Near-surface Qs and Qp estimations from Rayleigh waves using multi-channel analysis of surface waves (MASW) at an Arctic ice-sheet site

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Summary

We analyze seismic data acquired on the Jakobshavn Glacier, Greenland for reflection surveys. With the use of the multichannel analysis of surface waves (MASW) seismic method Rayleigh-wave attenuation versus frequency curves were measured and inverted not only for shear-wave quality factor Qs but also for compressional-wave quality factor Qp, which was possible as a result of the favorable relationship between the compressional (P)-wave (Vp) and shear (S)-wave velocity (Vs), i.e.,Vp /Vs ratio <2.2 typical for ice sheets. Changes in the a-priori Vp model used for the inversion had little impact on the resulting Qs, but impacted the Qp results, while still preserving the overall Qp trend. This suggests that Qs can be estimated with higher degree of reliability even when Vp errors are assumed. As well, this research showed the benefits of the seismic method for studying glaciers, i.e., that a single seismic survey can provide 3 sets of parameters, Vp reflection results, Vs sections, and Qs and Qp sections.

Introduction

Seismic reflection data were recorded on Jakobshavn Glacier, Greenland (Horgan et al., 2008). Further analysis revealed that these data can be successfully used for shear S-wave velocity (Vs) estimations using surface-wave analysis. This research also showed that acquired data and obtained results can be also used for Rayleigh-wave analysis for evaluating quality factors Q. We focus on multichannel analysis of surface waves (MASW) approach, which was initially used in previous research to evaluate ice-sheet Vs (Ivanov et al., 2009) to obtain quality factor Q estimates.

Stiffness properties of near-surface materials are important for various environmental and engineering applications. Stiffness is directly related to Vs, which increases as material shear strength (stiffness, rigidity) increases. Vs can be estimated by analyzing surface waves on seismic data records. We use the MASW method to estimate near-surface shear-wave velocity from high-frequency (≥ 2 Hz) Rayleigh-wave data (Song et al., 1989; Park et al., 1998; Miller et al., 1999b; Xia et al., 1999). Shear-wave velocities estimated using MASW have been reliably and consistently correlated with drill data. Using the MASW method, (Xia et al., 2000) non-invasively measured Vs within 15% of Vs measured in wells. (Miller et al., 1999b) mapped bedrock with 0.3-m (1-ft) accuracy at depths of about 4.5-9 m (15-30 ft), as confirmed by numerous borings.

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 subgrade (Ivanov et al., 2004; Ivanov et al., 2006b), investigation of sea-bottom sediment stiffness (Ivanov et al., 2000b; Kaufmann et al., 2005; Park et al., 2005), mapping of fault zones (Ivanov et al., 2006a), study of Arctic ice sheets (Tsoflias et al., 2008; Ivanov et al., 2009), detection of dissolution features (Miller et al., 1999a), and measurement of Vs as a function of depth (Xia et al., 1999). Applications of the MASW method have been extended to determination of near-surface quality factor Q (Xia et al., 2013) and the acquisition of more realistic compressional-wave refraction models (Ivanov et al., 2006c; Ivanov et al., 2010; Piatti et al., 2013). A review of established approaches of surface wave methods (SWM) can be found in Socco et al. (2010). Most recent developments of the SWM include the expansion with the use of the horizontal component of the Rayleigh wave (Boaga et al., 2013), the simultaneous use of guided-waves with multi-mode surface waves in land and shallow marine environments (Boiero et al., 2013) and evaluation at landfill sites (Suto, 2013).

