Multichannel analysis of underwater surface waves near Vancouver, B.C., Canada

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Summary

Surface (Scholte) waves acquired during underwater seismic surveys with hydrophone arrays are analyzed using the multichannel analysis of surface waves (MASW) method to construct shear-wave velocity (*Vs*) profiles for the upper 40-m of water-bottom sediments in the Fraser River delta area, near Vancouver, British Columbia, Canada. Shear wave profiles are obtained using the Rayleigh-wave inversion method (based on the multimodal dispersion curves) since theory suggests the difference in phase velocities between the two types of surface waves (i.e., the Scholte *vs*. the Rayleigh waves) is minor and usually falls below the uncertainty of the measurement. *Vs* profiles calculated from dispersion analysis are compared with measured *Vs* profiles available from nearby land boreholes (within a few hundred meters of the underwater sites). The comparison shows MASW values are in good agreement with the overall trend of borehole values, but lower in general by about ten percent. This shift seems to be attributable to the water-bottom sediments being softer and their density being greater (at depths < 5 m) than sediments on land. Simple multichannel processing (surgical mute) seems critical to suppress the influence of the strong broad-band channel waves trapped in the water layer before extracting the dispersion curve.

Introduction

Depth-varying stiffness measurements are often necessary for geotechnical site characterization of a site. Seismically, these measurements can be made through the dispersion analysis of the Rayleigh type surface waves. Successful terrestrial application of this method has been reported by many investigators in Spectral Analysis of Surface Waves (SASW) (Stokoe et al., 1994) and more recently Multichannel Analysis of Surface Waves (MASW) (Park et al., 1999b; Xia et al., 1999). Underwater application of this method, however, introduces somewhat unique difficulties associated with data acquisition and processing. Special receivers (e.g., gimballed receivers) have to be used or traditional vertical geophones need to be placed at water bottom by divers. Special inexpensive, environmentally friendly underwater sources have been developed (Good et al., 1999). Strong broad-band channel waves trapped in the water layer can alter the phase relationship of surface waves unless they are properly identified in time(t)-distance(x) domain and removed through a preliminary processing.

Because of the strong-vibratory nature of surface waves, conventional hydrophones laid down at the water bottom may be able to detect the motion of surface waves. Multichannel recording makes it possible to observe the time(t)-distance(x) relationship between surface-wave events and all other noise events and, therefore, allows optimal adjustment during both acquisition and processing parameters. The goal of this paper is to demonstrate feasibility of hydrophone arrays to accurately record underwater surface waves and analyze the acquired multichannel data to develop a shear-wave velocity (*Vs*) profile of the water-bottom sediments using the MASW method (Park et al., 1999b; Xia et al., 1999) originally developed for terrestrial near-surface investigation.

Multichannel Analysis of Surface Waves (MASW)

The MASW method was developed for the investigation of near-surface elastic parameters such as the shear-wave velocity (*Vs*) by recording and analyzing Rayleigh-type surface waves using a vertical (impulsive) seismic source and receivers. It is unique from other surface wave methods in data acquisition, processing and applications. For example, through multichannel recording and simple field processing, it is easy to detect any adverse effect (such as interference from strong body-wave and higher modes events, severe lateral inhomogenities of the area being surveyed, etc.) from a examination of coherency in phase velocity and attenuation properties of wavefields in time(t)-distance(x) domain (Park et al., 1999b). Key acquisition parameters can, therefore, be efficiently and effectively optimized from one site to another. Acquired data are first analyzed for dispersion characteristics (Park et al., 1998a and 1999a) and, second, the shear-wave velocity is estimated using inversion (Xia et al., 1999). Various types of conventional multichannel processing techniques (e.g., 2-D coherency evaluation, filtering, mute, etc.) can be applied whenever appropriate to further enhance the signal-to-noise ratio (S/N) or as an aid in interpretation of results. The MASW method has been successfully applied to map 2-D bedrock surface (Miller et al., 1999a), weak spots (Miller et al., 1999b), Poisson's ratio (Ivanov et al., 2000), voids (Park et al., 1998b), as well as to generate *Vs* profiles (Xia et al., 2000).

