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Analysis of Active MASW Test Data for a Convergent Shear Wave Velocity Profile

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ABSTRACT: Shear wave velocity is a direct indicator of stiffness of an isotropic medium which is frequently used to represent the subsurface stratification. Non-invasive seismic survey like Multichannel Analysis of Sur-face Waves (MASW), in both active and passive forms, is widely used in professional practice due to its rapid implementation. Various stages in analysis viz. preprocessing (muting, filtering, etc.), obtaining dispersion curve and inversion govern the accuracy and reliability of final shear wave velocity profile. This paper high-lights the effects of several factors involved in each stage of analysis. Active MASW tests were conducted at a test site with a particular test configuration and the recorded data were analyzed using SurfSeis. The conver-gence study for contributory factors at every stage is carried out for the reliable results. The efficacy of the in-version procedure is highlighted without any a-priori information on the site subsurface stratigraphy.

1 INTRODUCTION

The application of geophysical methods for geotechnical purposes has been appreciated from a few decades. The seismic survey methods which use seismic or elastic waves viz. P-waves, S-waves, Rayleigh waves etc. has their trademark in this area due to its rapid implementation and low cost methodologies. Seismic methods utilize the elastic properties of the medium such as Lame's parameters, shear modulus and elastic modulus to define the wave propagation in the medium. The behavior of waves is delineated to trace back the mechanical properties of the medium. Multichannel Analysis of Surface Waves (MASW) is one of the trending non-invasive seismic method which use the dispersive characteristics of the surface waves with a multi receiver approach for the stratification of, mostly, the assumed vertically heterogeneous subsurface conditions. Active and passive MASW are different forms which are classified based on the source considered for the generation of surface waves (Park *et al.* 1999). MASW was developed over other former surface wave methods of similar approach. They are steady state vibration method (Jones 1955) and spectral analysis of surface waves (Heisey *et al.* 1982). Any application of surface wave methods, including MASW, typically consists of three stages. They are data acquisition, dispersion analysis and inversion. Each stage is dependent on the previous. Data acquisition is related to the acquiring of the response of the subsurface particles due to the energy transmitted. A linear array of 12 or more receivers convert the particle vibration into electric voltage at respective locations. Typically, equipment required for active MASW testing include a sledge hammer as source of energy, geophones as receivers and data acquisition system to qualify and store the acquired data. It is a basic assumption that the subsurface is transversely homogeneous. As wave propagates a lag is expected from one receiver to the next. Dispersion is a property of surface waves that is defined as the dependence of phase velocity on the frequency. In the other words, wave of a particular frequency originating from the source point will traverse certain depth and passes through certain number of layers. The propagation velocity of that particular frequency of wave is decided by the mechanical properties of the layers it traversed through. In this manner, different frequencies are expected to have different phase velocities owing to the fact that they travel through different number of layers. This variation of phase velocity with frequency is called as dispersion (Park *et al.* 1998). Due to reasons such as stiffness reversals and lateral heterogeneities, a wave of a particular frequency may be observed to possess more than one phase velocity. This possession describes the phenomenon of multimodal dispersion (Xia et al 2000). In dispersion imaging scheme, the normalized amplitude is imaged on a 2D plane of phase velocity and frequency. Theoretical dispersion curve obtained from any of the methods available (Ke *et al.* 2011) is optimized towards experimental dispersion curve such that RMS error is minimum. This theoretical dispersion curve is optimized towards the experimental dispersion curve by updating the model properties such that the RMS error will be minimal, which is achieved through sequential and iterative model parameter updating scheme. The model which lead to the optimized theoretical dispersion curve is decided to be the final model which will be further used to obtain the subsurface stratigraphy profile

