Surface wave analysis sensitivity to assumptions in a-priori information

Julian Ivanov, Richard D. Miller, Anthony M. Hoch, Shelby L. Peterie, and Sarah Morton, Kansas Geological Survey*

Summary

We used multi-channel analysis of surface waves (MASW) to appraise Vs inversion sensitivity to variability and accuracy in a-priori information. We used a relatively wide range of Poisson's ratio values (0.25-0.467) to estimate initial Vp models, update the Vp or Poisson's ratio model during the inversion, and three density trend patterns to test more than 24 scanarios of a-priori information usage and evaluate its impact on final Vs inversion results. The biggest differences in the final 2D Vs estimates were observed between models with the smallest, 0.25, Poisson's ratio and the smallest between models with the largest, 0.467 Poisson's ratio. Vs values from using Poisson's ratio models of 0.25 versus 0.467 were also notably different. The observations made with accurate a-priori information may be have less of-an-effect on sites with Poisson's ratios equal or greater than 0.467, but have increasing importance as Poisson's ratio decreases from 0.467 to 0.25. These findings could be significant to both the applied applications and reasearch on the seismic surface wave method.

Introduction

The MASW method was initally developed 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., 1999b). Shear-wave velocities estimated using MASW have been reliably and consistently correlated with drill data. Using the MASW method, (Xia et al., 2000) noninvasively measured Vs were observed to be 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., 1999a). Applications of the MASW method have been extended to include 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 surface wave methods (SWM) can be found in Socco et al. (2010) and ample textbook information can be found in (Foti et al., 2015). 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), evaluation at landfill sites (Suto, 2013), and the use of the high resolution linear Radon transform (Ivanov et al., 2017a) to improve both the horizontal and linear resolution of the final 2D Vs models (Ivanov et al., 2017b).

The MASW method includes the following steps. A single seismic-data record (a.k.a. shot gather) is acquired. These data are 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., 1999b). 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.

MASW dispersion-curve inversion for Vs is commonly performed using predefined values for compressional-wave velocity (Vp) and density. It is recommended and assumed that such a-priori information is available and accurate from other measurements. However, practical MASW applications often lack this type of information and as a result the Vp and density estimates are determined based on vague a-priori information knowledge and/or assumptions for each specific site. It has been postulated that the resulting errors in the Vs estimates from using parameter assumptions are insignificant.

However, efforts to estimate Vs inversion errors due a-priori information inaccuracies have been relatively limited. Xia et al. (1999b) showed that a 25% increase in Vp resulted in less than 3% average change in the dispersion-curve phase-velocity values from forward modeling. Furthermore, forward modeling showed that decreasing the density in the top 2 layers by 25% and increasing it in the rest of the layers by 25% resulted in average Vs change of less than 10%. Impacts of accurate density information on inversion results were more closely evaluated on a range of models and real world data (Ivanov et al., 2016). The use of direct density measurements from well core in the initial model reduced almost half of the Vs values by approximately 10–11% (mostly at mid-depths) and a few by more than 17% in comparison to using constant density. More importantly, it was noticed that using accurate density trends can change the structural appearance of the final 2-D Vs sections, thus leading to different site interpretations. One of the valuable observations from this research effort was that it was not the actual density values that impact the surface

10.1190/segam2019-3216657.1

wave propagation charachteristics but the density ratios (e.g., the density ratios between neighboring layers trends).

It is expected that accurate Vp information estimated from other methods, such as refractions, refraction tomography, uphole survey, etc.is used for surface wave inversion. In the absence of such a-priori information it is possible to use Poisson's ratio assumptions about a particular site (e.g., 0.4 for a very near surface site) and calculate initial Vp models from the initial Vs model obtained from estimated surface-wave dispersion curve values. Next, however, keeping such an initial Vp model fixed during the inversion may lead to unrealistic Poisson's ratio values after obtaining the final Vs estimates. Consequently, to avoid such numerical possibilities, an approach of keeping Poisson's ratio fixed during the inversion can be adopted, i.e., the Vp model is updated with every inversion iteration.

