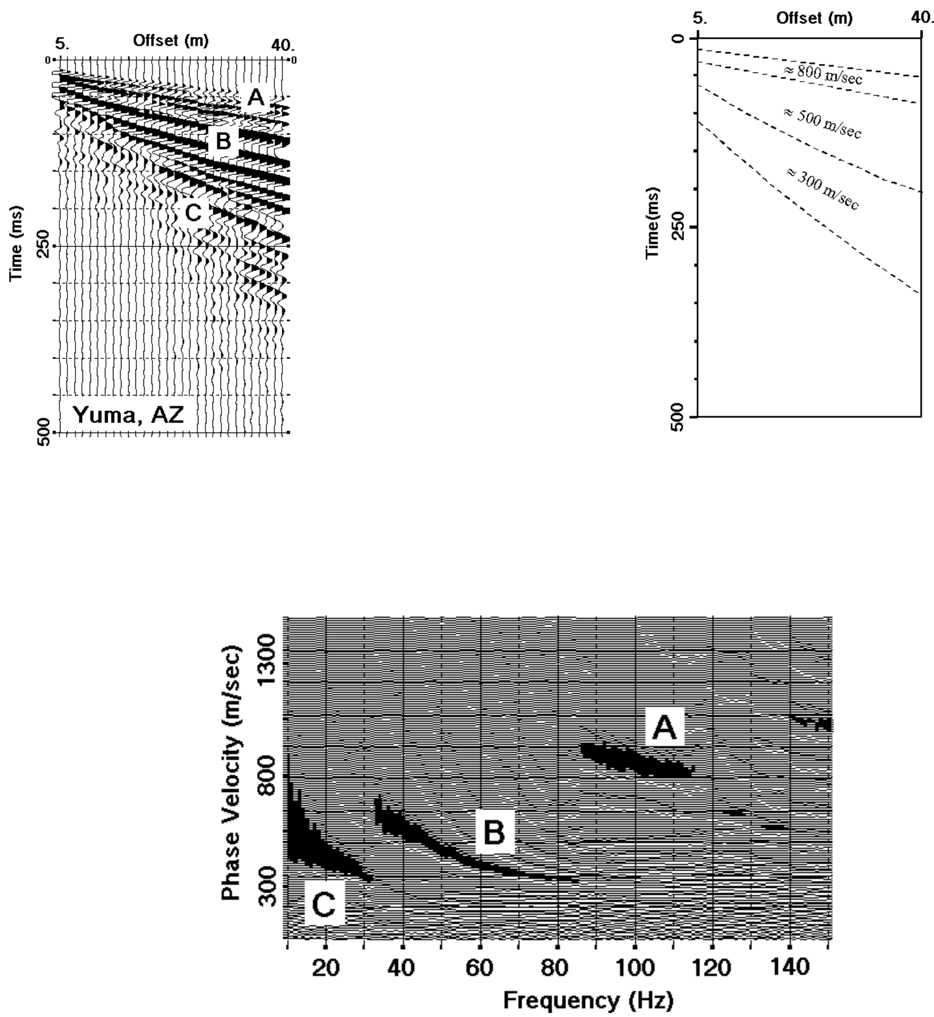

Offset (m)
33 66 99 132 165
Time (ms)
250 500 750
Phase Velocity (m/sec)
330 660 990 1320
Frequency (Hz)
10 20 30 40 50 60 70
Offset (m)
33 66 99 132 165
Time (ms)
250 500 750
Phase Velocity (m/sec)
330 660 990 1320
Frequency (Hz)
10 20 30 40 50 60 70

Figure 4.



5.
Offset (m)
40.
A
B
C
Time (ms)
250
500
Yuma, AZ
5.
Offset (m)
40.
0
250
500
Time(ms)
≈ 800 m/sec
≈ 500 m/sec
≈ 300 m/sec
Phase Velocity (m/sec)
1300
800
300
A
B
C
20
40
60
80
100
120
140
Frequency (Hz)

Figure 5.