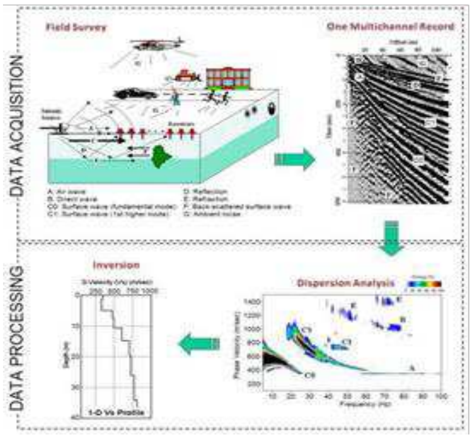


Figure 1. Overall procedure of MASW survey

There are many software available for data analysis i.e. dispersion analysis and inversion. SurfSeis, EasyMASW and Geopsy are the most prominent software available. The present study is based on active MASW tests carried out at Indian Institute of Technology Guwahati, India. The aim of this article is to highlight few of the most important parameters that govern each and every step of the testing and analysis. In the present study, SurfSeis is considered for the analysis. This is a commercially available software developed by Kansas Geological Society. This software is equipped to analyze both 1-D and 2-D data. In the present study, SurfSeis v3.45 is used for the analysis. From the literature and also the software tool methodology, it can be understood that many governing parameters are available. An attempt to decide the parameter or methodology to be considered during testing and analysis such that the solution converges is dealt and reported in this article. Commencing from the time sampling parameters in the field testing to the modeling parameters in inversion, crucial steps had been discussed elaborately. Few of the parameters that are exclusively available during analysis with SurfSeis viz. depth conversion ratio are also discussed. Most of the flaws that are more prone to happen involuntarily especially with SurfSeis are discussed.

2 DATA ACQUISITION DETAILS

2.1 *Site Details*

The study site is located at Indian Institute of Technology Guwahati, India. The site is used as cricket field. The latitude and longitude of the test site are 26.190494^0 and 91.696658^0 respectively. Next to the site, a lake is observed and so the ground water table is expected to be very near to the surface. Available bore logs at the site showed that the water table is at 1.5 to 2m from the ground surface. Other information available regarding the site is that the subsurface mostly contained silty clay and clays.

Figure 2. Satellite image of testing site location

2.2 *Testing Details*

Active MASW testing was conducted at the site specified above. A 10 kg sledge hammer with a steel base plate is used as source of energy. 4.5Hz geophones are used as receivers and a 24 bit data acquisition system is used for acquiring data. Figure 3 shows the linear array of geophones used for testing. Time sampling details of the testing include sampling frequencies of varied range are used for the convergence analysis. 500 Hz, 3750 Hz and 7500 Hz data is extracted at 5120 number of samples. Park *et al.* (2001, 2002) and Zhang *et al.* (2004) are few of the informative documents available for deciding the optimum field parameters. However such optimum parameters are observed to be site dependent. A receiver spacing of 2m was adopted with 24 number of receivers which makes as spread length of 46m. Foti el al. (2015) reported that the availability of a powerful preprocessing tool can sufficiently allow for a nominal near offset distance which efficiently overcomes the possibility of losing surface wave data with extremely larger near offset distances. Hence in the present study, a distance of 4m was used.

Figure 3. Linear array of geophones

2.3 *Time Sampling Parameters*

Time sampling parameters include number of data points to be recorded and sampling frequency. The ratio of number of samples to sampling frequency determines the recording time. The recording time needed depends on the site characteristics. Stiffer stratum lets the wave propagate faster than loose stratum, and hence requires lesser time of acquisition. The effect of the said time sampling parameters can be clearly observed from the amplitude spectra and phase spectra of the data. For 5120 number of samples, the effects of three different sampling frequencies (500 Hz, 3750 Hz and 7500 Hz) are shown in Figure 4 and 5. It can be observed that the total frequency content ranges from 5 Hz to 180 Hz though the effective range may be substantially smaller than this. Within this range the variability generated for the 500 Hz condition is far different from the other two scenarios. This spectrum is found to be very unclear and noisy unlike the other two cases. Similar behavior can be observed in the normalized phase spectrum as well. In comparison to the 500 Hz case, the 7500 and 3750 Hz cases have a nearly linear phase without much distortion. Based on these observations, 7500 Hz sampling frequency was selected for further study. It was observed that the effect of number of samples is negligible on both the phase and amplitude spectra of the data. This is evident from the spectrum of the 7500 Hz sampled data with different samples (5120, 10240 and 20480). All the three conditions are compared and are shown in Figure 6 and 7. In the absence of any substantial variation, in order to maintain the recording to be minimum of 600ms, 5120 number of samples is considered for the testing, choice of which lead to an actual recording time of 683ms.