In this research effort we used 20 seismic records from a selected site set to estimate Vs inversion variations resulting from using a relatively wide range of a-priori information possibilities that represent a reasonable scenario in real-world applications of the surface-wave method.

Poisson's ratio values of 0.25, 0.33, 0.4, and 0.467 (corresponding to Vp/Vs ratios of 1.73, 2.0, 2.5, and 4.0) were selected in efforts to cover a wider range of real-world possibilities.

We also used three types of density models. The first type employed a constant of 1.8 g/cm^3 for the whole 2D section, the second applied density values linearly increasing with depth from 1.55 to 2.0 g/cm^3. An increasing with depth density trend appears more appropriate in view of the geologic processes taking place within the very near surface; such as compaction, desiccation, etc. As a result, such a density assumption could increase the likelihood of obtaining more accurate final results. The third type involved Gardner's equation to obtain density values from the Poisson's- ratio-derived initial Vp model.

The above mentioned numbers lead to 12 combinations of Vp and density initial model pairs. Each one was inverted once using a fixed Vp and once using a fixed Poisson's ratio during the inversion step, thereby resulting in 24 2D Vs results.

Data

Seismic data were collected at Garland, Michigan. The near-surface geology of the area is known to be dominated by glacial till with some suggestions of boulders. Data were recorded using a Geometrics StrataView seismograph, 48channels, and 4.5-Hz geophones. Geophone spacing was 0.6m and the source offset was 12 m. We processed the data using SurfSeis software developed by the Kansas Geological Survey. The MASW technique was applied by obtaining a dispersion curve image from each seismic record, on which a dispersion curve of the fundamental mode of the Rayleigh wave was estimated. On some of the images the fundamental mode of the surface wave was well defined within a wide frequency range of about 12 to 70 Hz (images not shown for brevity). Dispersion curves were picked and saved to be used for inversion for Vs with depth.

Results

For each a-priori information scenario all 20 1D Vs inversion results were inverted and assembled into a corresponding 2D Vs image (Figure 1 and 2). Inversion was performed using stopping criteria of 1.5 m/s RMS (i.e., fit between the observed and calculated dispersion curve) and maximum of 5 iterations for most of the inversion sets. Inversions that used Poisson's ratio values of 0.25 required 10-15 iterations to converge to low RMS values.

For this particular data set the greatest Vs variations (up to 22%) can be observed between models that used fixed Vp (Figure 1a) vs fixed Poisson's ratio (Figure 1d) at constant density and Poisson's ratio 0.25. Such Vs variations decreased as adopted Poisson's ratios increased to 0.467 (e.g, Figure 1g vs Figure 1j and Figure 2a vs Figure 2b). It can be noticed that 2D Vs image from 0.25 Poisson's ratio are notably different compared to those from 0.467 Poisson's ratio. The diffence is smaller, Figure 1 a)-c) vs Figure 2 g)-i), or greater, Figure 1 d)-f) vs Figure 2 j)-l), depending on using Vp or Poisson's ratio fixed during the inversion. All 6 2D Vs results from using 0.467 Poisson's ratio were almost identical Figure 2 g)-l) . The difference for the most part was within 1-2 % and for a very few spots up to 9%. Vs variations due to different density models were most notable with fixed 0.25 Poisson's ratio Figure 2 d)-f).

Conclusions

Vs inversion findings from these data indicate that Vs result can be almost insensitive to Vp and density a-priori information accuracy for sites with Poisson's- ratio values of 0.467 (and higher) and become more and more different from those values as Poisson's- ratio decreases to 0.25.

Although a-priori information Vs variations may differ with other data sets, we hypothesize simillar variation patterns. Consequently, the demand for accurate a-priori information for a specific site may be high or low depending on the expected Poisson's ratio, 0.25 or 0.467 respectively.

Acknowledgments

We are thankful to our field crew for the help with data acquisition. We also appreciate Mary Brohammer for her assistance in manuscript preparation.

