DETECTION OF HIGHER MODE SURFACE WAVES OVER UNCONSOLIDATED SEDIMENTS BY THE *MSAW* METHOD

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SUMMARY

In engineering application of surface waves it is critically important to accurately extract the fundamental mode dispersion curve. Among several factors that may adversely affect the extraction is the existence of higher modes with significant amount of energy. A calculated phase velocity can be an average of the fundamental and the higher-modes phase velocities or it can be the phase velocity of a specific higher mode, depending upon the specific method used for the application, unless the higher modes are properly handled during the data acquisition and processing steps. Therefore, it will have a practical value to observe the higher mode generation through field experiments and examine for any parameter that can be controlled during data acquisition.

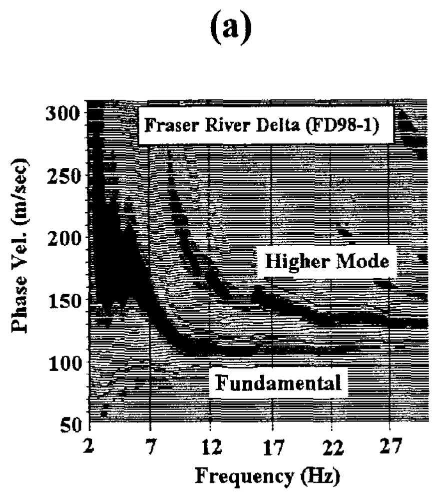
A higher mode (the first overtone) of high frequency (5–30 Hz) surface waves was observed by using the multi-channel analysis of surface waves (MASW) method at three boreholes located in unconsolidated sediments in the Fraser River Delta, near Vancouver, British Columbia. Each site has a unique near-surface shear (S)-wave velocity (*Vs*) structure as verified from downhole *Vs* measurements. The relative dominance of higher mode energy is examined in association with source distance as well as *Vs* structure. Our examination indicates that energy of higher modes tends to become more significant as the source distance becomes greater. It also reveals that the dominance may be related to a *Vs* structure: a greater dominance as *Vs* changes little with depth, or *Vs* has an overall low value, or a combination. The dependency on the source distance is observed to be stronger than that on the *Vs* structure. Attempts are made to explain the dependency by referring to one or a combination of three factors: attenuation, the near-field effects, and the intrinsic nature of surface waves. Inclusion of higher mode during a surface wave measurement for near-surface (<30 m) application can be either an advantage or a disadvantage, depending on the specific type of application and the method used during the data acquisition and processing steps. It is, therefore, important to recognize through field observations those conditions both favorable and unfavorable to the generation of higher modes of high-frequency surface waves.

INTRODUCTION

In most engineering application of surface waves the observation of higher mode dispersion curves has at least two practical values. First, it can enhance the accuracy of the dispersion curve analysis by providing a reference from which the credibility of the fundamental mode dispersion curve can be evaluated. The dispersion curve analysis that lacks examination of the higher mode inclusion can lead to a higher mode dispersion curve being mistaken as the fundamental mode (Figure 1) or credibility of the analysis speculative. Second, it can also enhance the accuracy of the dispersion curve inversion by providing more meaningful data points if the inversion scheme can account for the multimodal phase velocities.

In practice the multimodal analysis can be carried out only through the multichannel recording approach in which phase velocities of different modes are measured from different linear coherency. However, a successful separation of multimodal dispersion curves depends upon several factors: total number of channels used for recording, length of receiver spread, layer parameters, and the method of phase velocity calculation. In general, the existence of strong higher modes degrades the accuracy of the fundamental mode dispersion curve regardless of the specific method used for the phase velocity calculation. If the fundamental mode is the only critical information needed for the application, it is important to suppress the higher mode energy during data acquisition. On the other hand, if the application requires multimodal information, then the situation becomes opposite. It is therefore important to search for any parameters that can be controlled in the field so that we can either suppress or enhance the higher mode energy as much as needed by our application.

On this paper we examine the role of the source distance in the higher mode generation through several field observations. To ensure the generality of the examination we select three sites where near-surface (< 30 m) shear (S)-wave velocity (*Vs*) structures are significantly different from each other. This also enables the examination of *Vs* structure in association with its role in the higher mode generation. At each site three 30-channel records obtained with the same receiver spread length but different source distance are examined. Multimodal dispersion curves are constructed through the technique routinely used in the multichannel analysis of surface waves (MASW) method (Park et al., 1998a; 1999; Miller et al., 1999a; 1999b; Xia et al., 1999a; 1999b).