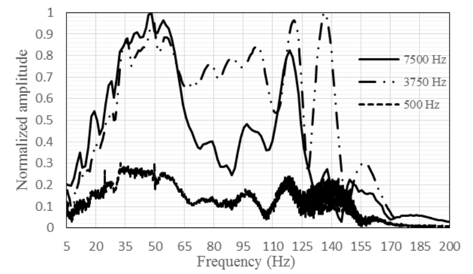


Figure 4. Normalized amplitude spectrum (different sampling frequency)

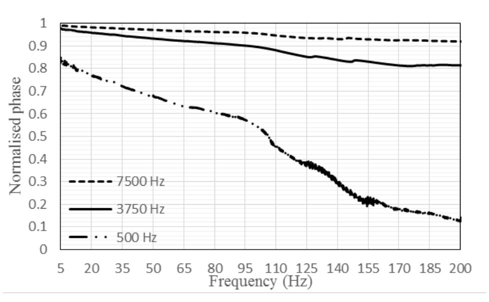


Figure 5. Normalized phase spectrum (different sampling frequency)

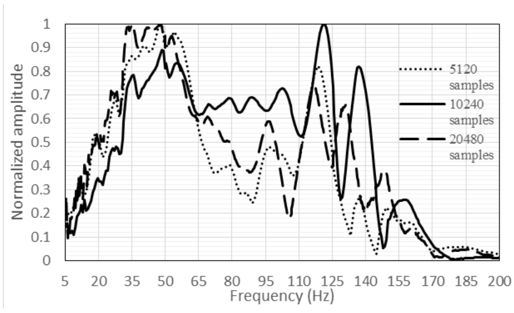


Figure 6. Normalized amplitude spectrum (different samples)

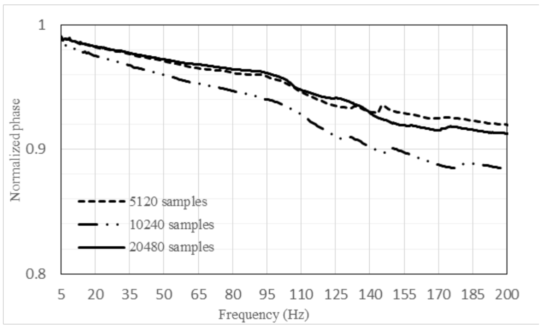


Figure 7. Normalized phase spectrum (different samples)

