Joint analysis of surface-wave and refraction events from river-bottom sediments

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Summary

An underwater seismic survey was performed in the Fraser River Delta area near Vancouver, B.C., Canada, using hydrophones. Data were analyzed using multichannel analysis of surface waves (MASW), and refraction tomography inversion provided an accurate P-wave velocity (*Vp*) profile for river-bottom sediments in the upper 30 m. To optimize the compressional wave velocity function in the 30 to 70 m depth interval, *Vp* information from a nearby well was used as a priori information.

Using shear wave velocity profiles from surface-wave inversion as a priori information allows a fast and reliable inversion of the first arrival events interpreted on an underwater shot gather. The inverted *Vp* profile, strongly suggesting the presence of gas within water-bottom sediments, corroborates a nearby land well. This example demonstrates the usefulness of joint inversion and its potential for detecting near-surface anomalies.

Introduction

The refraction method is incapable of detecting "hidden layers" (Burger, 1992) such as a high velocity thin layer or a low velocity layer "sandwiched" between two high velocity layers. Such "hidden layers" cause erroneous data interpretation. An improved way to interpret first arrival data is through use of refraction tomography. An initial model with close to the true *Vp* distribution, as well as smoothing constraints (Stork and Clayton, 1991), are necessary to achieve reliable results from inversion.

A technique for joint analysis of surface wave and P-wave refraction events designed to provide a 2-D Poisson's ratio (σ) map of the near-surface materials has the potential to overcome this initial model and smoothing constraints problem (Ivanov et al., 2000). This technique uses *Vs* information from the inversion of surface waves as a priori information to help resolve the indeterminacy of the refraction inversion.

Joint analysis of surface wave and refraction events significantly reduces the inherent risk with any inversion with the non-uniqueness of the solution.

The approach is very straightforward and requires only a minimal number of processing steps. The MASW surface wave inversion method was used to obtain a *Vs* profile. This *Vs* profile is used to create an initial 2-D *Vp* model using the functional relationship for σ that provides a close match between measured and calculated first arrivals. The match is improved by iteratively changing the *Vp* model until a satisfactory solution has been reached.

As described previously, through joint analysis of this shallow marine data set a reliable *Vp* solution will be obtained for the shallow sediments independent of the measurements made in the nearby control well.

River-Bottom Multichannel Data

Multichannel water-bottom data were collected by the Geological Survey of Canada (GSC) in Fraser River, near Vancouver, B.C., Canada, while testing the operation of a sea-bottom gun (Good et al., 1999). A 500-grain 8-gauge blank shot-gun shell and a set of 36-hydrophones spaced at 5 m intervals were used to record each shot. The hydrophones were 8 Hz Mark Products P44A damped at 70 percent. Both *Vs* and *Vp* profiles were acquired in boreholes near the site. The site had been previously studied by Hunter et al. (1998).

Data were collected at three underwater sites (Site16, Site4Feb, and Site25) in the Fraser River. At only one site (Site16) was a "strange event" observed that has been interpreted as a refraction from the water-bottom sediments. Apparent velocities of refractions (first arrivals) from middle and far offsets possess phase velocities very close to interval velocities measured below 30 m in a nearby land well. Close-offset apparent velocities suggest velocity values lower than predicted based on the borehole data for shallow, near water-bottom sediments. The values were significantly smaller than expected (1500 m/s, close to the water velocity or higher) or velocities measured at shallow depths in the land well data. At this site (Site16), depth to the bottom of the water layer was about 5 m. The nearest well (FD95-2) was about 600 m away.

Several major seismic events are evident on shot gathers (Figure 1). First arrivals from sound traveling through the water layer, guided waves trapped in the water layer, a "strange event" (refraction) immediately below the guided waves and the surface (Scholte) wave.

***Vs* from the Surface-Wave Inversion**

The multichannel analysis of surface waves (MASW) method (Park et al., 1999; Xia et al., 1999) provided a *Vs* profile. This information was used to generate an initial *Vp* profile for refraction inversion.

The water-bottom surface (Scholte) waves were processed through the Rayleigh-wave inversion method (based on the multimodal dispersion curves) (Park et al., 2000). Raw shot gathers were analyzed for the Scholte-wave dispersion curves after all body-wave events were removed through a simple 2-D surgical mute, significantly enhancing the quality of the surface wave analysis (Park et al., 1999).

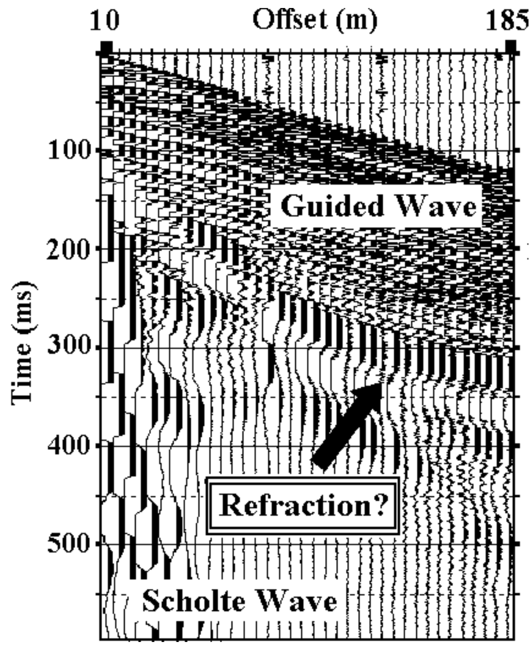

Figure 1. Water-bottom raw shot data.