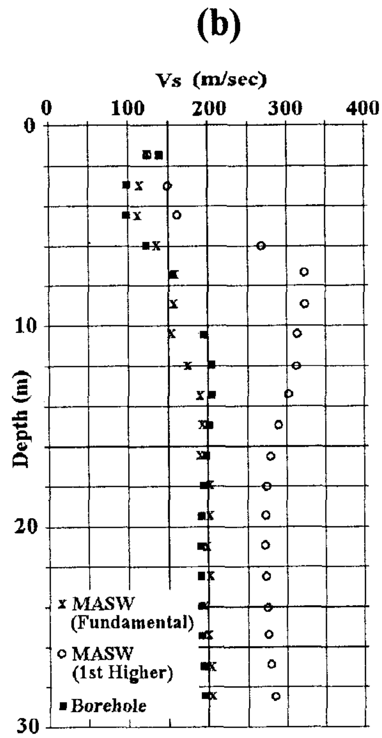


Figure 1. (a) Multimodal dispersion curve analysis by the MASW method. (b) Vs profiles obtained from the inversion of the fundamental mode and the higher mode (assuming as the fundamental mode). Borehole Vs profile is also shown.

HIGHER MODES IN ENGINEERING APPLICATIONS

Higher modes of surface waves can be viewed in theory as harmonic solutions to elastic wave equations (Haskell, 1953). Generation of higher modes can be predicted to a certain extent by referring to theory on global surface wave phenomena (Tokimatsu et al., 1992). In civil engineering application of high-frequency surface waves (SASW), the higher mode generation has been associated with presence of a velocity reversal (a lower *Vs* layer between higher *Vs* layers) (Stokoe et al., 1994). However, the high-frequency surface wave applications deal with near-surface materials that have elastic properties significantly different from those dealt in global applications. For example, *Vs* may change by an order of magnitude within only several meters of the uppermost depth range that usually accompanies a severe lateral *Vs* variation. Therefore, actual higher mode phenomena in the high-frequency case may be different from those observed in the global case. Some properties of high-frequency surface waves have been associated with source distance and near-surface *Vs* structure (Park et al., 1999; Stokoe et al., 1994; Tokimatsu et al., 1992).

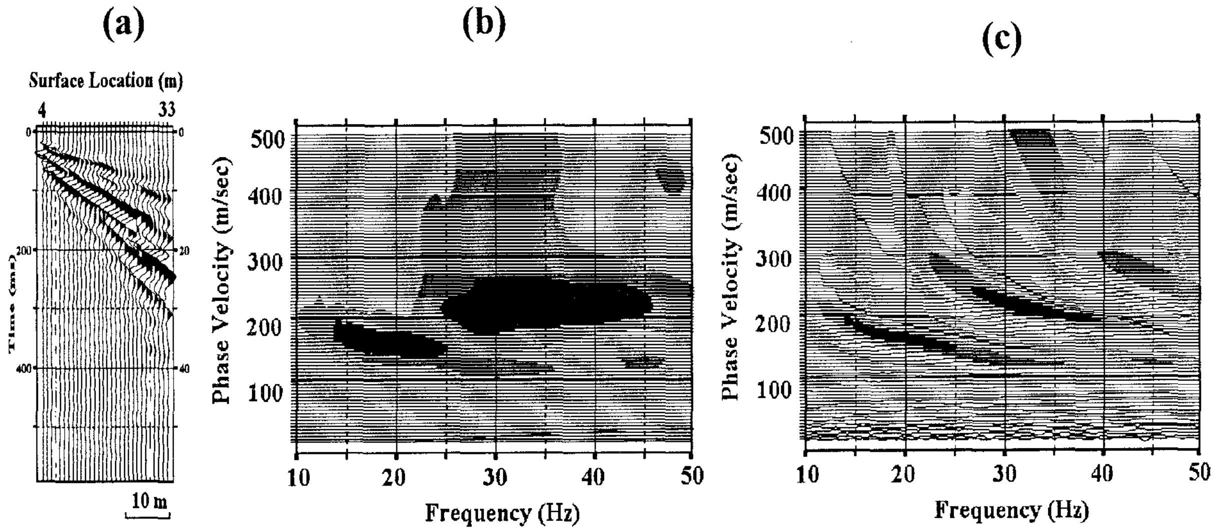


Figure 2. (a) A 30-channel shot record collected at a Geometrics test site, San Jose, California. A 20-lb hammer and 4.5-Hz geophone were used as source and receivers, respectively. (b) Result of multimodal dispersion curve analysis from the conventional method ($\tau - p$ transformation) (McMechan and Yedlin, 1981). (c) Same type of result from the new transformation method by Park et al. (1998b).