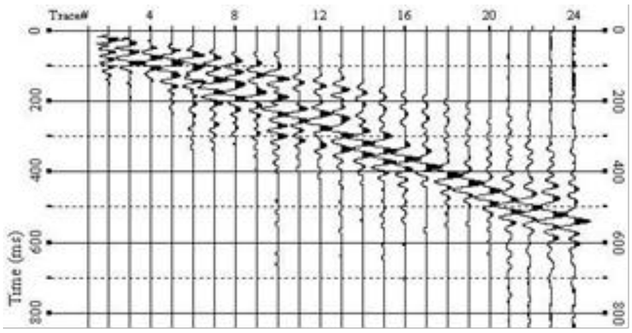


Figure 8. Raw wave field

3 DATA ANALYSIS AND DISCUSSIONS

3.1 *Preprocessing – Muting and Filtering*

Before the development of dispersion image, the raw wave field as in Figure 8 has to be groomed to create a dispersion image of high resolution. This renders the task of extraction of dispersion image (i.e. selection of high amplitude points) more subtle. Muting is one of the preprocessing task which is aimed at muting down the body wave intrusions and other low amplitude noises in the wave field. Muting is performed by selecting a slope on the wave field, above and below of which the events will be muted for top and bottom muting, respectively. In case of higher modes in the wave field, muting has to be carefully done. Filtering is another preprocessing task that is most common in any signal processing applications. The raw wave field is expected to contain both coherent and incoherent noise intruded into the wave field. This can be observed from the irregularities in amplitude and phase spectrum. Filtering reduces the noise in the signal i.e. increases signal to noise ratio. In SurfSeis, four kinds of filtering are possible viz. low cut, high cut, band stop and band pass. Filtering is done based on the response of the amplitude spectrum to the applied filter. Figure 4 shows that the amplitude spectra for all the cases seem to possess effective content in 5 Hz to 90 Hz. Hence a band pass filter should be perfect for the case. After top and bottom muting and applying a band pass filter of 5-30-60-90 Hz specifications, the wave field appears to be as shown in Figure 9. The effect of preprocessing on the dispersion image can be checked and if any changes are required, the preprocessing can be manipulated at any time.

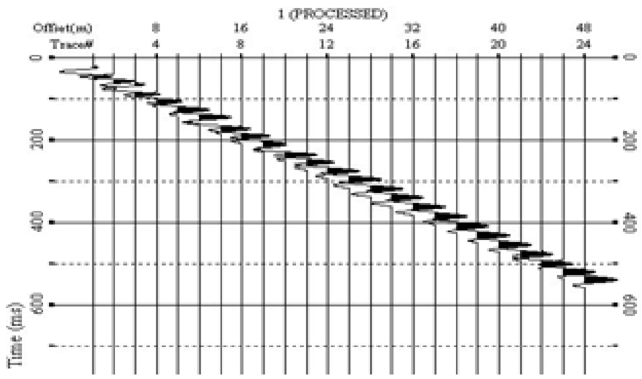


Figure 9. Wave field after preprocessing

3.2 *Dispersion Curve Extraction*

Dispersion image is a three dimensional variation of frequency and phase velocity with summed amplitudes over all the offsets. Generally the amplitudes are normalized and a contour of energy on the frequency-phase velocity plane is considered to be dispersion image. The points of maximum amplitude are selected and inversion is carried out. There are few precautions that are needed to be taken care while extracting the data points. Based on the spread length and the receiver spacing, the respective maximum and minimum wavelengths to be considered for inversion analysis are decided. For the present study the maximum waveleng th of 46 m and minimum wavelength of 2 m. The values are expected to be within this range but not out of the bounds. The data points for inversion are to be selected with in this range for reliable and practically possible results. Within the desired wavelength range peak amplitude points are selected for inversion. Two cases are presented here for understanding the criticality in proper selection of data points. A regular and smooth curve is extracted in one case (Case -1) and an irregular curve is extracted in another case (Case – 2). All the further analyses are carried out for both these cases. The typical dispersion curves and data points selected on them are shown in Figures 10 and 11 respectively. In both the cases the maximum and minimum wave lengths are 38.94m and 5.35m, respectively.

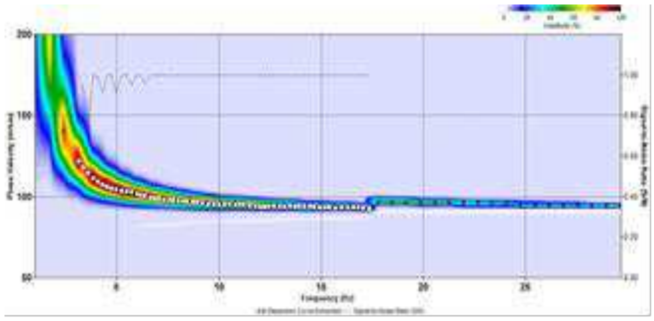


Figure 10. Dispersion curve extraction - smooth trend (Case-1)

