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Application of Surface-wave modeling and inversion in Cordova Embayment of northeastern British Columbia

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Summary

With increasing activities in shale plays, surface-wave analysis and inversion is finding growing applications in the hydrocarbon exploration industry. This is, perhaps, an acknowledgement that near-surface velocity anomalies play a critical role in imaging the deeper heterogeneous shale reservoirs. The spatial and vertical heterogeneities, seen in the shale reservoir must be corrected for any near-surface velocity effects, through proper statics correction or through imaging with a velocity model that properly takes account of the near-surface heterogeneities. Near-surface velocity anomalies are quite severe in the Cordova Embayment of northeastern British Columbia, where the Mid-Late Devonian shale are targets. Analysis and inversion of dispersive surface-waves appearing in the form of ground roll in land data is an appropriate tool for this purpose. One main goal is to estimate shear-wave statics, so mode-converted shear-wave data can be used in shale-reservoir characterization.

We applied a newly developed surface-wave analysis, modeling, and inversion method (SWAMI) to obtain near-surface velocity heterogeneities in the Cordova Embayment area. Pulse wave data on 2D test lines containing frequencies as low as 1 Hz were used for this purpose. The use of pulse data was challenging; but low-frequency contents in data helped model shear velocity to 100 m or more below surface. The inversion results were validated through inversion of synthetic Rayleigh-wave data generated with an appropriate and industry-standard elastic modeling program. The work with test lines helped develop strategies for additional surveys for building a detailed near-surface velocity model.

Introduction

A large part of the energy put into the ground in land seismic data acquisition appears as coherent noise in the form of ground roll that is quickly filtered out during processing. Dispersive Rayleigh and Love waves, which are the major components of the ground roll had been used by construction engineers (Lai and Rix,1998; Xia et al., 1999) to characterize near-surface soil strengths for construction purpose and by materials engineers for non-destructive testing of materials (Pecorari, 1983). Lately surface-waves, especially the Rayleigh waves are finding increasing applications in the hydrocarbon exploration industry (Roy and Stewart, 2011) for near-surface characterization.

Rayleigh waves propagate along the near surface. Their propagation properties depend directly upon the elastic properties of the near surface. The shear velocity is the most sensitive elastic parameter. The analysis and inversion of Rayleigh waves can be used for the characterization of the near surface (Park *et al*. 1999; Xia *et al*. 1999; Socco et al., 2010). Multiple modes are generated and each mode has a characteristic phase velocity which is dependent on the frequency. The depth of penetration of any mode depends on its wavelength. The longer the wavelength, the larger is the penetration depth. Fine sampling of the wavefield is helpful, but not necessary in the analysis of Rayleigh waves using SWAMI (Strobbia et al., 2011a and 2011b).

Figure 1: Typical surface characteristics in the Cordova Embayment area. Source: Photos by Garth Lenz.

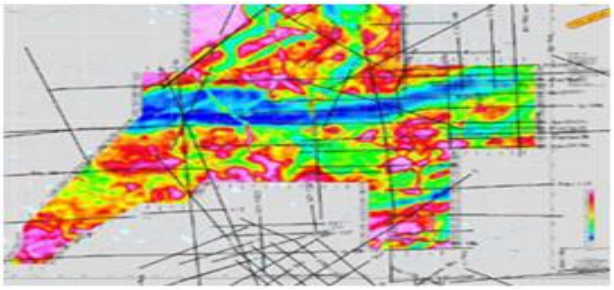

Figure 2: Cordova near-surface resistivity map. Note the east west blue-colored feature. This is a glacial channel cut down into unconsolidated glacial sediments nearly 350 m thick.

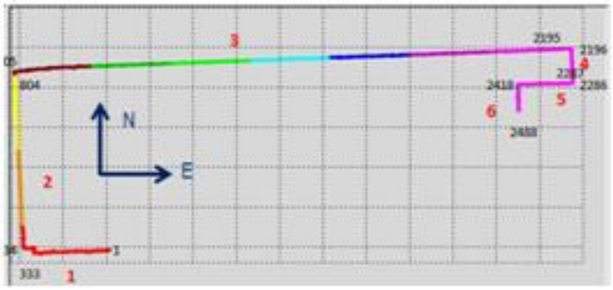

Figure 3: Line segments for analysis of near-surface velocity anomalies

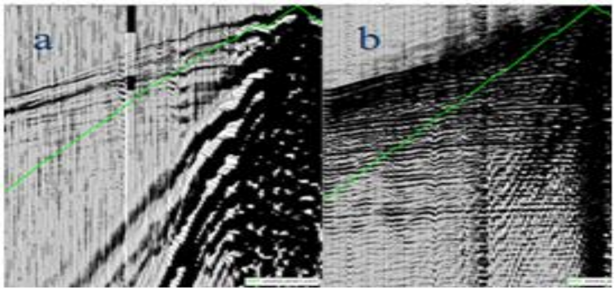

Figure 4: (a) Vibroseis Pulse sweep data and (b) Vibroseis conventional sweep data.