In engineering application of surface waves the higher modes have usually been ignored during the analysis. Two reasons seem to be responsible for this. First, it has been speculated that the higher modes usually take negligible energy and need not be accounted for. Second, it has not been effective to detect the higher modes with only conventional data acquisition and processing methods available. It seems that the first reason cannot be justified as Tokimatsu et al. (1992) verified through theoretical analysis that the higher modes can indeed take significant amount of energy comparable to that of the fundamental mode under some typical near-surface settings.

Furthermore, based upon observations with extensive field data, we found that the higher modes are very often generated with significant amount of energy. The second reason seems to originate from the acquisition and processing methods of surface waves conventionally used. The most-commonly-used acquisition method has been employing only two receivers (Stokoe et al., 1994). With only a pair of traces available the multimodal analysis can only be speculative whatever data analysis methods are used. Some investigators (e.g., Gabriel et al., 1987) took the multichannel recording approach only with conventional data processing techniques employed. The conventional processing techniques of slant-stacking (McMechan and Yedlin, 1981) and the *f-k* method (Gabriel et al., 1987) require an extraordinary number of traces (e.g., several hundred traces) that cover a wide lateral distance (e.g., several hundred meters). In the high-frequency application of surface waves, however, the surface distance to be covered by a single survey is often limited to a few to several tens of meters due to a severe lateral variation of near-surface materials, inhibiting the use of conventional techniques.

HIGHER MODE DETECTION BY THE MASW METHOD

For a reliable observation of the higher modes, the multi-channel recording is essential (Park et al., 1999; Tokimatsu et al., 1992). The multimodal phase velocities are detected and calculated from the different linear coherency on a multichannel record. A research project has been undertaken recently at the Kansas Geological Survey (KGS) to use surface waves as an another seismic tool to investigate near-surface (<30 m) targets. This method employs the multi-channel recording and processing techniques (Sheriff and Geldart, 1982) that have both similarities and dissimilarities to those used in a conventional reflection survey. This multi-channel analysis of surface waves (MASW) (Park et al., 1999) fully exploits the advantages of multi-channel recording and processing techniques, whose effectiveness have been proven during last several decades. MASW deals with a depth range of engineering interest (e.g., <30 m) and a frequency range (e.g., 5–100 Hz) much higher than that normally dealt in global seismology. Because velocity and attenuation properties of surface waves are most sensitive to shear (S)-wave velocity (*Vs*), the applications of MASW include *Vs* profiling (Park et al., 1999; Xia et al., 1999a) and near-surface anomaly detection (Miller et al., 1999a; 1999b; Park et al., 1998a).

Recent development of a new data-processing technique by Park et al. (1998b) allows direct construction of a high-resolution image of multimodal dispersion curves from a multichannel record of only a small number of traces (e.g., 30 traces) that cover only a narrow lateral distance (e.g., 30 m) (Figure 2). In addition to this imaging technique, the swept-frequency decomposition method (Park et al., 1999) provides another tool to detect the frequency range in which the higher modes take significant amount of energy through the coherency examination (Figure 3). Figure 3 illustrates one of the major advantages of the MASW method that allows the characterization of the full wavefields phenomenon in association with the origin.