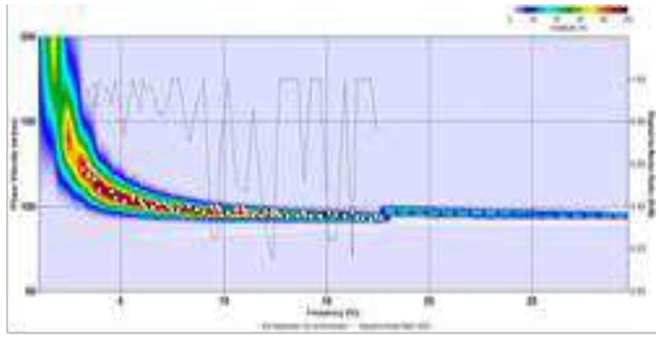
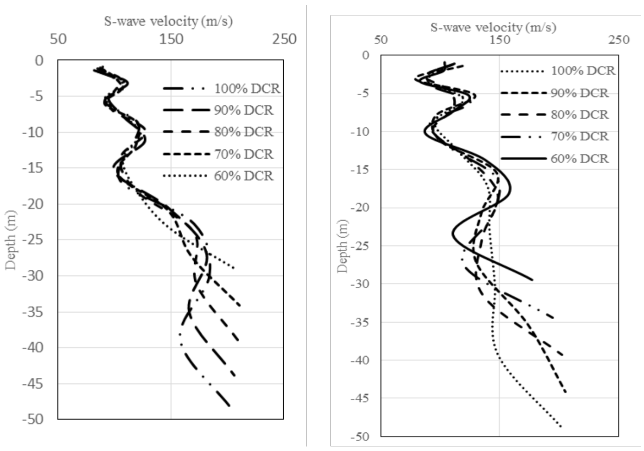


Figure 11. Dispersion curve extraction – irregular trend (Case-2)

3.3 *Inversion Process*

Depth conversion ratio (in percentage) determines the ratio between the wavelength and its corresponding depth of analysis. A 100% DCR indicates that the depth of half-space is equal to maximum wavelength available. A 0% DCR indicates automatic selection of modeling as per Park *et al.* (1999). Hence the variation of final shear wave velocity profiles with different DCR values are compared. All the analyses are carried out with a default 10 layer model in SurfSeis. The RMS errors with respect to phase velocity for each variation in DCR is plotted. Figure 12a and 12b show S-wave velocity variation with depth for different DCR values for case-1 and case-2 dispersion curves, respectively. DCR values from 100% to 60%, which includes practically possible and useful range of depth of analysis are adopted for analysis. In case-1, it can be observed from the figure that all the cases converge up to a depth of around 23m and then variability is seen. But in case-2 the depth decreased to around 12m and even up to 12m, the convergence is not as uniform as seen in case-1. At no depth, the observed variation is more than 10m/s. Owing to Figure 12a, based on the requirement of depth of analysis, any DCR value could be used subject to the condition that the maximum and minimum wavelengths of data points are in comparison with the field configuration adopted. DCR values which represent lesser depths i.e. less than 50% show unacceptable results. This is shown with respect to the RMS error associated as in Figure

13. The figure depicts that for a given change in the initial model (represented in terms of the DCR value), lesser change in the final model is expected which is possible with proper selection of data points and proper choice of DCR values corresponding to the wavelengths available in the data points for inversion.