Shear-wave quality factor, Qs, (dissipation factor Qs^{-1}, a.k.a. intrinsic attenuation) and conditionally compressional-wave quality factor, Qp (dissipation factor Qp^{-1}), can be estimated from the MASW seismic data. Rayleigh-wave attenuation-frequency curves can be measured (Xia et al., 2012; Xia et al., 2013) and then using estimated MASW Vs with available compressional P-wave (Vp) and density information numerical relationship between these variables can be applied Anderson et al. (1965).

$$\alpha_R(f)=\frac{\pi f}{C_R^2(f)}\,[\,\sum_{i=1}^{n}P_i(f)Q_{Pi}^{-1}]+\sum_{i=1}^{n}S_i(f)Q_{Si}^{-1}] \qquad (1)$$

Where $P_i(f)=V_{Pi}\frac{\partial C_R(f)}{\partial V_{Pi}}$,$S_i(f)=V_{Si}\frac{\partial C_R(f)}{\partial V_{Si}}$. $\alpha_R(f)$ is the Rayleigh-wave attenuation coefficient in 1/length, f is frequency in Hz, Q_{Pi} and Q_{Si} are the quality factors for P and S waves of the ith layer, V_{Pi} and V_{Si} are the P- and S-wave velocities of the ith layer. The suggested inversion system is sensitive to Qp only when Vp / Vs ratio is smaller than 2.2, (i.e., Vs/Vp>0.45) (Xia et al., 2002). Attenuation versus frequency curves. can by estimated in the frequency domain by measuring amplitude attenuation trend at a given frequency across a whole record (Xia et al., 2012).

The MASW method is applied by performing the following steps. A single seismic-data record is acquired. These data are

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transformed into a dispersion-curve image (Park et al., 1998; Luo et al., 2009), which is used to evaluate a dispersion-curve trend(s) of the Rayleigh wave. This curve is then inverted to produce a 1D Vs model (Xia et al., 1999). By assembling numerous 1D Vs models, derived from consecutive seismic shot records, 2D (Miller et al., 1999b) or 3D (Miller et al., 2003) Vs models can be obtained.

Inverting attenuation values for Qs in addition to Vs requires Vp and density information, which are assumed to be available from other geophysical methods, such as seismic reflection (Steeples and Miller, 1990), refraction tomography (Zhang and Toksoz, 1998; Ivanov et al., 2010) for Vp, well measurements, etc. Practical applications of MASW method Vp and density are rarely known with confidence and as a result use of approximations is adopted, which is commonly considered acceptable because of the low sensitivity of surface-wave inversion to Vp and density, i.e., errors in their estimation result in very small errors in final Vs results (Xia et al., 1999). When applied to near-surface seismic data Vp / Vs ratios are rarely below 2.2 or even known. In such cases, when solving for quality factors (Xia et al., 2012) the approximation Qp = 2 Qs is assumed.

However, availability of Vp , especially if the corresponding Vp / Vs ratio approaches 2.2 or less makes it possible to invert for Qp in addition to Qs. That is one of the reason for our special interest in ice-sheet data because the reported Vp / Vs ratio for ice can equal 2 (Waite et al., 1995).

Data Acquisition

A 2-D seismic line was acquired at Jakobshavn Glacier, Greenland (69.35° N, 47.2° W), using a 0.5 charge at 10 m depth as a source. The recever spread consisted of twenty-four 28 Hz vertical phones spaced at 20 m, resulting in a 460 m spread. Data were collected using a roll-along style of acquisition. The spread movement (roll) was 160 m (Horgan et al., 2008).

Results

The MASW technique was appraisedby evaluating the ability of the method to estimate the dispersion curve of the fundamental mode of the Rayleigh wave. The phase-velocity – frequency image of data showed a high-resolution fundamental-mode dispersion-curve trend within a frequency range, 10-50 Hz (Figure 1) which could typically be followed to ~110 Hz. With phase velocities ~1600-1700 m/s at ~10 Hz resulted in longest wavelengths of ~160-170 m that contributed to estimating Vs to a depth of~80 m. A 2-D Vs section was obtained (Figure 2) with the MASW inversion using a Vp model (Figure 3) estimated from a refraction survey in the Antarctic (King and Jarvis, 2007) and density information (Figure 4) from a near-by well. The resultant Vp / Vs ratio was less than 2.2 for the most part of the section (Figure 5). A set of 18 records was selected to estimate attenuation curves from each record and invert these data for Qs and Qp using the available Vs, Vp and density models. For half of the records the estimated attenuation curves followed close-to-linear trends. For the most of the frequency range (e.g., 20-65 Hz) these curves were matched very well by the curves calculated from the inversion (Figure 6). For a short frequency range (e.g., 10-15 Hz) the curve match was reduced but was considered still acceptable following previous research (Xia et al., 2002; Xia et al., 2012).