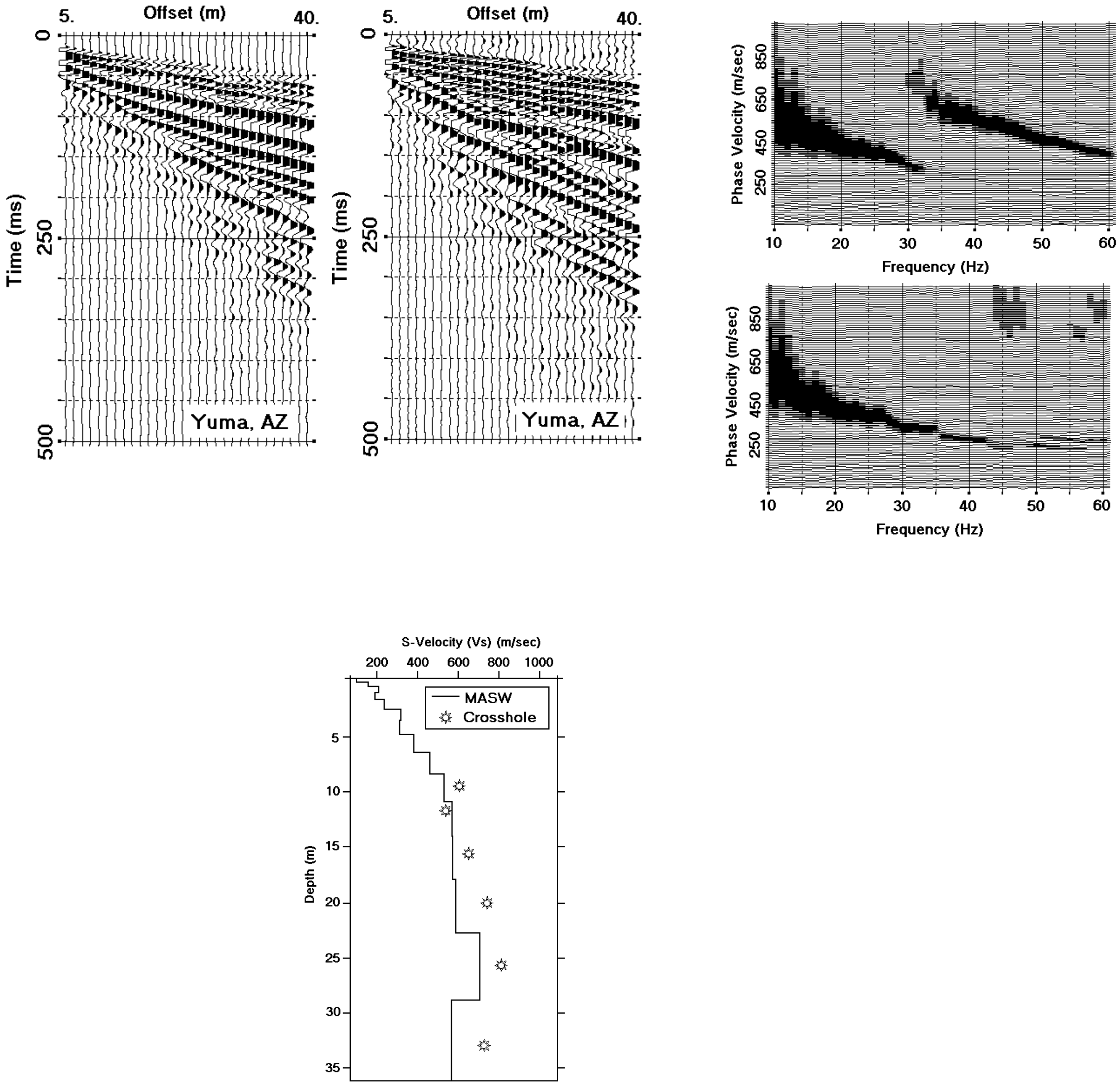

Offset (m)
5.
40.
Time (ms)
0
250
500
Yuma, AZ
Offset (m)
5.
40.
Time (ms)
0
250
500
Yuma, AZ
Phase Velocity (m/sec)
250
450
650
850
Frequency (Hz)
10
20
30
40
50
60
Phase Velocity (m/sec)
250
450
650
850
Frequency (Hz)
10
20
30
40
50
60
S-Velocity (Vs) (m/sec)
200
400
600
800