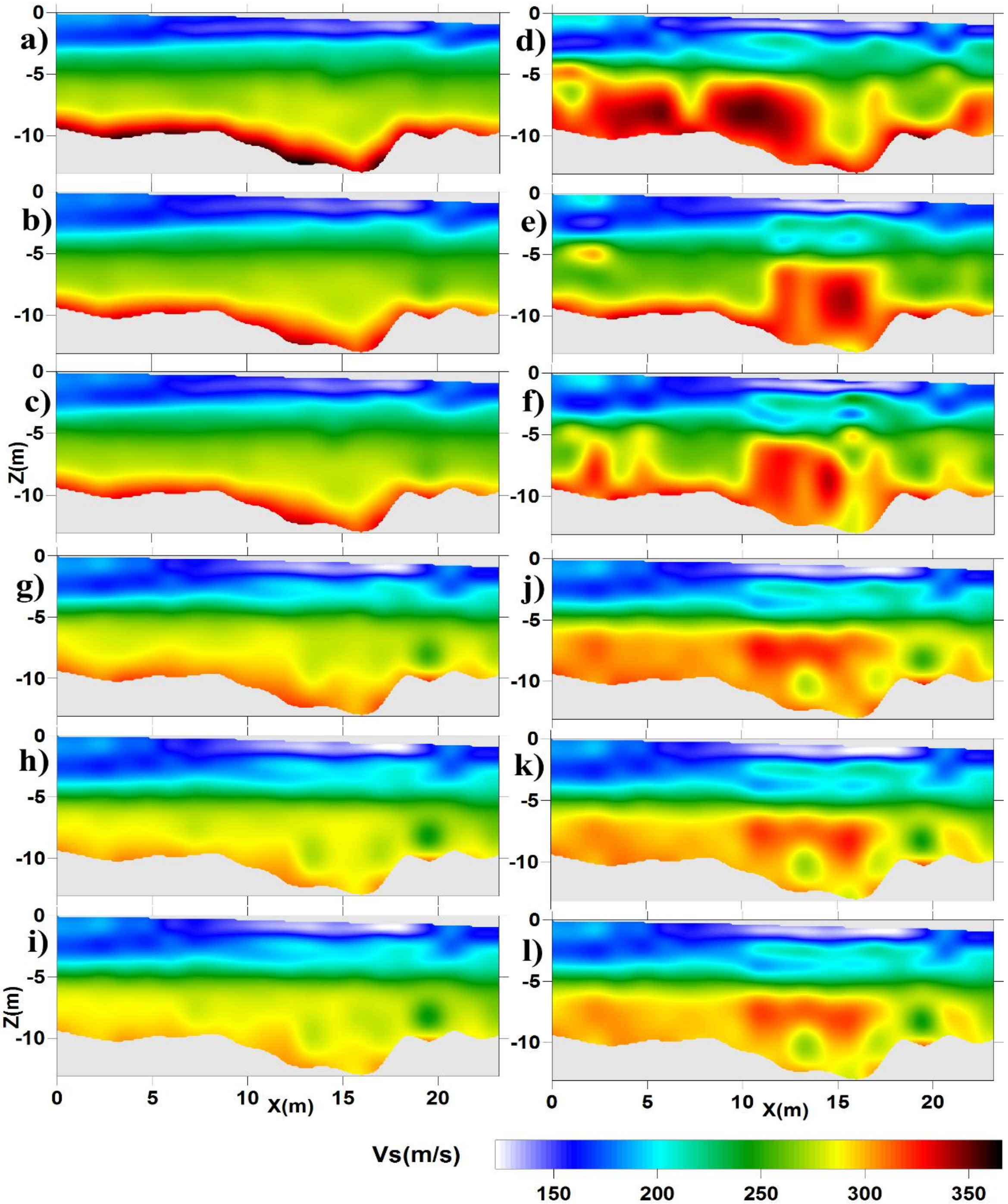

Figure 1. Vs inversion results from using initial Vp model derived from Poisson's ratio of 0.25 a)-f) and 0.33 g)-l) (i.e., top and bottom halves). Result on the left a)-c) and g)-k) were obtained by keeping the initial Vp model constant during the inversion and on the right d)-f) and h)-l) by keeping Poisson's ratio constant during the inversion. The density model used constant values for rows 1 and 4, i.e., a), b), g), and h); increased with depth rows 2 and 5, i.e., c), d), i), and j); and was derived from Vp rows 3 and 6, i.e., e), f), k), and l).