Multimodal dispersion curves were inverted for the *Vs* profiles using a Rayleigh-wave inversion method (Xia et al., 1999). Treating Scholte waves as Rayleigh waves is acceptable because theory indicates differences 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 level of the measurement (Park et al., 2000).

Vp from Refraction Inversion Assisted by *Vs*

Once *Vs* was calculated using MASW, the data underwent preliminary processing designed to enhance the interpretability of the refraction event. The direct wave was muted out and the guided wave was filtered out. This 30 Hz high-cut filter did not harm the refracted arrivals because their dominant frequency is only about 14 Hz (Figure 1).

Refraction inversion was performed in two steps. First, the 1-D *Vs* inversion result were extrapolated to generate a 2-D *Vs* model. This model was then used to generate an initial 2-D *Vp* model assuming a constant (Vp/Vs=3, σ =0.438) rate between *Vp* and *Vs*. This assumption provides a close match between the observed and the calculated first arrivals. Then the match was improved by iteratively changing the *Vp* model. After sufficient iterations a good match was obtained between the observed and the calculated arrivals for the first 80 m of offset (Figure 2). This was consistent with the general rule that the maximum depth of investigation is about one-fourth of the maximum shot offset (Zhu et al., 1992). Since the maximum depth of our preliminary model was about 22 m it was predictable that this model would have effect on the first 80 m offset.

To match the arrivals at further offsets (from 80 m to 180 m) the depth of our model was increased and additional information was included about the velocity distribution at these greater depths. *Vp* information from the nearest land well (FD95-2) was used to create the depth model from 28 m to 70 m depth. The interval between 22 m (the maximum depth of the preliminary model) and 28 m was interpolated. This model generated an almost perfect fit between the calculated and observed arrivals. Only two additional iterations were necessary to reach the best match (Figure 3). The *Vp* inversion result matches the borehole profile quite nicely (Figure 4).

Inverted *Vp* matched the overall trend using the *Vs* inverted from the surface wave at shallow (<20 m) depths, and it matched using actual well data for *Vs* at deeper (>28 m) depths.

If the *Vp* well data is shifted 5 m downward, it matches the inversion results with surprising similarity (Figure 4). This suggests that the layers below 28 m at the water site are dipping up toward the land well location. The exact dip angle cannot be determined without additional information about the interval between 22 m and 28 m.

Discussions

Processing and interpretation has been based on the assumption that the "strange event" is refractions from the under water sediments. That is, it has been assumed that *Vp* within the sediments, presumably saturated with water, may be lower than *Vp* of water (1500 m/s). This assumption is supported by the well *Vp* profile. The presence of gas was suggested within the land sediments.

Another possible interpretation for the "strange event" suggested that to be refractions is that it is a non-geometric PS wave apparent in the data when Poisson's ratio exceeds 0.438 (Roth and Holliger, 2000). Examples of PS waves have used velocity parameters similar to the alternative velocity distribution for this site; Vs=110 m/s, Vp=1500 m/s (σ = 0.498). Such *Vp* values would be expected for very near water bottom sediments since it is very probable that they are water saturated. The resultant modeled shot gather contained a PS wave with a phase velocity of 220 m/s (about twice the S-wave velocity), which was strongly attenuating with distance. At offsets