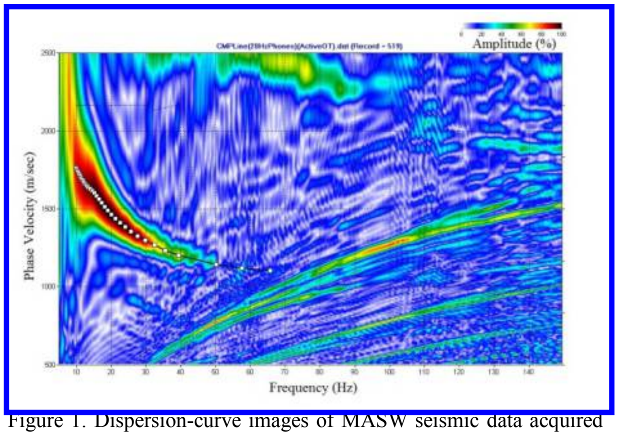

Figure 1. Dispersion-curve images of MASW seismic data acquired at Jakobshavn Glacier, Greenland.

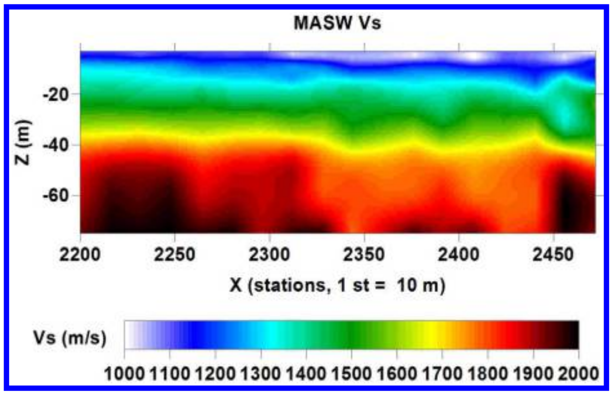

Figure 2. Portion of the 2-D MASW Vs section. Also used as a Vp model with values Vp = 2Vs.

For half of the records the attenuation curves appeared irregular (Figure 7), possibly due to noise, and the Q inversion failed to provide a good match between the calculated and estimated curves. These results were not included.

The inverted Qs model (Figure 8) had relatively high values at the very top ~5 m and relatively low Qs for the most of the remaining part of the section (below ~12 m), which implies low shear-wave dissipation at the very top and high dissipation below. The corresponding Qp section (Figure 9) exhibited different trends. There was a relatively high-Qp layer at

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25 m separated by a low-Qp layer at 40 m with two high-Qp dome-shaped anomalies below 45 m.

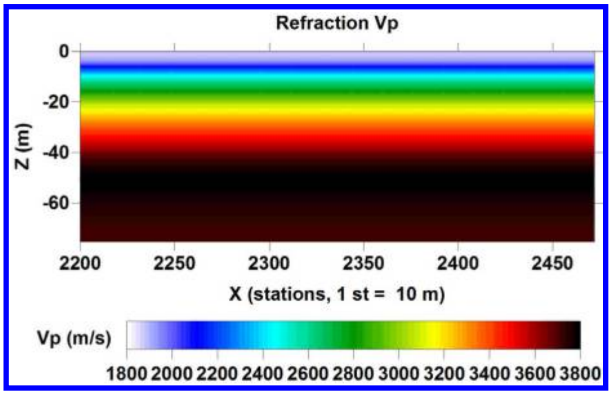

Figure 3. Vp estimated from refraction survey in the Antarctic.