Scholte Wave

In theory, surface waves may exist whenever there is a surface that separate media with different elastic properties (Sheriff and Geldart, 1982). In terrestrial applications, measurements are made at the boundary (the "free" surface) separating air and solid earth. *Surface waves* is commonly used as a synonym for the Rayleigh-type surface waves in recent applications. However, when measurements are made along the boundary where a body of water overlies solid materials, the behavior of surface waves changes slightly due to the interaction with the water (Stokoe et al., 1994). For the water over solid earth case, they are called either Scholte waves or generalized Rayleigh waves, depending on whether the Rayleigh-wave velocity (V_R) of the substrate layer (water bottom layer) being smaller (soft substrate) or greater (hard substrate), respectively, than the P-wave velocity (V_w) of water (Luke and Stokoe, 1998).

Analytical results indicate that the Scholte-wave velocity (V_{sch}) and the generalized Rayleigh-wave velocity (V_{GR}) are slightly different from the Rayleigh-wave velocity (V_R) at the free surface and change with the surface wave wavelength (λ) to water depth (h) ratio (Figure 1). In the soft-substrate case, the influence of the water layer becomes more significant for wavelengths shorter than several times the water depth ("deep water" condition). As the wavelength becomes longer than the water depth, the influence is no longer significant ("shallow water" condition). Inversion of the Scholte-wave dispersion curve to a Vs profile requires a proper modeling scheme that accounts for the existence of the water layer above the measurement surface. However, considering that the maximum deviation of V_{sch} from V_R is usually less than 5 percent, that correction usually falls below the uncertainty level of the measurement. Treating the Scholte waves as identical to the Rayleigh waves during the inversion analysis does not appear to significantly degrade the confidence level of the calculated Vs profile for the soft-substrate case.

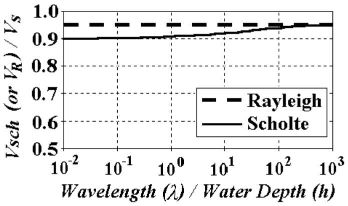


Figure 1. Approximate relationship between the Scholte-wave velocity (V_{sch}) and the Rayleigh-wave velocity (V_R) in comparison to the S-wave velocity (Vs) (From Stokoe et al., 1994).

Analysis of Water-Bottom Hydrophone Data

The Geological Survey of Canada (GSC), during tests to evaluate the operations of a sea-bottom gun (Good et al., 1999), collected multichannel water-bottom data at three sites (Site16, Site4Feb, and Site25) (Figure 2) in the Fraser River, near Vancouver, B.C., Canada. The source fired a 500-grain 8-gauge blank shot-gun shell into the sea floor to generate energy for each shot gather. A 36-hydrophone array with 5 m spacings was used to record the seismic waves. The hydrophones were 8-Hz Mark Products P44A at 70 percent damping. From more than 30 land boreholes available in the area, one was selected near each water site (FD95-2 and FD97-2 near Site16 and Site4Feb, and FD95-S1 near Site25) (Figure 2) for which Vs measurements were made during the downhole surveys. A thorough study of seismic velocities in this area has been previously done by Hunter et al. (1998). Depth to the bottom of the water layer changes from one site to another: 6 m at Site16, 3 m at Site4Feb, and 1.2 m at Site25. These depths correspond approximately to the depth below the top of the boreholes.

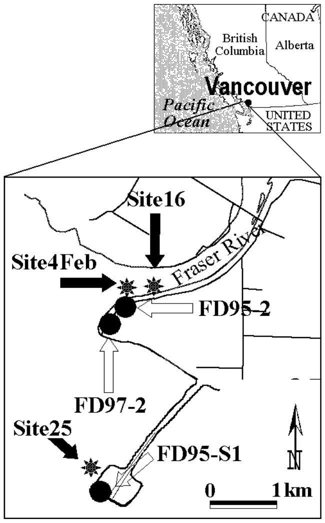
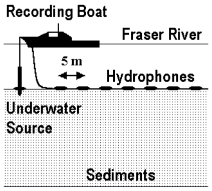


Figure 2. Site map showing locations of the underwater sites and nearby land boreholes in the Fraser River Delta area, near Vancouver, B.C., Canada. A schematic of the field setup is shown below.



One selected shot gather from each underwater site was used for Scholte wave analysis. Several major seismic events identified during the early portion of the seismogram are guided waves trapped in the water layer (Figure 3). These events have a broad bandwidth with dominant frequency near 100 Hz and reveal a dispersive character (Figure 4a). Range of the apparent Scholte velocity at Site16 has a velocity range of 80-160 m/sec based on analysis of the fan-shaped energy packet (Figure 3a).

