PRACTICAL ASPECTS OF MASW INVERSION USING VARYING DENSITY

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Abstract

We use multi-channel analysis of surface waves (MASW) on seismic data to assess the practical impact of the assumed compressional-velocity and density parameters on the inverted shear-wave velocity results. The practical secondary-parameter impact evaluation was performed on data acquired in the arctic. The ice-sheet compressional-, shear-wave velocity and density variations with depth were available from laboratory and field measurement and served as reference for analyzing the MASW inversion. Presented MASW results demonstrate that the a-priori knowledge of density variation with depth can reduce the final inverted shear-wave velocity results typically by 6-7 % for the most of the middle layers from the velocity model and as much as 15% for some individual layers. After comparing the optimal parameter selection approach with the general theoretical recommendations it was concluded that using constant density leads to overestimation of shear-wave velocities by 7-8 %. Such an overestimation can lead to liquefaction underestimation at earthquake sites. Therefore, these findings can be of value for the engineering community interested in accurate shear-modulus site evaluation. Optimal density parameter selection can improve the reliability and quality of the final 2D Vs section. However, optimal processing MASW parameter selection, such as density variation with depth, can be best achieved using field tests and is the preferred approach over theoretical recommendations.

Introduction

Estimation of shear-wave velocity (V_S) is important for the evaluation of the stiffness properties of the near-surface materials; V_S increases as material shear strength (rigidity) increases. The multi-channel analysis of surface-wave (MASW) method was developed to estimate near-surface S-wave velocity from high-frequency (≥ 2 Hz) Rayleigh-wave data (Park et al., 1999; Xia et al., 1999a). The practical application of MASW has provided reliable correlations to drill data. Using the MASW method, Xia et al. (2000) noninvasively measured V_S within 15% of V_S measured in wells. Miller et al. (1999a) mapped bedrock with 0.3-m (1-ft) accuracy at depths of about 4.5-9 m (15-30 ft), confirmed by numerous borings. Similar results were reported by Ismail and Anderson (2007). The MASW method has been applied to problems such as characterization of pavements (Ryden et al., 2004), the study of Poisson's ratio (Ivanov et al., 2000a), study of levees and sub-grade (Ivanov et al., 2005b, Ivanov et al., 2006c), investigation of sea-bottom sediment stiffness (Park et al., 2005; Ivanov et al., 2000b), mapping of fault zones (Ivanov et al., 2006a), detection of dissolution features (Miller et al., 1999b), and measurement of S-wave velocity as a function of depth (Xia et al., 1999b). Studies on the MASW method have been extended to areas of utilization of higher modes (Xia et al., 2003; Beaty et al., 2002; Beaty and Schmitt, 2003), determination of near-surface Q (Xia et al., 2002), and the acquisition of more realistic seismic refraction models (Ivanov et al., 2006b, Ivanov et al., 2007).

The MASW method is applied by performing the following step. A single seismic-data record is acquired by a set of low-frequency (e.g., 4.5 Hz) geophones evenly spaced along a line. The seismic data from such a shot record is transformed into a phase-velocity – frequency image, which is used to evaluate the dispersion-curve trend of the fundamental-mode of the Rayleigh wave. The estimated dispersion curve is then inverted to produce a 1-D V_s model, which is assigned to the middle of the geophone spread. By assembling numerous 1-D V_s models derived from consecutively recorded seismic shot records along a seismic line, a 2-D V_s model can be obtained.

MASW dispersion-curve inversion for V_s is performed by using predefined values for compressional-wave velocity (V_p) and density. It is preferred that such a-priori information is available from other measurements. However, practical MASW applications often lack such information and as a result the V_p and density estimates are provided based on assumptions for each specific site. It has been considered that the resulting error from using parameter assumptions is insignificant. Xia et al., (1999a) showed that a 25 % increase in V_p (provided for the MASW inversion) resulted in less than 3 % change in the final V_s values. Similarly, they reported that a decreasing the density in the top 2 layers and increasing the density in rest of the layers by 25 % of the inversion model the resulting change in the V_s is less than 10 %. However, that study did not provide sufficient practical understanding of the impact of density change on V_s inversion. Furthermore, the possibility for errors in the absolute V_s can be of lesser importance. Very often the MASW method is used for mapping purposes when errors in the absolute V_s, estimates are acceptable, such as mapping bedrock (Miller et al., 1999a), fault zones (Ivanov et al., 2006a), detection of dissolution features (Miller et al., 1999b), etc.