(a) (b)

Figure 12. S-wave velocity variation with depth for different DCR (a) Case-1 (b) Case-2

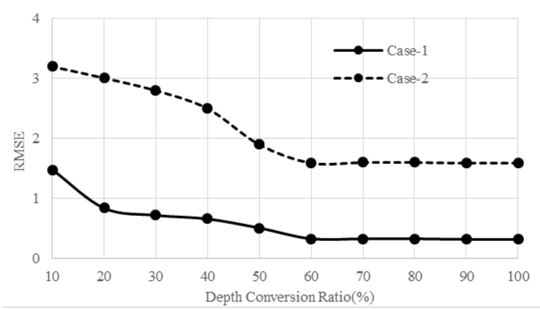


Figure 13. RMSE variation with DCR

In SurfSeis, layer modeling is discontinuous i.e. properties are considered to be constant in each layer of certain thickness. Hence the given depth of half-space will be divided into required number of layers. For the present study, a range from 2 to 20 number of layers are considered in the model for inversion (Maximum and minimum available with SurfSeis). For all the layer conditions 60% DCR is used. From Figure 14, after certain number of layers, there is not much change in the RMSE values and similar was the case with shear wave velocity profiles. Few of the instances are shown in Figure 15a and 15b.

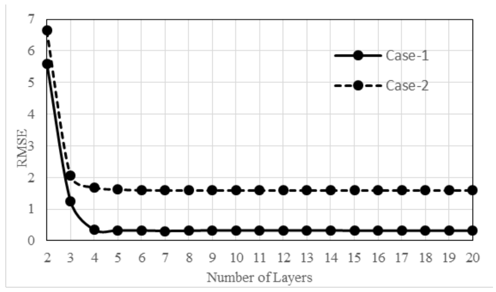
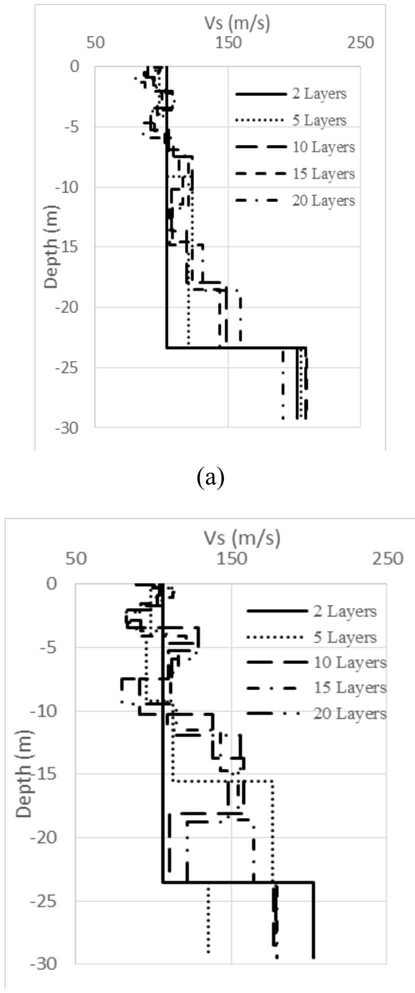


Figure 14. RMSE variation with number of layers

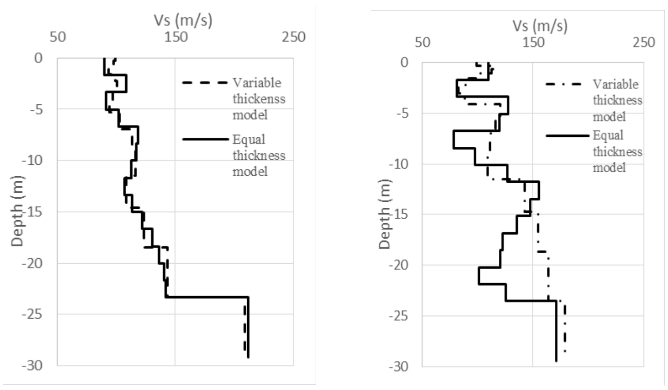


(b)

Figure 15. S-wave velocity variation with depth for different number of layers (a) Case-1 (b) Case-2

When the number of layers are more, there are exists more number of variables and corresponding matrix elements to represent the system accurately. Hence higher number of layers are to be considered for the model though it takes a little more time but acceptable. As expected from the observations in previous section, case-2 has more observed variation than case-1 due to the irregularity in the data points.