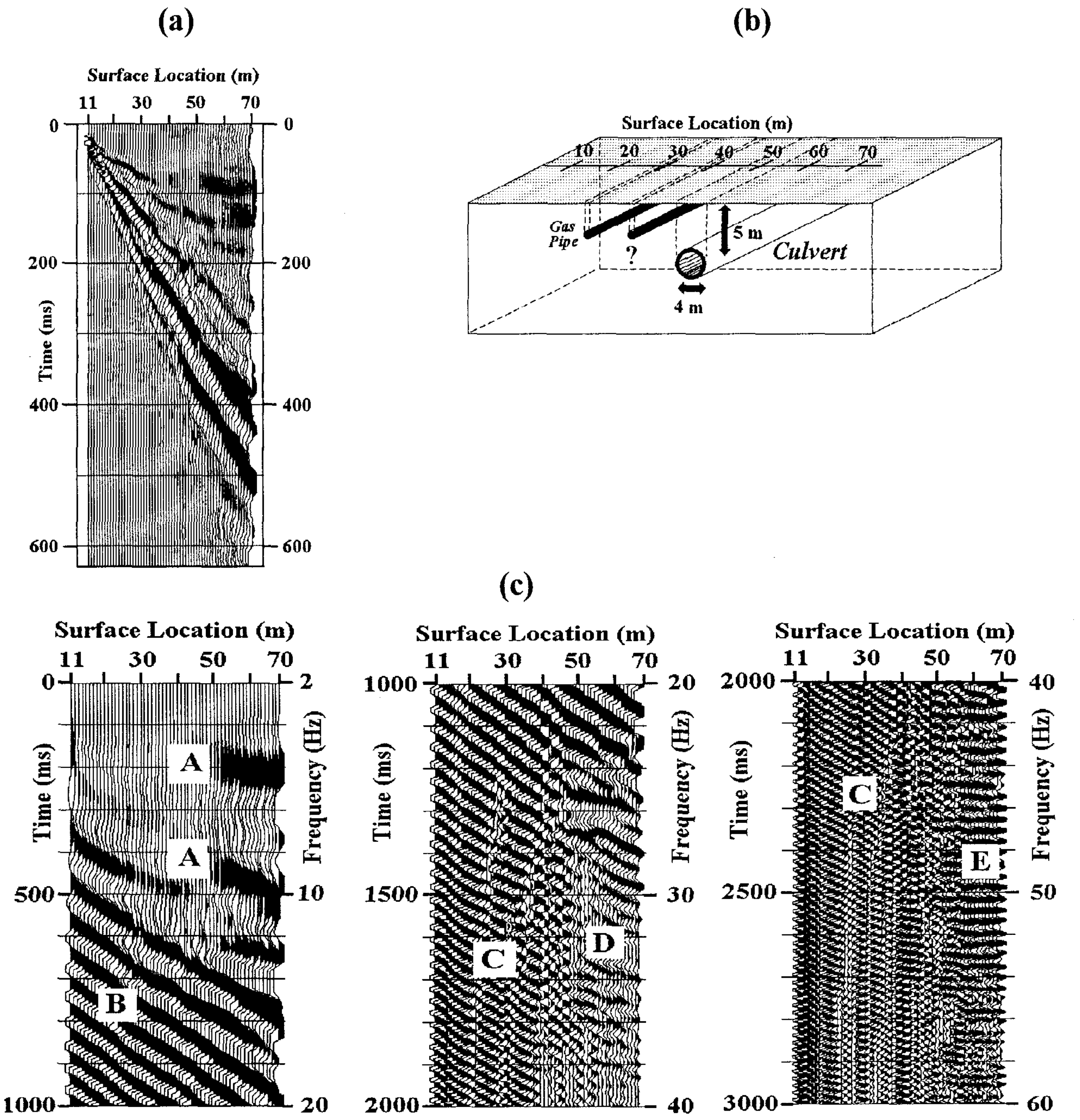


Figure 3. (a) A 60-channel shot record obtained by using 20-lb hammer and 4.5-Hz geophone at a Geometrics test site, San Jose, California. Result of the mutimodal dispersion curve analysis applied to a 30-channel record obtained at front end of the survey line is shown in Figure 2c. (b) A schematic of the site where a gas pipe and a culvert were the two main buried objects. Another gas pipe possibly exists nearby the known pipe. (c) The swept-frequency decomposition of (a). Decomposed record is displayed here into three segments. Frequency of the decomposed wavefields is indicated on the right-hand side of each panel. Marked features are: **A**-low frequency noise from a nèarby construction site, **B**-the fundamental mode, **C**-breaks in the linear coherency indicating inclusion of the higher mode with significant energy, **D**-attenuation by the culvert, and **E**-body wave (refraction) domination.

FIELD DATA FROM FRASER RIVER DELTA, VANCOUVER, CANADA

Multi-channel data used for this study were acquired at three borehole sites of unconsolidated sediments in the Fraser River Delta, near Vancouver, British Columbia (Hunter et al., 1998). Figures 4a, 5a, and 6a show *Vs* profiles at each site obtained from a downhole S-wave survey. The downhole *Vs* profile at FD98-1 (Figure 4a) was available only after the analysis result of *Vs* profile by MASW was obtained (Xia et al., 1999b). The results in Figure 4a illustrate the credibility of MASW in *Vs* profiling. Each site has a distinctive characteristic in the pattern of *Vs* change with depth: little change with overall low velocity (FD98-1), rapid change (FD92-3), and intermediate change with significant velocity reversals (FD92-4).

