Multi-channel analysis of surface waves using Vibroseis (MASWV)

Choon Byong Park, Richard D. Miller, and Jianghai Xia, Kansas Geological Survey*

Summary

On uncorrelated Vibroseis shot gathers, each frequency component of ground roll is represented with a unique slope as a function of arrival time and sweep function with excellent isolation from other components. The calculation of phase velocity becomes a simple matter of measuring the slope of each different frequency using an appropriate coherency measure. Possible contamination by coherent noise can readily be determined for each frequency by visual inspection. Any change in field configuration or extra efforts during data processing steps can be immediately designated. The multi-channel measurement method allows averaging and therefore effective reduction in any random noise introduced during recording. Therefore, the dispersion curve is constructed in a fast, accurate, and fully automated manner. Qualitative information about near-surface conditions can also be inferred from visual inspection, making it possible to detect near-surface anomalies.

Multi-channel analysis of surface waves using Vibroseis (MASWV) has advantages over the Spectral Analysis of Surface Waves (SASW) method which employs only two receivers with an impact source. First of all, because of the high spectral integrity of acquired data, a high degree of accuracy can be placed on the results of the method. Furthermore, the method is much faster and less labor-intensive than SASW since only a single or a few recorded shot gathers are usually necessary to produce a well behaved dispersion curve.

Introduction

Different wavelengths of surface waves have different penetration depths and therefore propagate with different phase velocities (Bath, 1973). This dispersion property can be utilized in various ways. The shear (S)-wave velocity *(Vs)* profile obtained by analyzing dispersion properties provides key parameters in the evaluation of near-surface stiffness critical to many important tasks in geotechnical engineering. Detection of certain near-surface anomalies which body-wave methods such as high-resolution reflection profiling fail to be effective are possible with surface-wave methods.

In the early 1980's, a surface-wave method, called Spectral Analysis of Surface Waves (SASW), that makes use of the spectral analysis of ground roll generated from impact sources like hammers to produce the near-surface *Vs* profile was introduced (Nazarian and Stokoe, 1983). The method has been widely and effectively used in many geotechnical engineering projects.

Multi-channel analysis of surface waves using Vibroseis (MASWV) is completely different method of acquiring and processing seismic data for acquiring near-surface *Vs* information. It requires a swept source and multiple receiver locations tuned for the generation and recording of ground roll. MASWV has advantages over the SASW method because of unique acquisition and processing techniques.

The main purpose of this paper is to introduce a unique surface-wave method and to show the effectiveness of the method through field test results. More involved discussion on the acquisition and processing techniques will be possible in future publications.

SASW vs. MASWV

The SASW method uses an impact source like a sledge hammer and usually only two receivers (geophones). It is therefore usually necessary to repeat the test with many different field setups to insure the coverage of the desired depth range (Figure la). The repeated field tests are also necessary to reduce random disturbances introduced during the measurements. Because of the necessity to repeat testing, it usually takes several hours to complete the whole procedure for a single location. Furthermore, the inclusion of noise wavefields such as body waves (Sanchez-Salinero et al., 1987), reflected ground roll (Sheu et al., 1988), and higher-modes of ground roll (Gucunski and Woods, 1991) cannot be identified and handled effectively. Because of these complications the accuracy of the results may be significantly reduced.

MASWV method employs multiple (usually twelve or more) receivers with an equivalent channel seismograph and a swept source (Figure lb). Receivers are planted with equal spacing. Because the basic field configuration is very similar to that for body-wave surveying with only slightly different criterion for selecting the optimum field configuration and aequisitionparameters, in many cases the surface-wave survey can be performed as a by-product or coincident with body-wave surveying, making a large percentage of recorded seismic energy useful. Examples of the demonstrated effectiveness and dramatic enhancement of interpretation of seismic reflection data will be part of future publications.

Because on uncorrelated records the dispersion characteristics of ground roll for different frequencies can be separated, the quality control during acquisition and processing can be highly efficient with a simple algorithm used to construct the dispersion curve in an accurate, fast, and fully automated manner. Various types of multi-channel data processing techniques may be used for the construction of dispersion curves (Herrmann, 1973; McMechan and Yedlin, 198 1; Mari, 1984). Cross-correlation of stacked amplitude with sweep (CCSAS) method (Park et al., 1996) has proven to be extremely accurate with excellent computational speed. CCSAS method employs a coherency measure that makes use of cross-correlation of stacked ground roll data with the appropriate portion of sweep. The method has an excellent capacity to average out random disturbances and also discriminate surface wavefields from other noise wavefields. When this method is employed in MASWV, the entire procedure including inversion step usually takes less than fifteen minutes on a 80486 class PC.