When the raw data were analyzed without any preliminary processing, the strong broad-band guided waves interfered with the weaker Scholte waves. This problem was observed in spite of the dominant frequencies being significantly different. The obtained image of the dispersion curves suffered from a narrow useable bandwidth (Figure 4b). Removal of all body-wave events through a simple 2-D surgical mute enhanced quality of the image significantly (Figure 5a).

Shot gathers (Figure 3) were analyzed for the Scholte-wave dispersion curves after the aforementioned surgical mute was applied. The dispersion curves obtained (Figure 5) were then inverted to obtain the preliminary Vs profiles using a Rayleigh-wave inversion method by Xia et al. (1999) which seeks the solution through the comparison of theoretical and experimental phase velocities of only the fundamental mode. The preliminary profiles were then modified through a forward-modeling method until a best-match was obtained between the multimodal dispersion curves of both theoretical and experimental cases (Figure 5). A P-wave velocity (Vp) of 1500 m/sec and density of 2 gm/cc were used during the entire inversion process. The final Vs profiles obtained this way are compared along with profiles from nearby boreholes (Figure 6). Depth here represents the depth from the water bottom for MASW profiles, and depth from the top of the well for the borehole profiles.

Discussions

Spectral characteristics of Scholte waves observed in all three shot gathers appear narrow-band and low-frequency. There are two likely reasons for this: First, the source-to-receiver offset for most receivers might be large enough that high-frequency components of Scholte waves have been attenuated below the energy level. This is commonly observed body wave during the land execution of MASW (Park et al., 1999b). A second reason for this character is the use of hydrophones (pressure sensitive) as receivers. Surface-wave motion consists of the macroscopic (retrograde elliptical) motion of bulk mass. The effectiveness of transforming surface-wave motion into pressure is not clear. It is possible that the measured surface wave energy degrades as the amplitude of the motion becomes smaller at higher frequencies.

Comparison of surface-calculated *Vs* profiles with borehole-measured *Vs* profiles suggests that underwater sediments have lower velocities (by about 10 percent on the average) than nearby land sediments. In theory, shear-wave velocity (*Vs*) is determined by shear modulus (μ) (resistance to tangential stress) and bulk density (ρ): $Vs = \sqrt{\mu/\rho}$. The land sediments have gone through cultivation for more than a hundred years, whereas the underwater sediments are "fresh." This indicates that the underwater sites may have experienced a lesser degree of compaction and, therefore, have lower μ, resulting in lower *Vs*. The most significant lowness in *Vs* at shallow depths (< 5 m) can be explained by referring to the role of bulk density (ρ) that can change appreciably, depending upon the type of saturating fluid. It has been said that *Vs* is not sensitive to fluid presence. This statement, however, normally applies to the (deep) consolidated rocks in which the shear modulus (μ) has already been established before the fluid took the interstitial spaces (that usually comprise only a small fraction of the matrix volume), so both the shear modulus and the bulk density are not significantly changed. The situation may be different in the case of near-surface unconsolidated sediments. First of all, these near-surface sediments usually have a large percentage of empty (inter-particle) spaces changing the bulk density significantly based on the type of fluid (air or water). Therefore, with the same fraction of empty spaces being assumed for all the shallow (< 5 m) sediments in the surveyed area, *Vs* for the underwater sediments (completely filled with water) would be lower than *Vs* for the land sediments (some shallow parts filled with air) as a result of the larger bulk density. This is a reasonable explanation for comparatively lower *Vs*'s at underwater sites at shallow (< 5m) depths.

It is possible that the lower *Vs* at the underwater sites might be related to the treating the Scholte wave as Rayleigh wave and ignoring the influence of the overlying water layer. However, the maximum lowness predicted by theory at shallow (< 5 m) depths is less than five percent. This is also confirmed through an actual comparison made in Figure 6c.

Conclusions

Underwater surface waves detected using a hydrophone array can be analyzed to produce *Vs* profiles of water-bottom sediments by the multichannel analysis of surface waves (MASW) method. As long as P-wave velocity of the sediments does not exceed the velocity of the water layer (soft substrate), Scholte waves can be treated as being identical to the Rayleigh waves during the inversion process.

Acknowledgments

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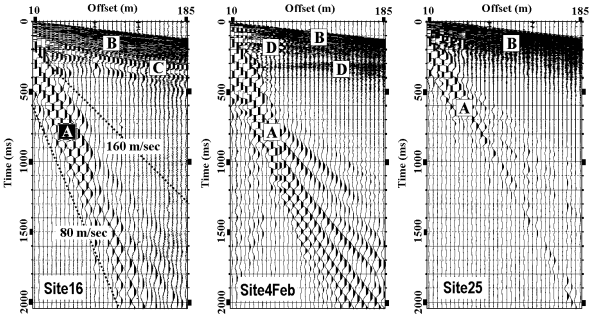

Figure 3. Shot gathers from each underwater site. Marked events are the Scholte (A), guided (B), refraction (C), and reflection (or scattered) (D) waves. Range of apparent velocities for the Scholte waves is marked on the shot gather from Site16.