Initial models in SurfSeis are generated based on Park *et al.* (1999) as mentioned in manual. Selection of equal thickness model is possible in SurfSeis. The selected depth of half-space will be equally divided into the selected number of layers. For this study, a 60% DCR that corresponds to half-space depth of around 23m and 15 layers are considered. Both variable and equal thickness models are compared as shown in Figure 16 for both case-1 and case-2. It can be observed from Figure 16a that there is not much difference with either of the model. This is due to the proper dispersion curve extraction. Thickness hence has not much influence on the inversion process if and only if the dispersion curve trend is smoother.



(a) (b)

Figure 16. S-wave velocity variation with depth for different thickness models (a) Case-1 (b) Case-2

4 CONCLUSIONS

An attempt was made to understand the influence of various parameters at different stages of MASW testing and analysis with the leverage of one of the robust and sophisticated tool SurfSeis. It was observed that at any number of samples, higher sampling frequencies provided appealing results. However this can further be understood on continuing the analysis up to dispersion image development. During preprocessing, top and bottom muting and then bandpass filtering was observed to be more useful. During the extraction of data points from the dispersion image, selecting the peaks with a regular and smooth trend is very much necessary. The users had to consider the field configuration adopted while selecting the maximum and minimum wavelength points for inversion. If the data points are in the practical limits, any DCR value would give a reliable result and it is up to the user to adopt a particular DCR value. Zero DCR would not always provide accurate results and so required DCR value is to be adopted. Number of layers adopted in the discontinuous model also govern the robustness and uniqueness of the final profile. Greater the number of layers, greater the number of unknowns and equations to solve and so greater will be the convergence. A variable thickness and an equal thickness models are compared at 60% DCR and 15 number of layers. They are almost matching with each other in case of a regular trend, ascertaining that thickness is not an important parameter for inversion. It can be discerned that selection of data points is one of the most critical steps in analysis. A perfectly extracted dispersion curve with regular and smooth trend within the correct wavelength limits would provide a convergent and robust final shear wave velocity profile.

5 REFERENCES

Foti, S., Lai, C.G., Rix, G.J., Strobbia, C. 2015. *Surface Wave Methods for Near-Surface Site Characterization*. Boca Raton: CRC Press.

Heisey, J.S., Stokoe II, K.H., and Meyer, A.H. 1982. *Moduli of pavement systems from Spectral Analysis of Surface Waves.* Transportation Research Record (852): 22-31.

Jones, R. 1955. *A Vibration Method for Measuring the Thickness of Concrete Slab In-Situ.* Magazine of Concrete Research (7): 97-102.

Ke, G., Dong. H., Kristensen, A., and Thompson, M. 2011. *Modified Thomson–Haskell Matrix Methods for Surface-Wave Dispersion-Curve Calculation and Their Accelerated Root-Searching Schemes.* Bulletin of the Seismological Society of America. 110(4):1692-1703.

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

Park, C.B., Miller, R.D., and Xia, J., 1999. *Multichannel analysis of surface waves.* Geophysics:64(3):800-808.

Park, C.B., Miller, R.D., and Xia, J. 2001. *Offset and resolution of dispersion curve in multichannel analysis of surface waves (MASW).* Proceedings of the SAGEEP. Denver.

Park, C.B., Miller, D.M., and Miura, H. 2002. *Optimum field parameters of an MASW survey*. Proceedings of the 6th SEG-J International Symposium. Tokyo:22–23.

Park, C.B., R.D. Miller, J. Xia, and J. Ivanov. 2007. *Multichannel Analysis of Surface Waves (MASW) - Active and Passive Methods.* The Leading Edge. January.

Xia, J., Miller, R.D., and Park, C.B. 1999. *Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves.* Geophysics. 64(3):691-700.

Zhang, S.X., Chan, L.S., and Xia, J. 2004. *The Selection of Field Acquisition Parameters for Dispersion Images from Multichannel Surface Wave Data.* Pure Application Geophysics (161):185-201.