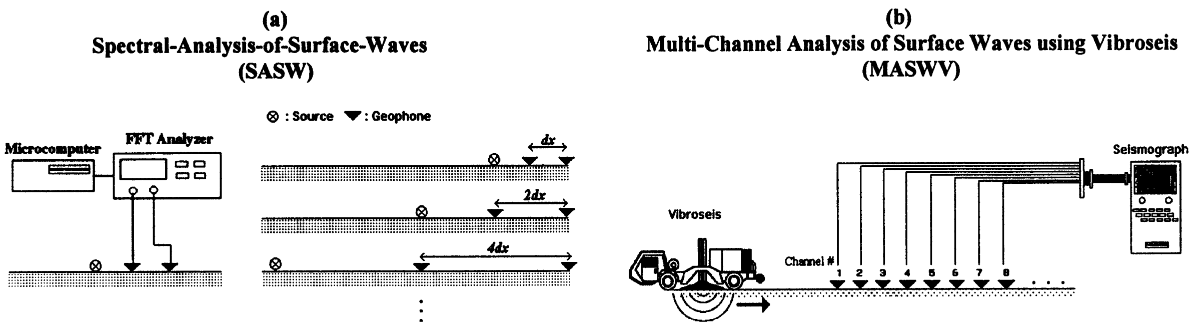

Figure 1. Basic configurations of (a) Spectral Analysis of Surface Waves (SASW) and (b) Multi-channel analysis of surface waves using Vibroseis (MASWV) methods.

Field test of MASWV

Surface-wave (ground roll) data were collected at the Kansas Geological Survey test site using an IVI Mini Vib. The site consists of a thin (< 8 m) accumulation of unconsolidated materials overlying a sequence of unsaturated, consolidated sedimentary rocks. The main purpose of the test was to examine the effectiveness of MASWV method in obtaining ***Vs*** profile for the near surface. A 48-channel Geometrics StrataView seismograph was used with only 41 10-Hz geophones. The first seismograph channel was dedicated to recording the sweep. The receiver spacing was 1 m. The 10-s linear upsweep was designed to produce a 10 Hz to 50 Hz spectra with 0.25-s tapers.

Two different source offsets (1.8 m and 27 m) were selected after consideration of the optimum field configuration. Figure 2 shows uncorrelated raw field records obtained with the two different source offsets. The shot gather (Figure 2a) recorded with the smaller source offset (1.8 m) shows a break in coherency in the arrival time of ground roll for the frequencies lower than about 20 Hz. This indicates these frequencies of ground roll behave differently than higher-frequency components. According to Stokoe et al. (1994), this is believed to be a result of failure to record plane-wave ground roll due to the source offset being small. They refer to this phenomenon as the near-field effect. Comparison of this record with the record with the larger source offset (27 m) (Figure 2b) reveals the near-field effect is greatly reduced with the increased source offset.

Once the frequency becomes high enough and the near-field effects are not apparent, ground roll with good coherency can be identified on both records with the change in the phase velocity obvious as evidenced by the changes in the slope with time. This frequency range is then followed by a higher-frequency range in which attenuation of ground roll is so severe that body-wavefields (refractions) start to dominate the record (e.g., at times later than 9 s in Figure 2a and 7 s in Figure 2b). Although it is generally true that ground roll is much more energetic than body waves, the high-frequency (short wavelength) components of ground roll lose their energy quite rapidly because they normally propagate through the shallowest veneer of the surface where attenuation is most significant (Bullen, 1963). The adverse effects caused by the inclusion of strong body waves is called far-field effect in this paper.