At each site, three records were chosen for the dispersion curve analysis that were obtained by using three different source-to-nearest receiver offsets (x_1's) (2.4 m, 8.5 m, and 17.1 m). Although each record contained 60 traces, only the first 30 traces (the nearer-offset traces) were analyzed because a preliminary examination of the swept-frequency records revealed a severe degradation of signal-to-noise ratio (S/N) by body waves at further-offset traces.

Image of the dispersion curves was constructed by using the method of Park et al. (1998b). Darkness of a dispersion curve is proportional to the dominance of energy. Range of analyzed frequency was originally from 5 Hz to 100 Hz. All the displayed images, however, have focused on the range of 5–30 Hz because no features worthy of note were observed outside this range. At least one higher mode (the first overtone) is observed in most dispersion curves.

DISCUSSIONS

One of the most prominent features is the dependency of the higher mode energy on the source distance (x_1); the higher mode energy increases as x_1 increases. This dependency may be explained by one or a combination of the followings:

1. It is generally known that attenuation of surface waves is most sensitive to S-wave dissipation factor (Q_β^{-1}) (Mitchell, 1975) and Q_β^{-1} usually decreases with depth at shallow (<1 km) depths (Mokhtar et al., 1988). The penetration depth of surface waves is proportional to wavelength (λ). Because higher-mode surface waves penetrate deeper than the fundamental mode due to the higher velocity, the higher modes may experience less attenuation due to the smaller overall Q_β^{-1}. This indicates the higher modes may prevail the fundamental mode after both types of modes have traveled a certain distance although the fundamental mode energy may be appreciably greater at places near source.

2. Horizontally propagating surface waves are generated only after they have traveled a certain distance (x_{nf}) from the source (the near-field effects) (Stokoe et al., 1994). x_{nf} is proportional to λ; $x_{nf} = \xi\lambda$ with ξ a proportionality constant. An empirically determined value of 0.5 is usually used for ξ in the spectral analysis of surface waves (SASW) (Stokoe et al., 1994), but several different investigators reported different values (Gucunski and Woods, 1991). The values were determined from the measurements of fundamental mode only. Park et al. (1999) reported values smaller than 0.3 from actual observation of the near-field effects of

fundamental mode on multi-channel records. According to the dispersion curve characteristics shown in Figures 4–6, the value of ξ may be smaller than 0.1 for the fundamental mode and about 0.5 for the higher mode if the observed characteristics are to be attributed solely to the near-field effects.

3. Using theoretical formulation, Tokimatsu et al. (1992) showed that the phase velocity of different modes of surface waves can depend on the distance between source and receiver as well as layer parameters. The dependency they showed is related to neither attenuation nor the near-field effects. This dependency of phase velocity strongly suggests the possibility of similar dependency for the higher mode energy. This indicates that the observed dependency may represent (at least in part) an inherent property of surface waves that can be explained from a theoretical analysis of surface wave generation.

It seems that the higher mode energy changes also with *Vs* structure. The strongest higher mode energy at FD98-1 indicates that near-surface materials of little *Vs* change with depth (or a low *Vs*, or both) are apt to produce more energy for higher modes. The higher mode generation in association with presence of velocity reversal is not obvious in this study as indicated by the higher mode energy at FD92-4 (Figure 6) being not significantly different from that at the other two sites.

Strong higher mode energy (especially that at FD98-1) may cause erroneous results for the calculation of fundamental mode dispersion curve if its presence is not identified and properly accounted for during the analysis.

CONCLUSIONS

Relative dominance of higher mode energy of the high-frequency surface waves is observed to intensify as the source distance becomes greater and also as *Vs* changes little with depth (or has a low overall value, or both). The dependency on the first factor seems to be more significant than that on the second. This dependency can be related to one or combination of the attenuation, the near-field effects, and the intrinsic phenomena of surface waves.