We examined the MASW inversion sensitivity to V_p and density using seismic data acquired in the Arctic. The advantages of using this data were the available information of compressional-, shear-wave velocity and density variations with depth in ice from laboratory and field measurements (Waite et. al., 1999; Heinz, 1974, King and Jarvis, 2007). Such information could be used as a reference during the MASW inversion.

Testing MASW inversion with various constant and vertically varying density values showed that increasing density variation with depth can reduce the final inverted V_s results typically by 6-7 % for the most of the middle layers from the velocity model and as much as 15% for some individual layers. Using a constant density for the whole depth section, regardless of its absolute value, provided identical V_s results that were 6-8 % higher than those obtained when using density increasing with depth.

Optimizing MASW inversion

Arctic seismic data

The MASW data dispersion-curve inversion was applied to data originally acquired for a reflection survey in the Arctic. The goal of the survey was to evaluate the top near-surface section of the ice. Data were collected using a 0.5 charge at 10 m depth as a source and twenty-four 28 Hz P-wave vertical phones on 20 m spacing resulting in a 460 m spread. The spread incremental movement (roll) was 160 m. The phase-velocity – frequency image of data showed the high-resolution fundamental-mode dispersion-curve trend within a wide frequency range, 15-100 Hz (Figure 1). With a phase velocity of 1500 m/s at 15 Hz and 1000 m/s at 100 Hz with corresponding wavelengths between 100 m and 10 m, the expected (50% of the wavelengths) approximate depth estimates were from 50 m to 5 m.

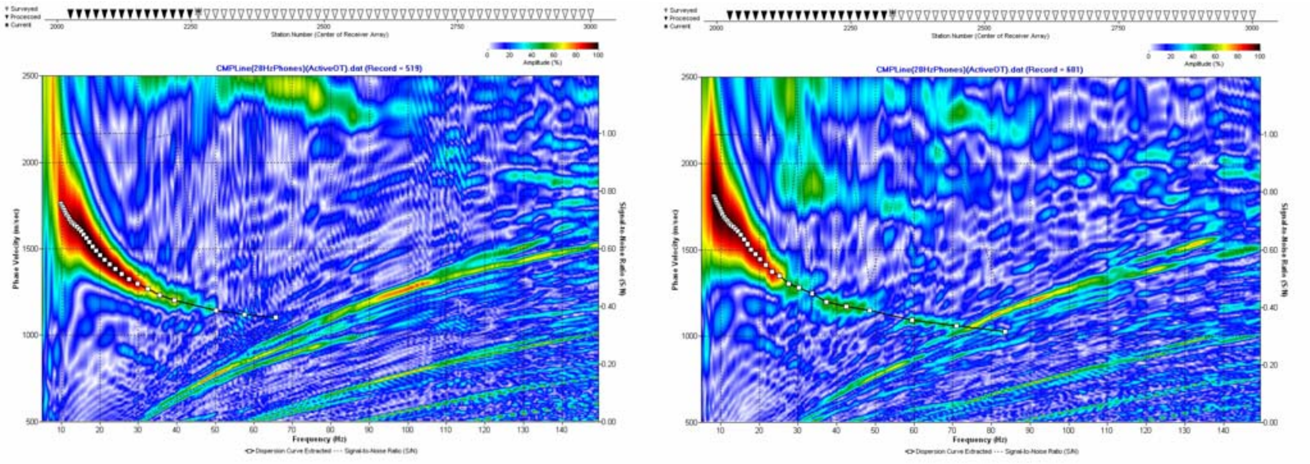

Figure 1. Dispersion-curve images of arctic MASW seismic data acquired with source distance from the nearest receiver at 10 m and spread size 460 m.