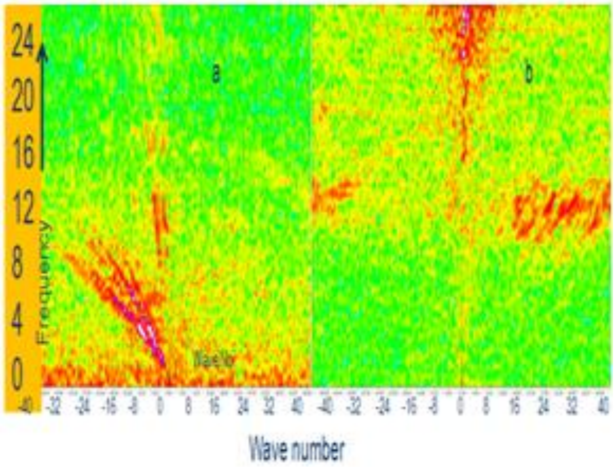

Figure 5: F-K Spectrum of data in Figure 4. Usable frequencies in pulse data between 1-16 Hz. Sweep data does not have significant signal below 10 Hz.

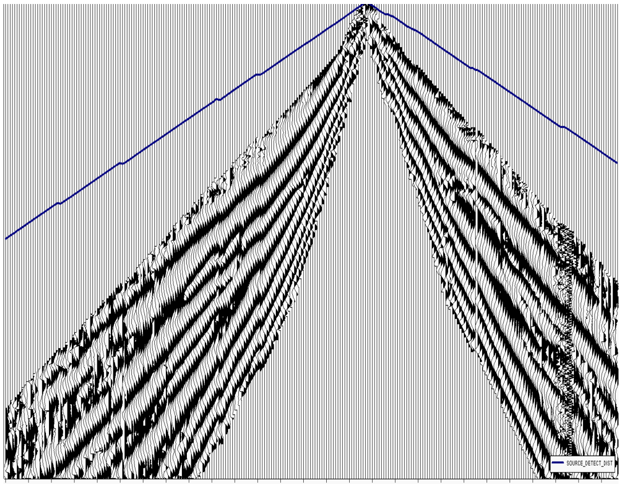

Figure 6: Processed shot gather example.

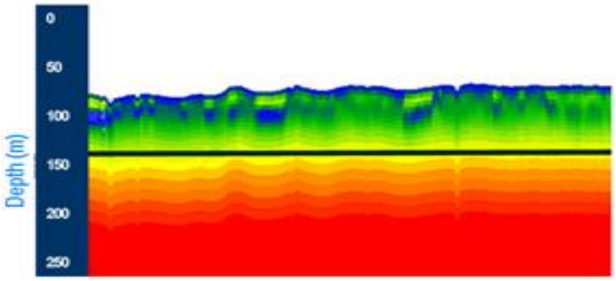

Figure 7: Typical inversion results of sweep data. The solid black line indicates the maximum reliable penetration depth.

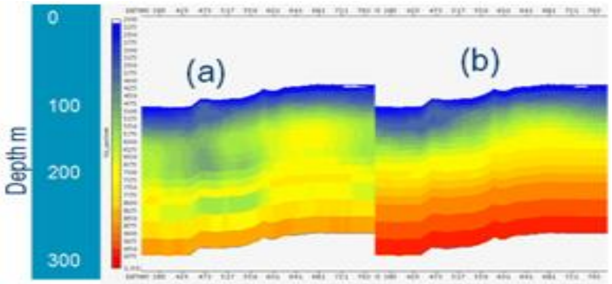

Figure 9: Depth model from pulse data for 2-20 Hz (a) and 4-20 Hz (b).