10.1190/segam2019-3216657.1

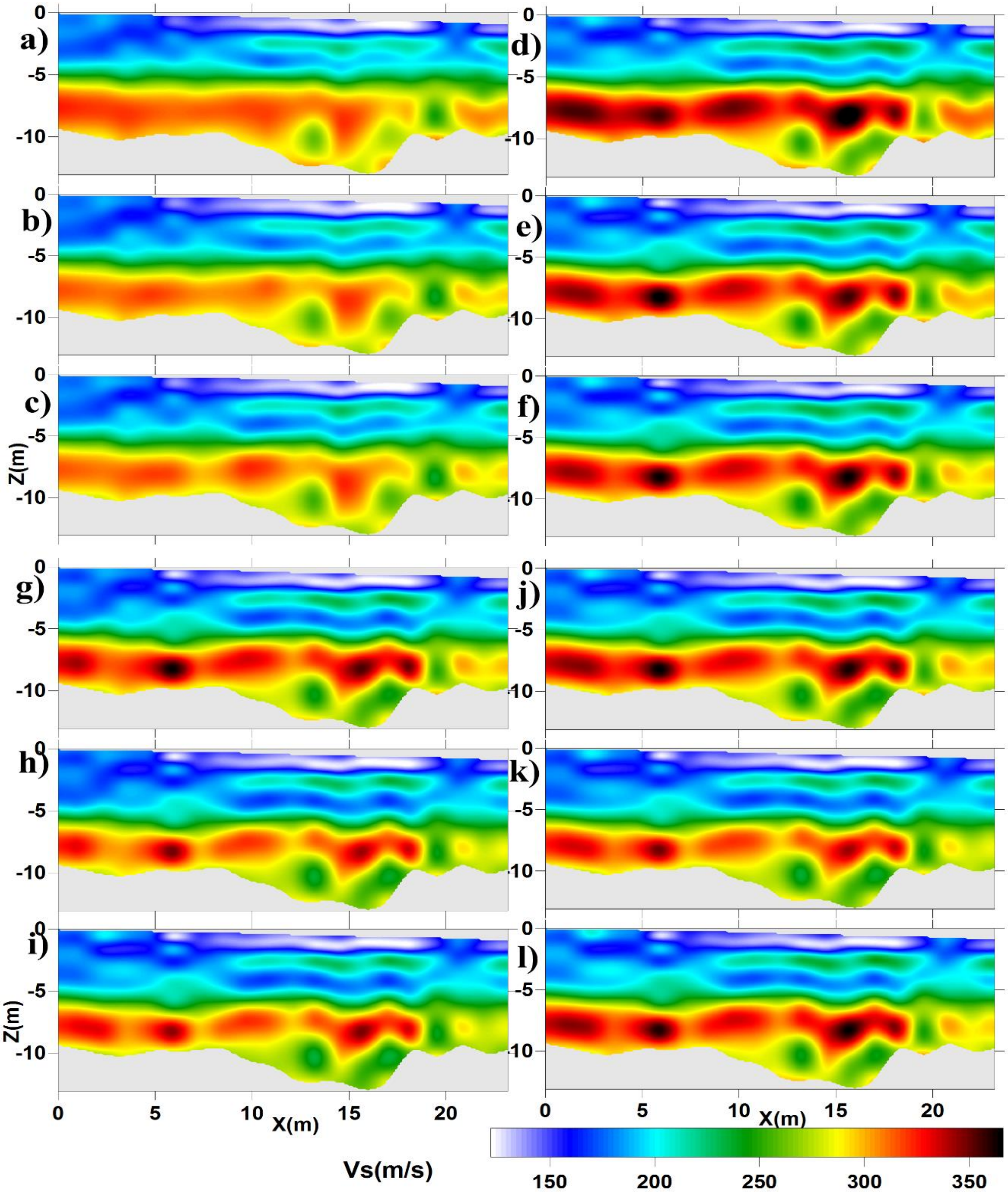

Figure 2. Vs inversion results from using initial Vp model derived from Poisson's ratio of 0.4 a)-f) and 0.467 g)-l) (i.e., top and bottom halves). Results on the left, a)-c) and g)-k), were obtained by keeping the initial Vp model constant during the inversion and on the right, d)-f) and h)-l), by keeping Poisson's ratio constant during the inversion. The density models used were constant values for rows 1 and 4, i.e., a), b), g), and h); increased with depth for rows 2 and 5, i.e., c), d), i), and j); and were derived from Vp for rows 3 and 6, i.e., e), f), k), and l).