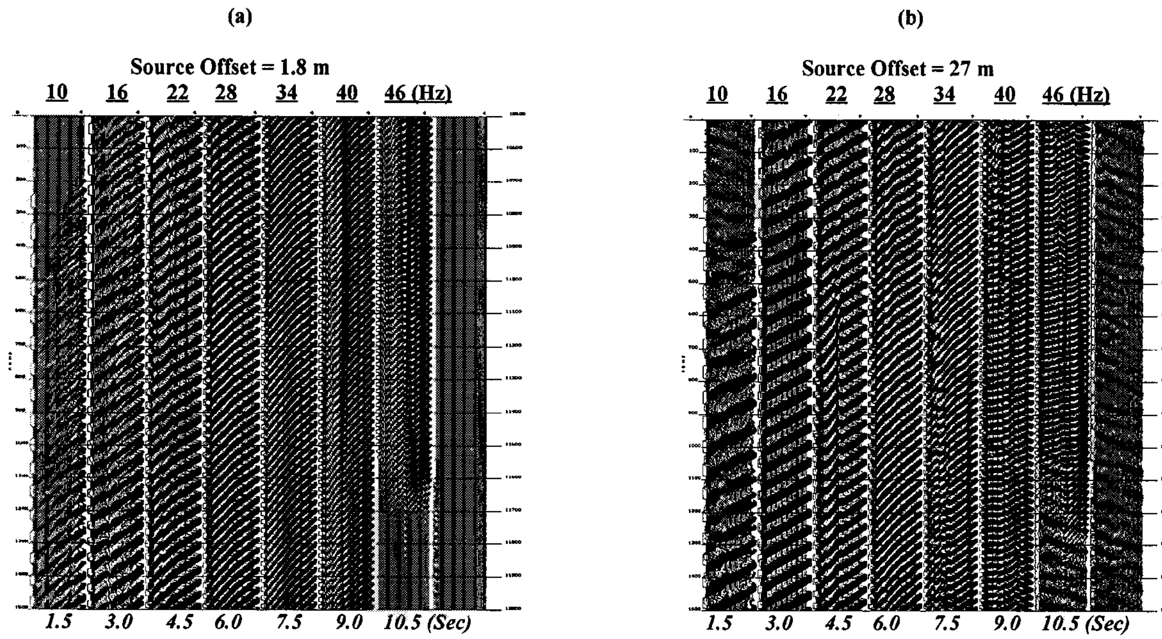

Figure 2. Uncorrelated field records obtained by using two different source offsets of (a) 1.8 m and (b) 27 m, respectively. The record is displayed in 1 S-s segments by using a significant gain function. On top of each record is shown the sweep frequency that begins each segment, whereas at bottom the recording time at the end of each segment is displayed.

Dispersion curve and inversion by forward modeling

Phase velocities are calculated from the two records shown in Figure 2 by using Cross-Correlation of Stacked Amplitudes with Sweep (CCSAS) method. The two dispersion curves calculated from the two records match well for the middle frequency range (20 Hz - 40 Hz). The dispersion curve from the record with the smaller source offset, however, shows unrealistic fluctuations for the low frequency range (12 Hz - 20 Hz) due to what we have identified as the near-field effect. On the opposite end, the record with the larger source offset produced a dispersion curve that showed an unrealistic trend for the high frequency range (40 Hz - 50 Hz) due to what we are calling the far-field effect. The empirical dispersion curve displayed in Figure 3a was constructed by combining the portions from the two curves that are relatively unaffected by either of these two effects.

Forward modeling (Stokoe et al., 1994) was used to calculate the *Vs* profile from the empirical dispersion curve shown in Figure 3a. An algorithm by Schwab and Knopoff (1972) was used to calculate phase velocity of fundamental mode Rayleigh waves. Figure 3a shows the dispersion curve which matches the empirical curve fairly well. The velocity and density models used for the forward modeling are also shown in Figures 3b and 3c, respectively. Considering that the medium consists of weathered consolidated materials, a moderately high value of 0.4 was assumed for Poisson's ratio (σ) to model P-wave velocity (Burger, 1992). Moderately low values were also assumed for the density model with a minor changing trend with depth.

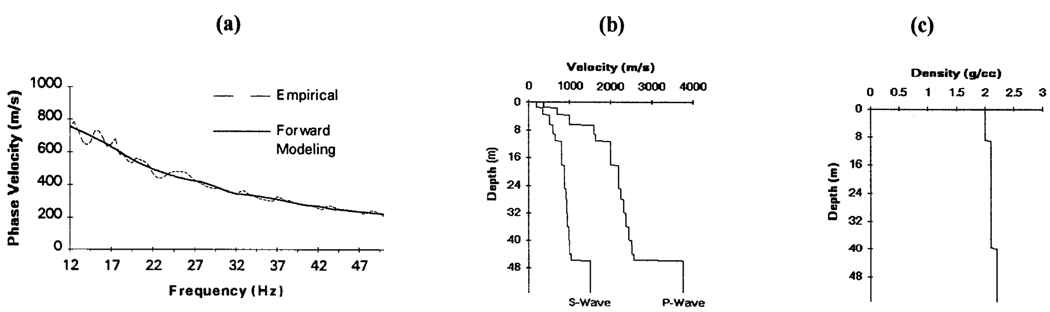

Figure 3. (a) Dispersion curves from acquired data (empirical) and forward modeling, (b) velocity, and (c) density models used for the forward modeling.

Discussions

We could not evaluate with confidence the final shear-wave velocity profile because of the unavailability of shear-wave velocity information from up-hole survey at this time. However, upon comparing the dispersion curve from CCSAS method with the dispersion curve constructed by manually picking the slopes of linear arrivals on the uncorrelated records for many different frequencies, we believe the empirical dispersion curve is accurate enough to justify the validity of the results from inversion.

Conclusions

On uncorrelated swept multi-channel records, different frequency components of ground roll appear isolated from each other. Therefore, phase velocities for different frequencies can be calculated accurately, fast, and in a fully automated manner using the appropriate algorithm. Possible contamination of acquired data by noise wavefields can be readily determined through visual inspection of records allowing changes in field configuration or extra efforts during processing period to be immediately identified. MASWV method used here provides a highly accurate and fast way of generating S-wave velocity profile for the upper-most part of the earth.

Because dispersion characteristics are represented for each individual frequency, qualitative judgment on the near-surface condition and, therefore, detection of certain kinds of near-surface anomalies are possible from visual inspection of uncorrelated swept field records.

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