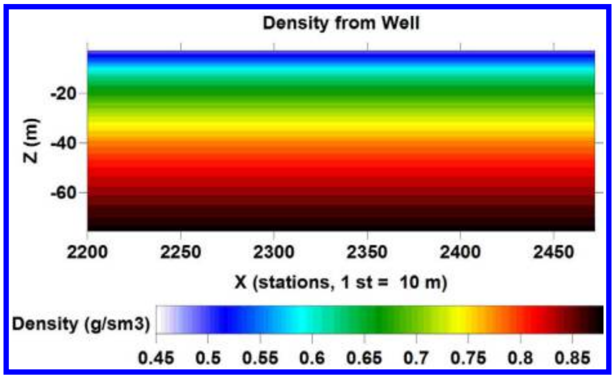

Figure 4. Density information from a near-by well.

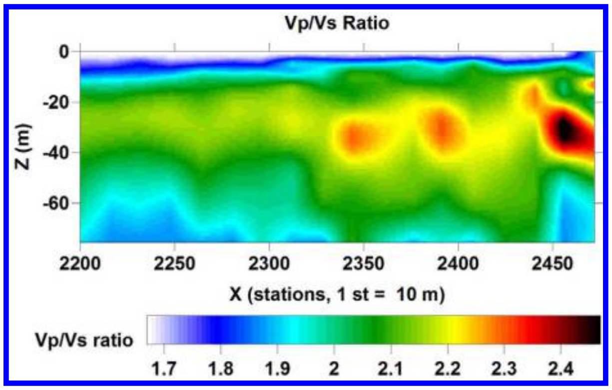

Figure 5. Vp/Vs ratio after inverting for Vs.

To evaluate the impact of the Vp model on the Q inversion. we used a significantly different model using Vp = 2 Vs from MASW (Figure 2; the Vp model would appear identical with values twice bigger) based on Waite et al. (1995). The inverted Qs model (Figure 10) remained almost identical to the previous with the exception of the increased values of the two previously existing bull-eyes anomalies at about 60 m depth. Qp results changed. The low-Qp layer at 40 m disappeared and the dome-shaped features expanded in width and height (Figure 11). However, both Qp results suggest low dissipation factor (Qp^{-1}) with depth (high Qp) and high dissipation factor very shallow (low Qp). These relatively high Qp values below ~35 m depth range between 80-100 are consistent with previous glacier research estimates (e.g., 50-160; by using frequencies above 100 Hz) summarized by Gusmeroli et al. (2010). With that respect our estimates may appear a bit lower than the average.

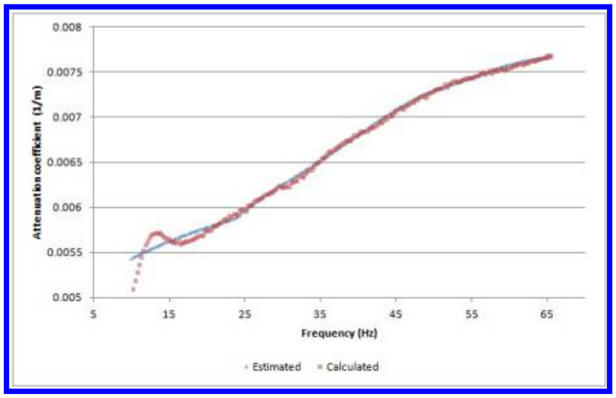

Figure 6. Attenuation curves estimated from the data (blue stars) and calculated (red squares) from the inverted Qs and Qp models.

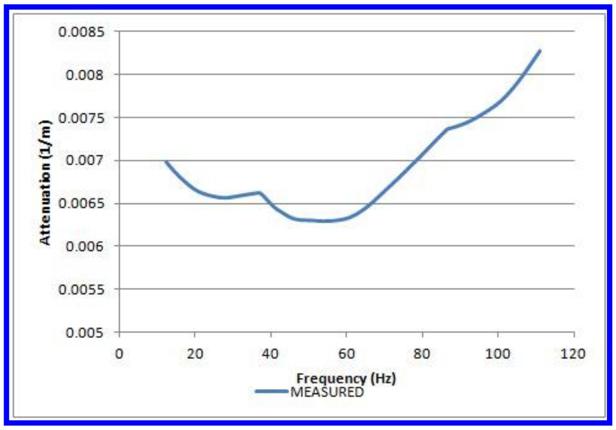

Figure 7. Estimated attenuation curve with irregular trend.