10.1190/segam2019-3216657.1

REFERENCES

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, doi: https://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, doi: https://doi.org/10.1190/tle32060638.1.

Foti, S., G. L., Carlo, G. J., Rix, and C., Strobbia, 2015, Surface Wave Methods for Near-Surface Site Characterization: CRC Press.

Ivanov, J., R., Miller, D., Feigenbaum, and J., Schwenk, 2017a, Benefits of using the high-resolution linear Radon transform with the multichannel analysis of surface waves method: 87th Annual International Meeting, SEG, Expanded Abstracts, 2647–2653, doi: https://doi.org/10.1190/segam2017-17793766.1.

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, 23, 1413–1416, doi: https://doi.org/10.4133/1.2924728.

Ivanov, J., R. D., Miller, D., Feigenbaum, S. L. C., Morton, S. L., Peterie, and J. B., Dunbar, 2017b, Revisiting levees in southern Texas using Love-wave multichannel analysis of surface waves with the high-resolution linear Radon transform: Interpretation, **5**, no. 3, T287–T298, doi: https://doi.org/10.1190/INT-2016-0044.1.

Ivanov, J., R. D., Miller, P., Lacombe, C. D., Johnson, and J. W., Lane, 2006a, Delineating a shallow fault zone and dipping bedrock strata using multichannel analysis of surface waves with a land streamer: Geophysics, **71**, no. 5, A39–A42, doi: https://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 **15**, 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, doi: https://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: Symposium on the Application of Geophysics to Engineering and Environmental Problems, **13**, 11–19, doi: https://doi.org/10.4133/1.2922727.

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, 19, 1307–1310, doi: https://doi.org/10.1190/1.1815636.

Ivanov, J., G., Tsoflias, R. D., Miller, S., Peterie, S., Morton, and J., Xia 2016, Impact of density information on Rayleigh surface wave inversion results: Journal of Applied Geophysics, **135**, 43–54, doi: https://doi.org/10.1016/j.jappgeo.2016.09.011.

Ivanov, J., G., Tsoflias, R. D., Miller, and J., Xia, 2009, Practical Aspects of MASW Inversion Using Varying Density: Symposium on the Application of Geophysics to Engineering and Environmental Problems, **22**, 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 and Engineering Geophysics, **10**, 87–98, doi: https://doi.org/10.2113/JEEG10.2.87.

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**, 254–264, doi: https://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, 3D characterization of seismic properties at the smart weapons test range, YPG: 73rd Annual International Meeting, SEG, Expanded Abstracts, 22, 1195–1198, doi: https://doi.org/10.1190/1.1817493.

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, 18, 492–495, doi: https://doi.org/10.1190/1.1821061.

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, doi: https://doi.org/10.1190/1.1438226.

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, doi: https://doi.org/10.1190/1.1820161.

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, doi: https://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, doi: https://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**, 636–645, doi: https://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, doi: https://doi.org/10.1190/1.3479491.

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, 8, 509–512, doi: https://doi.org/10.1190/1.1889669.

Suto, K., 2013, MASW surveys in landfill sites in Australia: The Leading Edge, **32**, 674–678, doi: https://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: Symposium on the Application of Geophysics to Engineering and Environmental Problems, 21, 1240–1243.

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

Xia, J., R. D., Miller, C. B., Park, J. A., Hunter, and J. B., Harris, 1999a, Evaluation of the MASW technique in unconsolidated sediments: 69th Annual International Meeting, SEG, Expanded Abstracts, 437–440, doi: https://doi.org/10.1190/1.1821046.

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**, 1–13, doi: https://doi.org/10.4133/JEEG5.3.1.

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, doi: https://doi.org/10.1190/tle32060612.1.

10.1190/segam2019-3216657.1