Higher mode observation by the MASW method

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Summary

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 (V_S) structure as verified from downhole V_S measurements. The relative dominance of higher mode energy is examined in association with source distance as well as V_S 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 V_S structure: a greater dominance as V_S changes little with depth, or V_S has an overall low value, or a combination. The dependency on the source distance is observed to be stronger than that on the V_S 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.

Multi-channel Analysis of Surface Waves (MASW)

Surface waves usually comprise more than two-thirds of the total seismic energy generated and have been treated as the most troublesome source-generated noise in the history of exploration seismology. 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 that are difficult to image by the conventional reflection method. 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. Called MASW (multi-channel analysis of surface waves) (Park et al., 1999; Xia et al., in press), this method 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 with in global seismology. Because velocity and attenuation properties of surface waves are most sensitive to shear (S)-wave velocity (V_S), the applications of MASW include V_S profiling (Park et al., 1999; Xia et al., in press) and near-surface anomaly detection (Park et al., 1998b; Miller and Xia, 1999).

Higher Modes of High-Frequency Surface Waves

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). For example, in the civil engineering application of high-frequency surface waves (SASW), the higher mode generation has been associated with presence of a velocity reversal (a lower V_S layer between higher V_S 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 with in global applications. For example, V_S may change by an order of magnitude within only several meters of the uppermost depth range that usually accompanies a severe lateral V_S 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 V_S structure (Park et al., 1999; Stokoe et al., 1994; Tokimatsu et al., 1992).

For a reliable observation of the higher modes, the multi-channel recording is essential (Park et al., 1999; Tokimatsu et al., 1992). The actual number of traces necessary for the successful observation depends upon the subsequent data-processing technique used. Conventional techniques of slant-stacking (McMechan and Yedlin, 1981) and the *f-k* method (Gabriels 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. Recent development of a new technique by Park et al. (1998a) allows direct construction of a high-resolution image of multimodal dispersion curves from a multi-channel record of only a small number of traces (e.g., 30 traces) that cover only a narrow lateral distance (e.g., 20 m).

Objectives of this paper are:
1. to actually observe higher modes of the high-frequency surface waves by following field and data-processing

procedure normally taken in the MASW method,
2. to analyze dominance of higher mode energy in relation to source distance and *Vs* structure, and
3. to make an attempt to explain the observed relationship.

Data

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). Figure 1 shows *Vs* profiles at each site obtained from a downhole S-wave survey. The downhole *Vs* profile at FD98-1 (Figure 1a) was available only after the analysis result of *Vs* profile by MASW was obtained (Xia et al., 1998). Figure 2 shows the image of the corresponding dispersion curves used to produce the MASW *Vs* profile, whose theoretical dispersion curves are overlaid on the image. The results in Figure 1a and

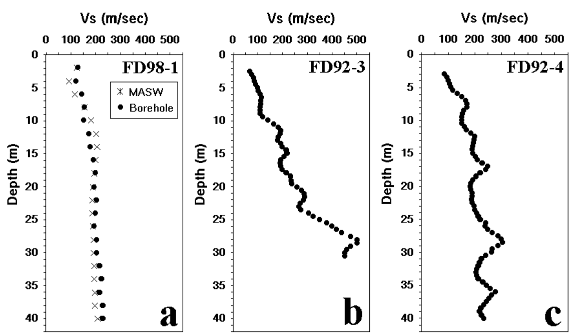

Figure 1. Shear (S)-wave velocity profiles obtained at three borehole sites of unconsolidated sediments in Fraser River Delta, near Vancouver, Canada. Well numbers are (a) FD98-1, (b) FD92-3, and (c) FD92-4. Vs profile obtained from the MASW method is overlaid in (a).

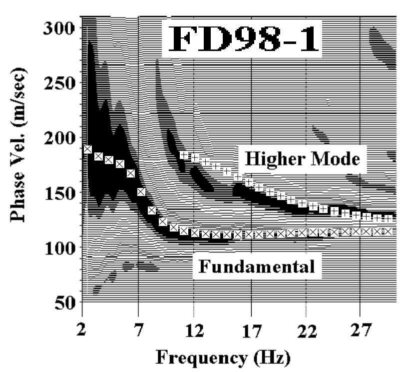

Figure 2. Image of dispersion curves (fundamental and first overtone) analyzed from a 30-trace record collected at FD98-1 using source-to-nearest-receiver offset of 17.1 m. The theoretical dispersion curves corresponding to the MASW profile in Figure 1a are marked on the image.

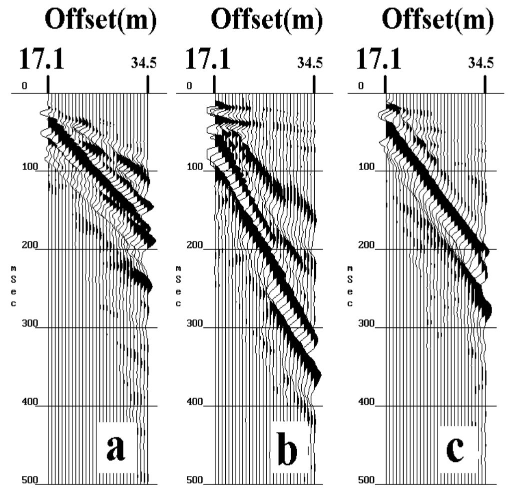

Figure 3. Multi-channel (30-channel) records obtained with source-to-nearest-receiver offset of 17.1 m at (a) FD98-1, (b) FD92-3, and (c) FD92-4.