We presented two Vp models (one from well data, and another from lab measurements. Considering the wide possible range of refraction nonuniqueness, more Vp models can be obtained using algorithms, such as, GRM (Palmer, 1981), refraction tomography (Zhang and Toksoz, 1998), JARS (Ivanov et al., 2010), etc. for potentially detailed Qp results (e.g., Figure 9).

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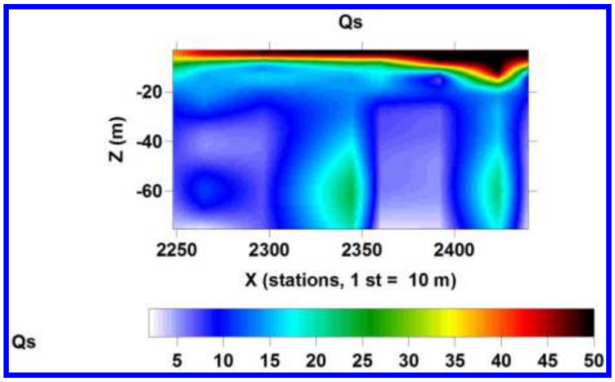

Figure 8. Qs estimates using MASW Vs and refraction Vp.

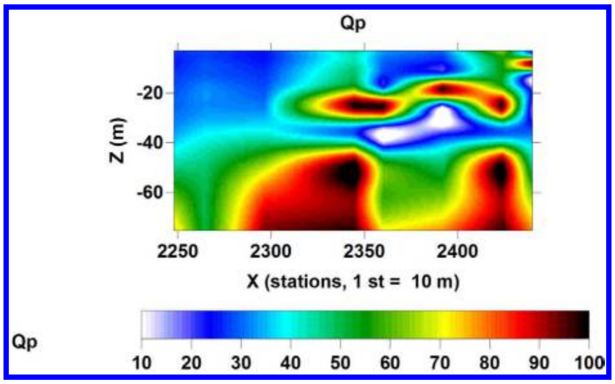

Figure 9. Qp estimates using MASW Vs and refraction Vp.

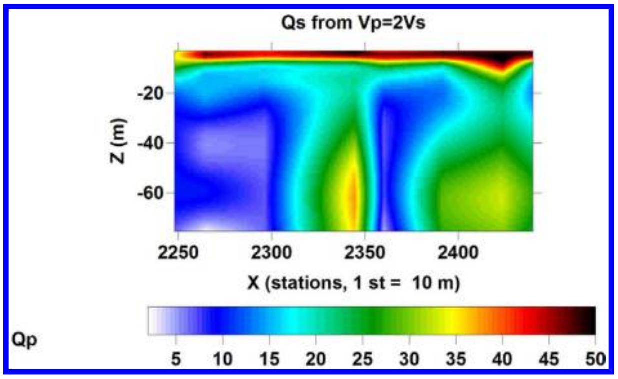

Figure 10. Qs estimates using MASW Vs and Vp=2Vs.

This research showed that using the significantly different Vp models resulted in different Qp; however, the overall Qp trend is preserved. As well, Qs is largely unaffected by changes in the Vp model.

High Qs and Qp (lower dissipation factors Qs^{-1} and Qp^{-1}) with depth are consistent with our expectations of glacier changes with depth.

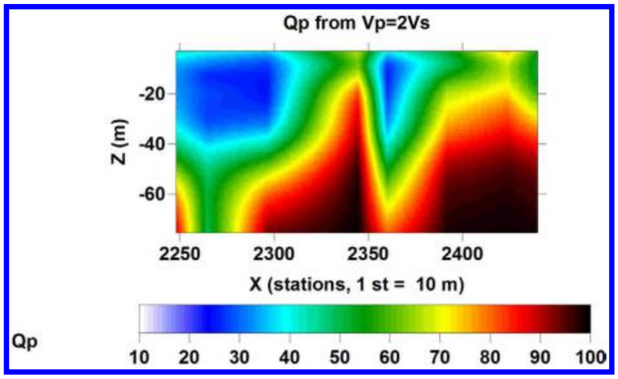

Figure 11. Qp estimates using MASW Vs and Vp=2Vs.