Initial inversion results were obtained using the default V_p (derived from assumed constant 2.5 V_p/V_s ratio, equivalent to Poisson's ratio of 0.4) and density (2 g/sm^3) parameters of the SurfSeis software (Figure 2a). The obtained V_s values were higher then expected at about 50 m and deeper, exceeding 2000 m/s, which was higher than the velocity values found in the literature. In efforts to achieve more realistic results we incrementally used reference values for ice: a constant V_p/V_s ratio of 2 (Waite et. al., 1999) and density of 0.8 g/sm^3 (Patterson, 1994) every time obtaining identical final V_s estimates. Other constant density values were tested without having any impact on the final results (Figure 2a). Additional inversion tests were performed trying to find parameters (e.g., number of layers, initial model, depth conversion ratio) that would match or get closer to the referenced values.

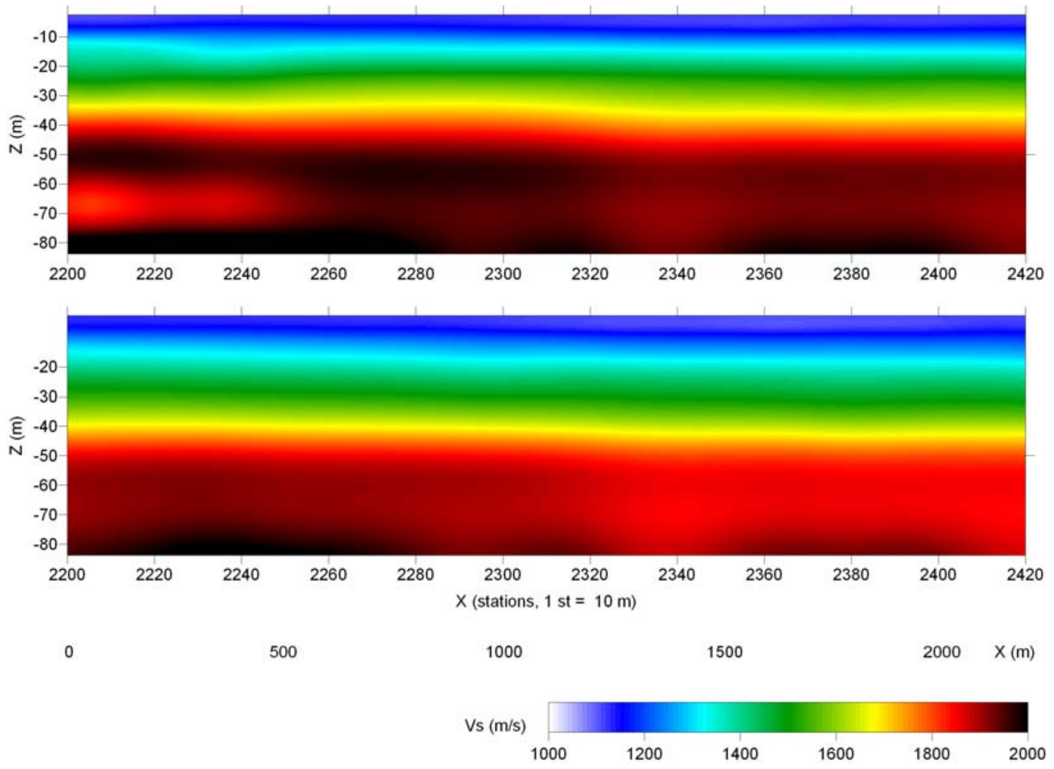

Figure 2. S-wave velocity model estimated using the MASW method by inverting Rayleigh-wave dispersion curves using a) constant density, and b) varying density.

The change occurred when the density values, namely increasing with depth, proposed by King and Jarvis (2007) was assumed for the inversion. Not only that the final V_s results changed but their absolute values decreased and matched those reported in the literature values (Figure 2b). V_s value changes for individual layers varied between 2% and 6% and were consistent for the majority of the inversions (Figure 3) and for a very few layers the change was as much as 17 %. Closer examination of layer V_s decreases indicated that the biggest changes occurred for the middle 5 layers of the 10-layer model, while there were no changes for the first layer (Figure 4)