Figure 2 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).

Dispersion Curves

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 (Park et al., 1999) revealed a severe degradation of signal-to-noise ratio (S/N) by body waves at further-offset traces. The 30-trace records obtained at each site using the longest x_1 (17.1 m) are displayed in Figure 3. Apparent velocities of surface waves on each record approximately conform to S-wave velocities at shallower (<10 m) depths.

The image of dispersion curves was constructed using the method by Park et al. (1998a). 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 location (x_1); the higher mode energy increases as x_1 increases. This dependency may be explained by one or a combination of the following:

1. It is generally known that attenuation of surface waves is most sensitive to the 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) (Stokoe et al., 1994). 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 mode energy may dominate that of the fundamental mode after both 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 only generated 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 SASW, but several different investigators reported different values (Stokoe et al., 1994; 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 V_S structure. The strongest higher mode energy at FD98-1 indicates that near-surface materials of little V_S change with depth (or a low V_S, 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) 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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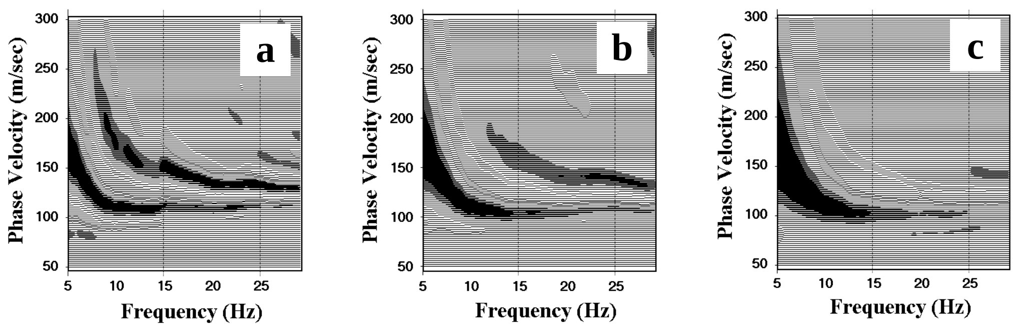

Figure 4. Dispersion curve images of multi-channel records obtained at FD98-1 by using the source-to-nearest-receiver offset of (a) 17.1 m, (b) 8.5 m, and (c) 2.4 m.

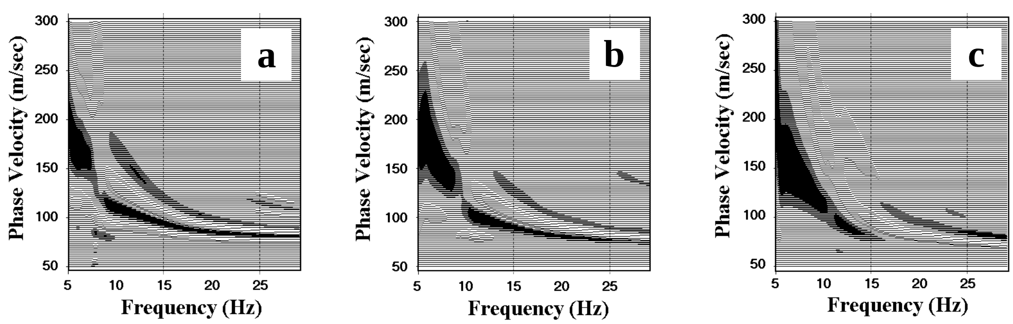

Figure 5. Dispersion curve images of multi-channel records obtained at FD92-3 by using the source-to-nearest-receiver offset of (a) 17.1 m, (b) 8.5 m, and (c) 2.4 m.

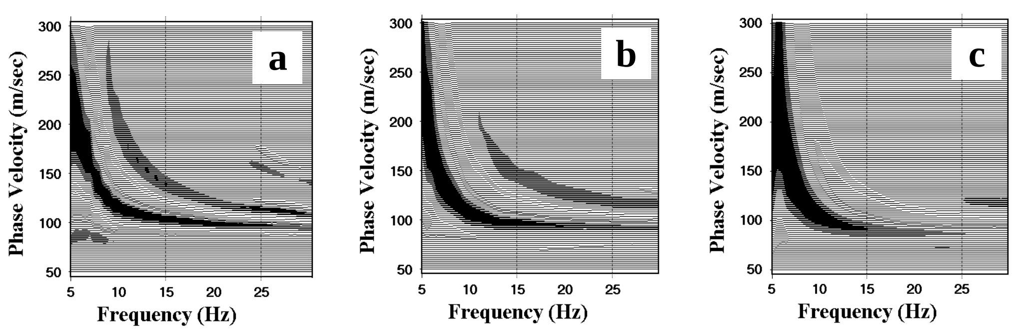

Figure 6. Dispersion curve images of multi-channel records obtained at FD92-4 by using the source-to-nearest-receiver offset of (a) 17.1 m, (b) 8.5 m, and (c) 2.4 m.