Conclusions

This work shows that in addition to estimating quality factor Qs from Rayleigh wave attenuation coefficients, it is also possible to obtain from these same data Qp estimates that look different from the Qs trends (i.e., they were not a scaled version of Qs). This was possible only by using Vp models that provide Vp/Vs ratio < 2.2.

To the best of our knowledge our work is a unique attempt to estimate Qp from Rayleigh-wave attenuation coefficients for the very near-surface (i.e., 10-80 m), for which Vp/Vs ratio are < 2.2. We speculate that this may be due to the fact that at great majority of the very near-surface sites Vp/Vs > 2.

Future research can include the estimation of more accurate Vp models for this site using other geophysical methods, such as refractions, tomography, well measurements, etc.

We demonstrate that the seismic method can provide more than one physical attribute for observing status and processes taking place in a glacier. In this instance a single seismic survey for reflection purposes could also be used for the estimation of 2-D MASW Vs, Qs, and Qp sections.

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EDITED REFERENCES

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REFERENCES

Anderson, D. L., A. Ben-Menahem and C. B. Archambeau, 1965, Attenuation of seismic energy in upper mantle : Journal of Geophysical Research, **70**, no. 6, 1441–1448, http://dx.doi.org/10.1029/JZ070i006p01441.

Boaga, J., G. Cassiani, C. L. Strobbia, and G. Vignoli, 2013, Mode misidentification in Rayleigh waves: Ellipticity as a cause and a cure: Geophysics, **78**, no. 4, EN17–EN28, http://dx.doi.org/10.1190/geo2012-0194.1.

Boiero, D., E. Wiarda, and P. Vermeer, 2013, Surface- and guided-wave inversion for near-surface modeling in land and shallow marine seismic data: The Leading Edge, **32**, 638–646, http://dx.doi.org/10.1190/tle32060638.1.

Gusmeroli, A., R. A. Clark, T. Murray, A. D. Booth, B. Kulessa, and B. E. Barrett, 2010, Seismic wave attenuation in the uppermost glacier ice of Storglaciaren, Sweden: Journal of Glaciology, **56**, no. 196, 249–256, http://dx.doi.org/10.3189/002214310791968485.

Horgan, H. J., S. Anandakrishnan, R. B. Alley, L. E. Peters, G. P. Tsoflias, D. E. Voigt, and J. P. Winberry, 2008, Complex fabric development revealed by englacial seismic reflectivity: Jakobshavn Isbræ, Greenland: Geophysical Research Letters, **35**, no. 10, doi: 10.1029/2008GL033712.

Ivanov, J., R. D. Miller, R. F. Ballard, J. B. Dunbar, and J. Stefanov, 2004, Interrogating levees using seismic methods in southern Texas: 74th Annual International Meeting, SEG, Expanded Abstracts, 1413–1416.

Ivanov, J., R. D. Miller, P. Lacombe, C. D. Johnson, and J. W. Lane, Jr., 2006a, Delineating a shallow fault zone and dipping bedrock strata using multichannal analysis of surface waves with a land streamer: Geophysics, **71**, no. 5, A39–A42, http://dx.doi.org/10.1190/1.2227521.

Ivanov, J., R. D. Miller, N. Stimac, R. F. Ballard, J. B. Dunbar, and S. Smullen, 2006b, Time-lapse seismic study of levees in southern New Mexico: 76th Annual International Meeting, SEG, Expanded Abstracts, 3255–3259.

Ivanov, J., R. D. Miller, J. Xia, J. B. Dunbar, and S. L. Peterie, 2010, Refraction nonuniqueness studies at levee sites using the refraction-tomography and JARS methods, *in* R. D. Miller, J. D. Bradford, and K. Holliger, eds., Advances in near-surface seismology and ground-penetrating radar: SEG, 327–338.