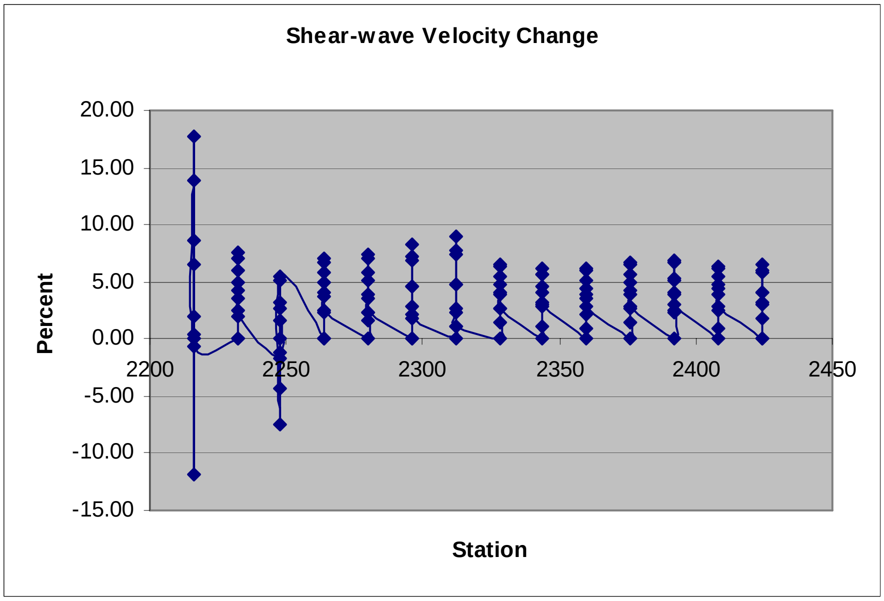

Figure 3. MASW S -wave velocity changes along the seismic line due to using varying density with depth. There are 10 values at each station, representing the percent change of each individual layer.

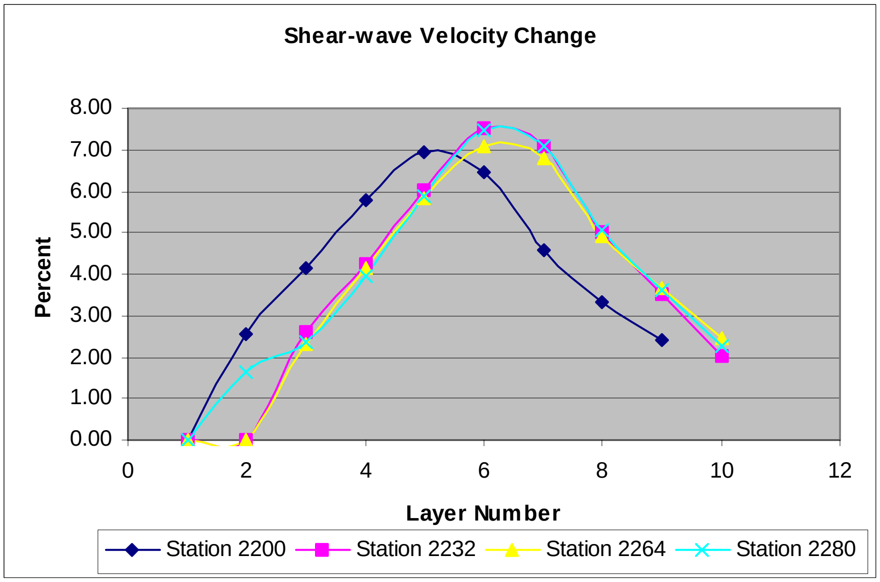

Figure 4. Typical 1-D S -wave layer-velocity changes due to using varying density with depth.

Conclusions

Presented results from MASW data inversion tests demonstrate that using density increasing with depth can reduce the final absolute V_s values by about 6-7 % and as much as 17 %. Such a corrected estimate can influence the shear-modulus evaluation and site characterization for engineering purposes. The main contribution of this work is the observation that varying a single constant density value for the whole model does not affect the final V_s result but it is the vertical density gradient that does.

These results suggest the use of as much as possible a-priori information about the density distribution with depth when absolute V_s evaluations are important for a specific site investigation. When such a-priori information is not available, then using and assumption of density increasing with depth appears more appropriate in view of the geologic processes taking place at the very near surface, which could lead to more accurate final results.

The utilization of density increasing with depth parameter has the potential of providing an even better match between the MASW and well measurements V_s.

Testing various V_p model assumptions did not contribute to observing changes in the final V_s values and supported our previous observations that V_p model assumptions are of lesser importance.

This manuscript provides practical examples for the utilization of density values at a given site.

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