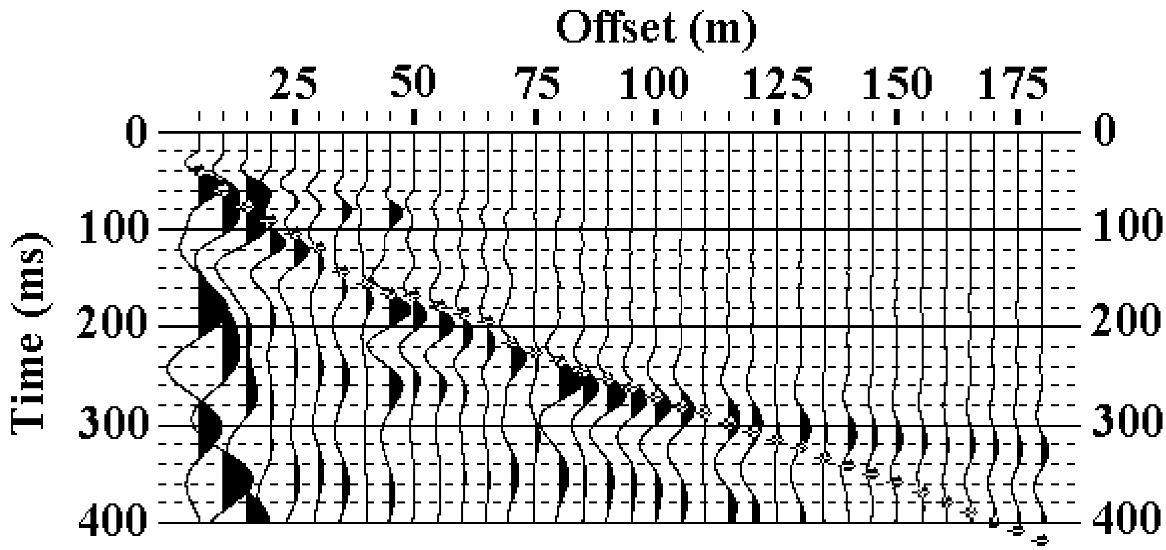

Figure 2. Refraction inversion using only 21 m deep velocity model.

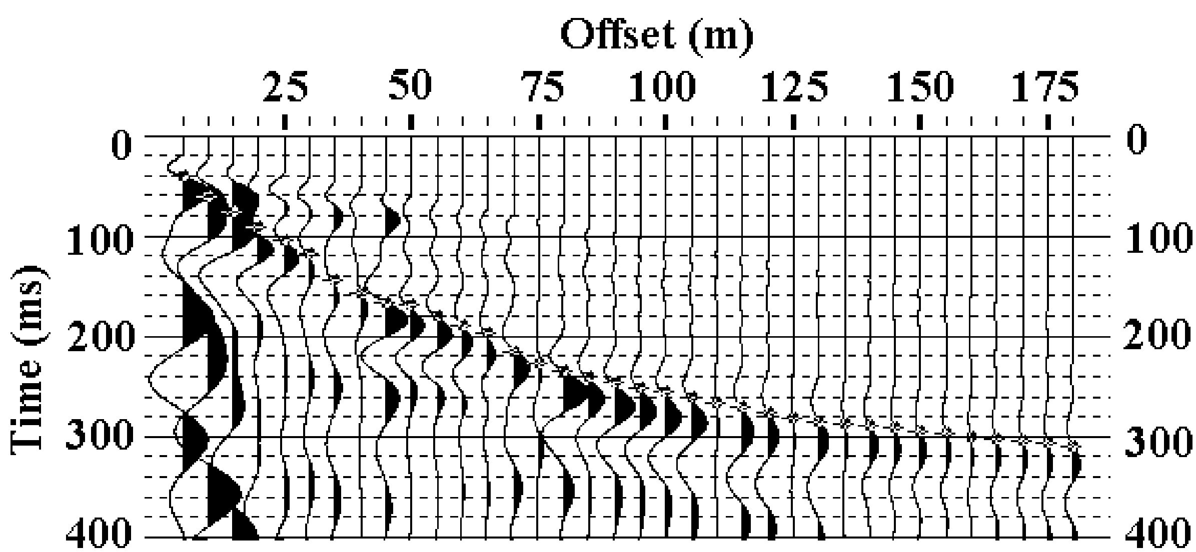

Figure 3. Refraction inversion using 70 m deep velocity model.

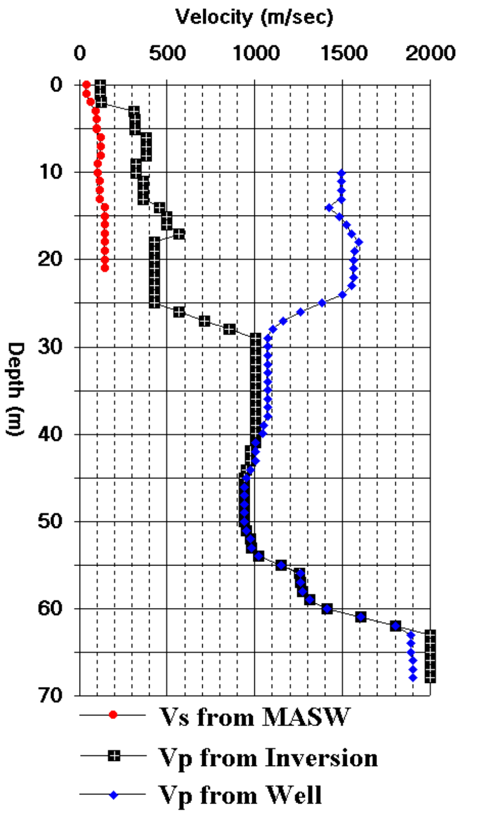

Figure 4. *Vs* profile from surface (Scholte) wave inversion and *Vp* profile from well and refraction inversion.

greater than about 25 m the PS wave was practically gone in the model case (Roth and Holliger, 2000). However, the event identified here as a refraction possesses large amplitudes to offsets greater than 180 m and the apparent velocity observed at the nearest offset is greater than 300 m/s.

Conclusions

The joint pseudo 2-D inversion presented here is a quick and efficient way to establish the vertical *Vp* profile. Results from this joint analysis suggest this water-bottom sediments may be gas charged.

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