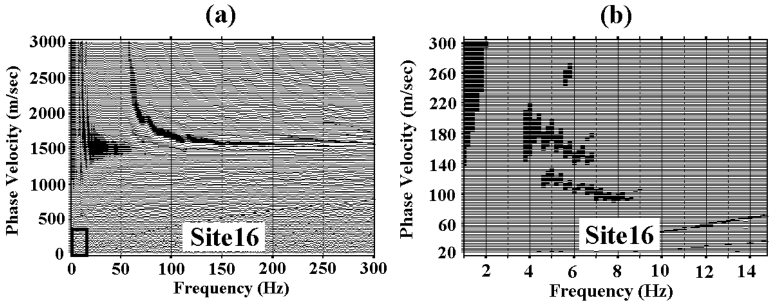

Figure 4. (a) Phase velocity analysis of the shot gather in Figure3a that basically shows the dispersive nature of the strong broad-band guided waves. (b) Enlarged analysis of the rectangular part in the lower-left corner of the image in (a) that shows the dispersion curves of the Scholte waves. Only a narrow band-width is observed due to the adverse effects from the guided waves.

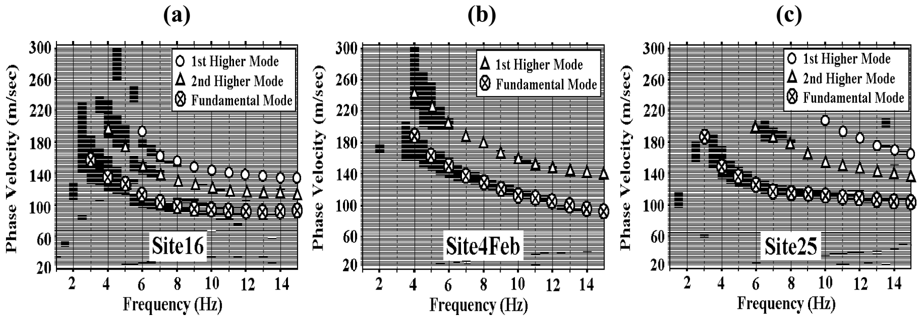

Figure 5. Images of dispersion curves analyzed from the Scholte waves of each shot gather after the surgical mute has been applied to remove all body-wave events. Theoretical dispersion curves for the inverted Vs profiles are marked up to second (or third) higher modes.

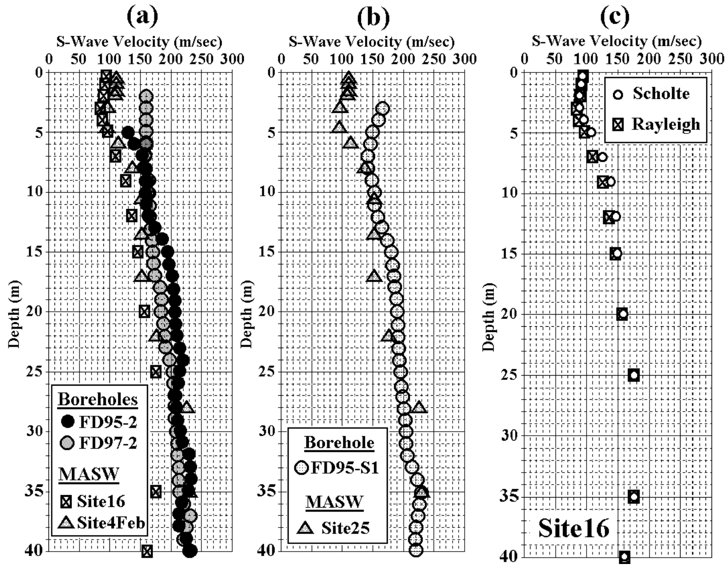

Figure 6. Vs profiles inverted from the multimodal dispersion curves for Site16 and Site4Feb (a), and for Site25 (b) displayed along with the Vs profiles from the nearby land boreholes. (c) Comparison of the two types of the inversion method using the dispersion curve for the Site16: the Scholte- and Rayleigh-wave inversion.