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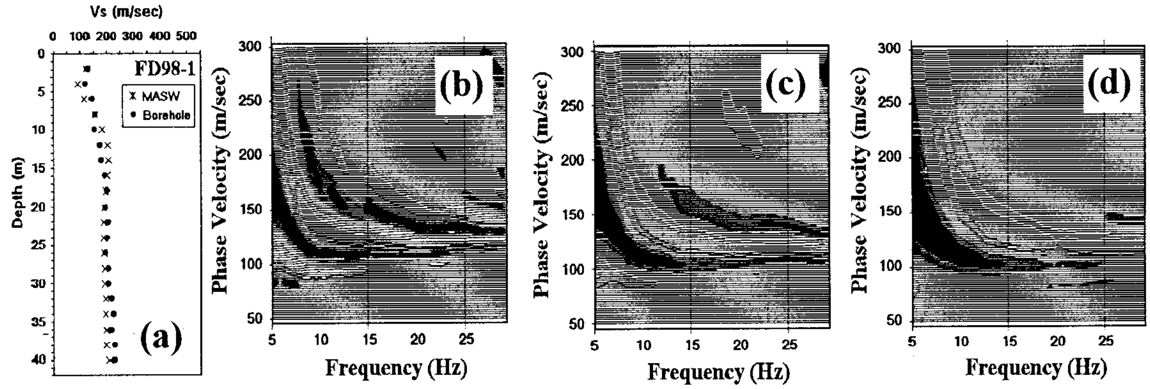

Figure 4. (a) Down-hole *Vs* profile for FD98-1 well and multimodal dispersion curve analysis for three shot records obtained with source-to-nearest receiver distance of (b) 17.1m, (c) 8.5 m, and (c) 2.4 m.

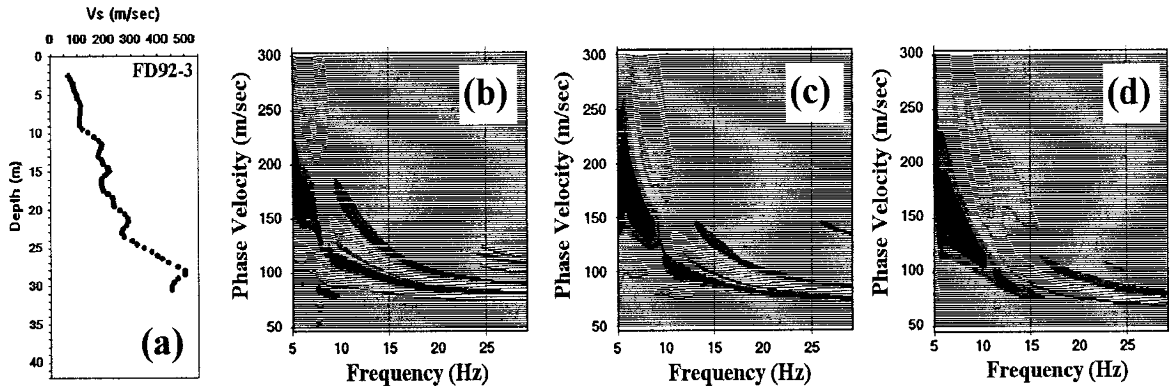

Figure 5. (a) Down-hole *Vs* profile for FD92-3 well and multimodal dispersion curve analysis for three shot records obtained with source-to-nearest receiver distance of (b) 17.1m, (c) 8.5 m, and (c) 2.4 m.

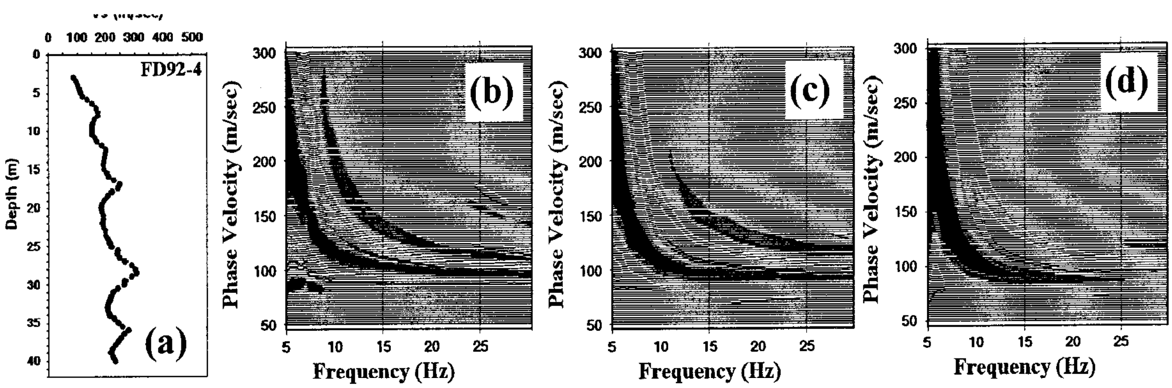

Figure 6. (a) Down-hole *Vs* profile for FD92-4 well and multimodal dispersion curve analysis for three shot records obtained with source-to-nearest receiver distance of (b) 17.1m, (c) 8.5 m, and (c) 2.4 m.