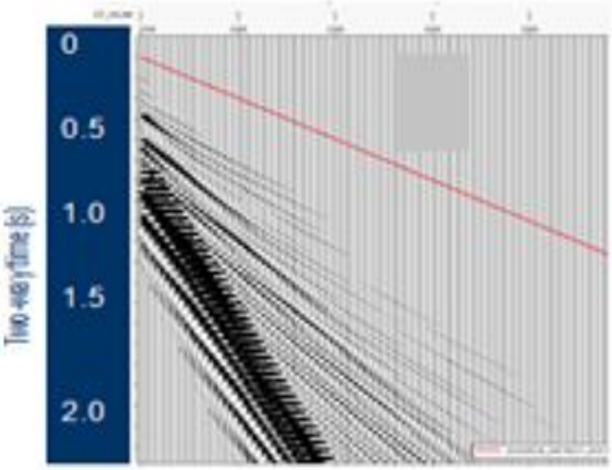

Figure 11: Anivec synthetic for a shot location using the inverted shear velocity at the location.

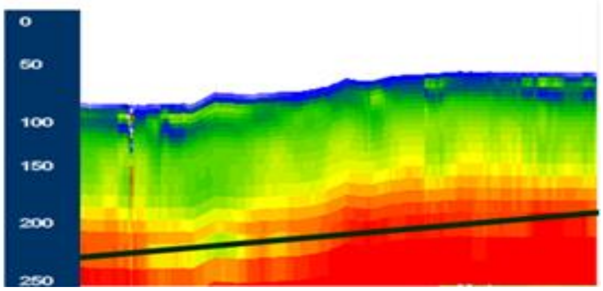

Figure 8: Typical inversion results of pulse data. The solid black line indicates the maximum reliable penetration depth.

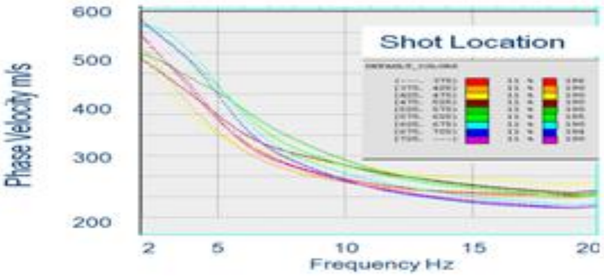

Figure 10: Phase velocity of fundamental Rayleigh wave mode for 8 different shot locations on line segment 2 in Figure 3.

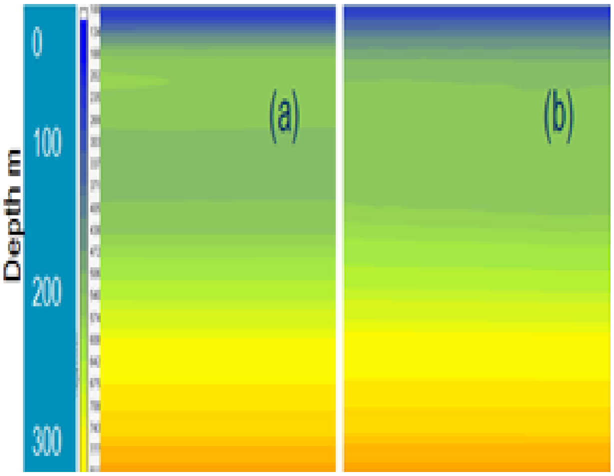

Figure 12: (a) Inversion of synthetic data from inverted model at a shot location in Figure 9. (b) Final inversion model of real data at the location.

The main objective of surface-wave inversion is to model the near-surface shear wave velocity. Like any seismic inversion, the Rayleigh wave inversion problem is ill-posed. To minimize the potential uncertainties in the inversion results, the SWAMI method uses a model-based approach. The local surface wave modal dispersion curves are extracted using an adaptive high-resolution wavefield transform for each local super-gather. The super-gather is created with multiple shots and receivers within a small aperture (Strobbia, et al., 2011b). Depending on the data quality, processing options may be chosen. Only the fundamental mode Rayleigh wave is used. The wavenumber and frequency values are automatically picked. Quality control checks and required editing are done by the user.

The Cordova Embayment in northeastern British Columbia is a new area for shale gas exploration in Canada. It is associated with the Horn River Basin, one of the largest shale basins in North America. Muskeg, river channels, and glacier fills (Figures 1 and 2) are the main causes of near-surface velocity heterogeneities. The Vp/Vs ratio in near-surface rock-facies could vary from 2 to 7 (von Lunen, 2012).