Ivanov, J., R. D. Miller, J. H. Xia, D. Steeples, and C. B. Park, 2006c, Joint analysis of refractions with surface waves: An inverse solution to the refraction-traveltime problem: Geophysics, **71**, no. 6, R131–R138, http://dx.doi.org/10.1190/1.2360226.

Ivanov, J., C. B. Park, R. D. Miller, and J. Xia, 2000a, Mapping Poisson's ratio of unconsolidated materials from a joint analysis of surface-wave and refraction events: 13th Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), EEGS, Extended Abstracts, 11–19.

DOI http://dx.doi.org/10.1190/segam2014-0887.1

Ivanov, J., C. B. Park, R. D. Miller, J. Xia, J. A. Hunter, R. L. Good, and R. A. Burns, 2000b, Joint analysis of surface-wave and refraction events from river-bottom sediments: 70th Annual International Meeting, SEG, Expanded Abstracts, 1307–1310.

Ivanov, J., G. Tsoflias, R. D. Miller, and J. Xia, 2009, Practical aspects of MASW inversion using varying density: 22nd Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), EEGS, Extended Abstracts, 171–177.

Kaufmann, R. D., J. H. Xia, R. C. Benson, L. B. Yuhr, D. W. Casto, and C. B. Park, 2005, Evaluation of MASW data acquired with a hydrophone streamer in a shallow marine environment: Journal of Environmental & Engineering Geophysics, **10**, no. 2, 87–98, http://dx.doi.org/10.2113/JEEG10.2.87.

King, E. C., and E. P. Jarvis, 2007, Use of shear waves to measure Poisson's ratio in polar firn: Journal of Environmental & Engineering Geophysics, **12**, no. 1, 15–21, http://dx.doi.org/10.2113/JEEG12.1.15.

Luo, Y. H., J. H. Xia, R. D. Miller, Y. X. Xu, J. P. Liu, and Q. S. Liu, 2009, Rayleigh-wave mode separation by high-resolution linear Radon transform: Geophysical Journal International, **179**, no. 1, 254–264, http://dx.doi.org/10.1111/j.1365-246X.2009.04277.x.

Miller, R. D., T. S. Anderson, J. Ivanov, J. C. Davis, R. Olea, C. Park, D. W. Steeples, M. L. Moran, and J. Xia, 2003, 3-D characterization of seismic properties at the smart weapons test range, YPG: 73rd Annual International Meeting, SEG, Expanded Abstracts, 1195–1198.

Miller, R. D., J. Xia, C. B. Park, J. C. Davis, W. T. Shefchik, and L. Moore, 1999a, Seismic techniques to delineate dissolution features in the upper 1000 ft at a power plant site: 69th Annual International Meeting, SEG, Expanded Abstracts, 492–495.

Miller, R. D., J. Xia, C. B. Park, and J. M. Ivanov, 1999b, Multichannel analysis of surface waves to map bedrock: The Leading Edge, **18**, 1392–1396, http://dx.doi.org/10.1190/1.1438226.

Palmer, D., 1981, An introduction to the generalized reciprocal method of seismic refraction interpretation: Geophysics, **46**, 1508–1518, http://dx.doi.org/10.1190/1.1441157.

Park, C. B., R. D. Miller, and J. Xia, 1998, Imaging dispersion curves of surface waves on multi-channel record: 68th Annual International Meeting, SEG, Expanded Abstracts, 1377–1380.

Park, C. B., R. D. Miller, J. Xia, J. Ivanov, G. V. Sonnichsen, J. A. Hunter, R. L. Good, R. A. Burns, and H. Christian, 2005, Underwater MASW to evaluate stiffness of water-bottom sediments: The Leading Edge, **24**, 724–728, http://dx.doi.org/10.1190/1.1993267.