1000
Depth (m)
5
10
15
20
25
30
35
MASW
Crosshole

Figure 6.

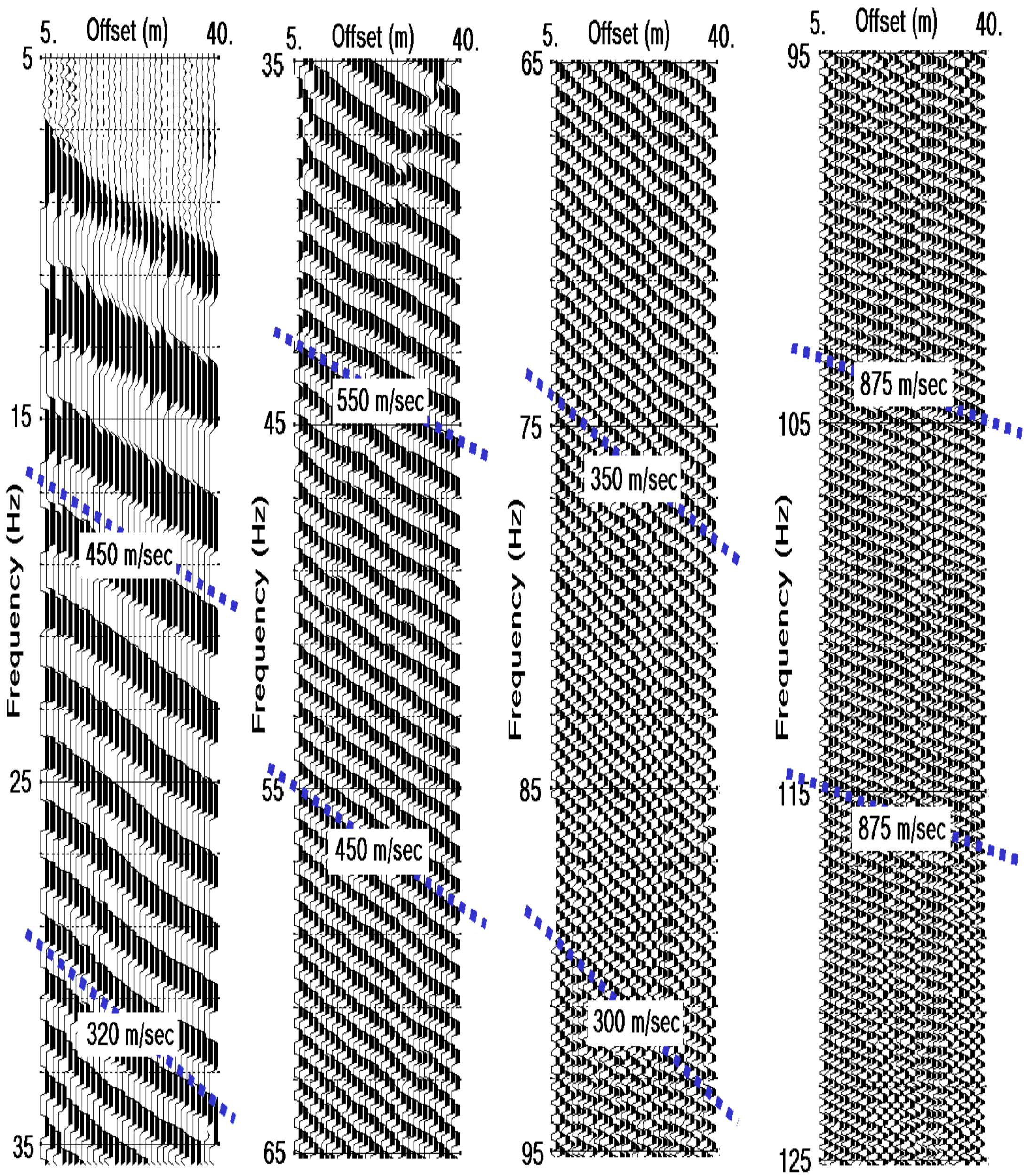
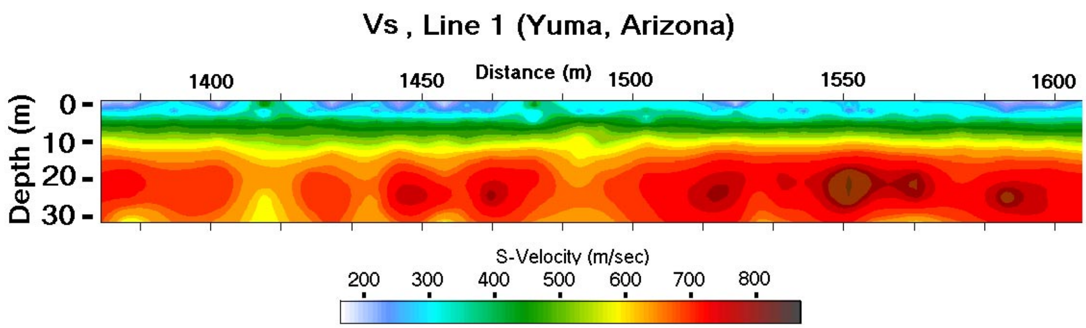
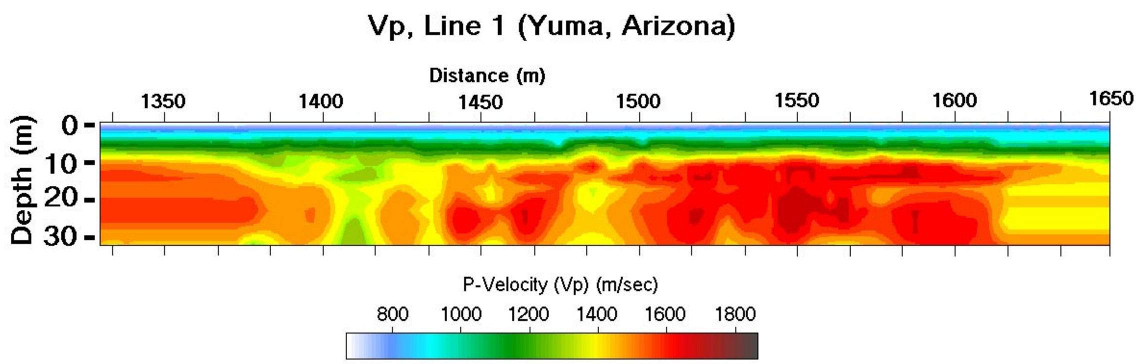

5. Offset (m) 40.
Frequency (Hz)
5
15
25
35
450 m/sec
320 m/sec
35
45
55
65
550 m/sec
450 m/sec
65
75
85
95
350 m/sec
300 m/sec
95
105
115
125
875 m/sec
875 m/sec

Figure 7.


Vs , Line 1 (Yuma, Arizona)
Distance (m)
1400
1450
1500
1550
1600
Depth (m)
0
10
20
30
S-Velocity (m/sec)
200
300
400
500
600
700
800


Vp, Line 1 (Yuma, Arizona)
Distance (m)
1350
1400
1450
1500
1550
1600
1650
Depth (m)
0
10
20
30
P-Velocity (Vp) (m/sec)
800
1000
1200
1400
1600
1800