Seismic Data

Nexen Energy Inc. acquired 2D line surface seismic data with three different source types along the line segments shown in Figure 3. Pulse (vibrator-sweep time 1-2 s) source, conventional sweep vibrators, and shear-wave sources were used. We examined pulse and sweep data. No shear-wave and pulse data were available on the same line segment for direct comparison.

Given the low-frequency contents in the pulse data and the requirement that we would like to model as deep as possible, we decided to continue with pulse data alone in segment 2 of Figure 3. Sample gathers and F-K spectra of pulse and sweep data are shown in Figures 4 and 5, respectively. Note that the significant signals in sweep data start at about 10 Hz (Figure 4b) and pulse data contains signal down to about 1 Hz (Figure 5a).

Surface-wave data are characterized by low velocities. The data analysis is further complicated by the low fold (nominal fold is about 16) 2D geometry. To extract optimally the surface wave properties, some pre-processing was applied, to enhance the Rayleigh wave energy in the gathers and balance the amplitude variations. An envelope scalar function was used to balance the amplitude in this case. Then the dispersion curves were automatically picked. Quality control checks and required editing were done. To isolate the Rayleigh wave modes, we applied normal moveout (NMO) corrections, an appropriate inside mute and outside mute to each shot gather, and then inverse NMO to the gathers. A representative processed gather on line segment 2, is shown in Figure 6. These gathers are then input to SWAMI for further analysis, modelling, and inversion. The modelling part was discussed by Strobbia et al. (2011a) for filtering out the ground roll. Below we concentrate on the analysis and inversion.

Inversion Results

As shown in the previous section, the conventional sweep data do not contain usable low frequencies. The F-K spectra shown in Figure 5 exemplify this point. If we work with the frequency range 6-12, the velocity model so obtained from sweep data is spatially flat below about 40m from the surface (Figure 7); this is geologically unrealistic. On the other hand, the pulse data have usable low frequencies down to about 1 Hz and extend up to 10 Hz. Then, the inverted model is reliable deeper into the earth, greater than 100 m below surface. This is evident in Figure 8. Even pulse data will not provide suitable model in deep sections if extreme low frequencies are not included. This is evident when we compare the results of inversion for two ranges of frequencies with pulse data. This is shown in Figure 9. In the left part of figure we have the inverted velocity model using 2-20 Hz. In the right part we used frequencies 4-20 Hz. Otherwise, everything else was kept the same. Thus, low frequency is critical in obtaining reliable velocity model to great depths. The model shown in Figure 9a is the final inversion model. The phase velocity dispersion curves at 8 locations on the line segment 2 are shown in Figure 10. Substantial variations in phase-velocity characteristics are seen.

Model validation

Validation of the final model is an essential part of the inversion process. In the absence of a logged drill hole, this can be done by creating synthetic shot gathers using the inversion results and inverting the synthetic gathers with the same parameters as in the original inversion. We can then compare the resultant inversion with the initial model. A stable inversion program should return the same input model. This was done using an industry-standard 1D elastic modeling program, ANIVEC (Mallick and Frazer, 1988). ANIVEC uses a Thomson-Haskel-type matrix method in the frequency-wavenumber domain to calculate synthetic seismograms. The shot-receiver geometry was chosen as in the real data. Multiple shot locations along the line direction can be used concurrently to verify the model results. Figure 11 shows the synthetic at a shot location on line segment 2 with the shear velocity model (shown in Figure 9a) inverted from real data. The Vp model was created using a Vp/Vs ratio of 2 and the density model was generated from a Gardner-type relation. Please note that neither Vp nor density significantly affects Rayleigh-wave phase velocity. The inversion of the synthetic data produces the same result as the input model within 2-3% accuracy (Figure 12). Several other locations were checked in this way and similar results were obtained.

Conclusions

We applied a newly developed surface-wave analysis, modeling, and inversion method to create a near-surface shear-wave velocity model using pulse data. We showed that low-frequency contents, down to 1 Hz, in data are essential to obtain reliable near-surface velocity model to sufficient depths. Inversion results were validated through inversion of synthetic seismograms at specific locations. With this particular data set, we found that a special trace-amplitude scaling method helped improve the data quality in the F-K domain for automatic picks and in extending the usable frequency band. The work was the basis for recommendation of additional vibroseis-pulse data for detailed near-surface shear-velocity modeling in the Cordova Embayment field of British Columbia.

Acknowledgements

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