Piatti, C., L. V. Socco, D. Boiero, and S. Foti, 2013, Constrained 1D joint inversion of seismic surface waves and P-refraction traveltimes: Geophysical Prospecting, **61**, 77–93, http://dx.doi.org/10.1111/j.1365-2478.2012.01071.x.

Ryden, N., C. B. Park, P. Ulriksen, and R. D. Miller, 2004, Multimodal approach to seismic pavement testing: Journal of Geotechnical and Geoenvironmental Engineering, **130**, no. 6, 636–645, http://dx.doi.org/10.1061/(ASCE)1090-0241(2004)130:6(636).

Socco, L. V., S. Foti, and D. Boiero, 2010, Surface-wave analysis for building near-surface velocity models — Established approaches and new perspectives: Geophysics, **75**, no. 5, 75A83–75A102.

Song, Y. Y., J. P. Castagna, R. A. Black, and R. W. Knapp, 1989, Sensitivity of near-surface shear-wave velocity determination from Rayleigh and Love waves: 59th Annual International Meeting, SEG, Expanded Abstracts, 509–512.

DOI http://dx.doi.org/10.1190/segam2014-0887.1

Steeples, D., and R. Miller, 1990, Seismic reflection methods applied to engineering, environmental, and groundwater problems, *in* S. H. Ward, ed., Geotechnical and environmental geophysics vol. 1: SEG, 1–30.

Suto, K., 2013, MASW surveys in landfill sites in Australia: The Leading Edge, **32**, 674–678, http://dx.doi.org/10.1190/tle32060674.1.

Tsoflias, G. P., J. Ivanov, S. Anandakrishnan, and R. D. Miller, 2008, Use of active source seismic surface waves in glaciology: 21st Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), EEGS, Extended Abstracts, 1240–1243.

Waite, W. F., M. B. Helgerud, A. Nur, J. C. Pinkston, L. A. Stern, S. H. Kirby, and W. B. Durham, 1995, Laboratory measurements of compressional and shear wave spreads through methane hydrate: 3rd International Conference on Gas Hydrates, Preprint UCRL-JC-136096, accessed 10 June 2014, www.e-reports-ext.llnl.gov/pdf/236814.pdf.

Xia, J., R. D. Miller, and C. B. Park, 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: Geophysics, **64**, 691–700, http://dx.doi.org/10.1190/1.1444578.

Xia, J., R. D. Miller, C. B. Park, J. A. Hunter, and J. B. Harris, 1999, Evaluation of the MASW technique in unconsolidated sediments: 69th Annual International Meeting, SEG, Expanded Abstracts, 437–440.

Xia, J., R. D. Miller, C. B. Park, J. A. Hunter, and J. B. Harris, 2000, Comparing shear-wave velocity profiles from MASW with borehole measurements in unconsolidated sediments, Fraser River Delta, B.C., Canada: Journal of Environmental and Engineering Geophysics, **5**, no. 3, 1–13, http://dx.doi.org/10.4133/JEEG5.3.1.

Xia, J., R. D. Miller, C. B. Park, and G. Tian, 2002, Determining *Q* of near-surface materials from Rayleigh waves: Journal of Applied Geophysics, **51**, no. 2-4, 121–129, http://dx.doi.org/10.1016/S0926-9851(02)00228-8.

Xia, J., C. Shen, and Y. Xu, 2013, Near-surface shear-wave velocities and quality factors derived from high-frequency surface waves: The Leading Edge, **32**, 612–618, http://dx.doi.org/10.1190/tle32060612.1.

Xia, J., Y. X. Xu, R. D. Miller, and J. Ivanov, 2012, Estimation of near-surface quality factors by constrained inversion of Rayleigh-wave attenuation coefficients: Journal of Applied Geophysics, **82**, 137–144, http://dx.doi.org/10.1016/j.jappgeo.2012.03.003.

Zhang, J., and M. N. Toksöz, 1998, Nonlinear refraction traveltime tomography: Geophysics, **63**, 1726–1737, http://dx.doi.org/10.1190/1.1444468.

DOI http://dx.doi.org/10.1190/segam2014-0887.1