PRACTICAL FOCUSING OF SURFACE-WAVE INVERSION TO IMAGE LEVEES IN SOUTHERN NEW MEXICO

Julian Ivanov, Kansas Geological Survey, Lawrence, KS
Richard D. Miller, Kansas Geological Survey, Lawrence, KS
Shelby Peterie, Kansas Geological Survey, Lawrence, KS
Joseph B. Dunbar, Engineer Research and Development Center, Vicksburg, MS

Abstract

Existing algorithms for inversion of dispersion-curves estimated from analyzing the seismic surface-wave data provide a reasonable representation of the overall shear-wave velocity structure. However, in some cases these results may not meet the resolution requirement of the survey objectives targeting the upper portion of the subsurface section. Near-surface geophysical surveys often look for greater detail in the very near surface, such as the case for levees, while still being interested in the overall velocity structure at greater depth. The proposed method for applying surface-wave inversion revolves around applying a greater degree of focusing on the very near-surface component of the inversion model through the practical use of existing algorithms. Specifically by eliminating the low frequency portion of the dispersion-curve data and using a shallower model. The proposed inversion technique is demonstrated using the multi-channel analysis of surface waves (MASW) inversion algorithm. As a result of using this near-surface focusing approach, surface-wave velocity estimates of the levees possess greater detail and resolution. Results presented here demonstrate the potential of the proposed approach to more accurately image the very shallow subsurface top portion of other near surface MASW sites.

Introduction

This work represents a continuation of an applied research project designed to evaluate the feasibility and applicability of several seismic techniques with the potential to identify, delineate, and estimate changes in physical characteristics or properties within levees during a simulated flood event. Several surface seismic measurements were taken using state-of-the-art equipment and analyzed using well-established and new research methods (Ivanov et al., 2006). These methods included P- and S-wave refraction tomography, surface-wave propagation, surface-wave dwell, and surface-wave (Rayleigh wave and Love wave) dispersion curve analysis (MASW).

Seismic investigations were conducted at a levee site located along Rio Grande river in the La Mesa Quadrangle, New Mexico, USA (Figure 1).

Multichannel surface-wave inversion techniques have proven capable of revealing anomalous shear-wave velocity zones within and below fill materials (Miller et al., 1999). Surface-wave analysis provided the greatest reliability in shear-wave velocity determination in the levee.

The MASW method involves the following steps. A single seismic-data record is acquired by a set

Figure 1. Survey site near Las Cruces, New Mexico.

of low-frequency (e.g., 4.5 Hz) geophones evenly spaced along a line. The seismic data from each shot record is transformed into a phase-velocity – frequency image, which allows the evaluation of the dispersion-curve trend of the fundamental-mode of the Rayleigh wave. The estimated dispersion curve is then inverted to produce a 1-D shear-wave velocity (V_s) model and assigned to the middle of the geophone spread. A 2-D V_s model can be obtained by assembling numerous 1-D V_s models derived from consecutively recorded seismic shot records along a seismic line,.

A popular approach for surface-wave inversion is to use a constant number of layers for each of which a V_s value is estimated. The actual number of layers used is a trade off between the vertical resolution and inversion instability. The latter can be observed as extreme high- and low-velocity V_s estimates from the inversion results. Such instabilities can be resolved by smoothing (i.e., regularization; Meju, 1994) or by reducing the number of layers (which can be regarded as a form of local smoothing as well). Both of these approaches can lead to a reduced vertical resolution and loss of desired detail. The conventional approach uses the optimum number of layers (e.g., 5 to 10) that provide sufficient resolution and requires minimum regularization.

In our work we demonstrate a practical approach for increasing the vertical resolution of the shallowest part of the existing section without increasing the number of layers and thereby increase the risk of instability in the inversion results. We typically select the optimal number of layers at levee sites necessary to allow a relatively deep overall estimation of V_s with depth and simultaneously focus on the top several meters of the levees by using only the high-frequency portion only of dispersion-curve data and a relevant shallow depth model that uses the same number of layers (e.g., 10). Using this approach we obtained more detailed results at these levee sites that are consistent with the local geologic understanding and drill data.

Data Acquisition

A compressional-wave geophone survey line was deployed along the riverside edge of the levee road (parallel to the river and levee). The levee crest was approximately 6 m wide, while the levee itself was 3 m high with a uniform 1-to-3 slope on each side (Figure 2). Single 10 Hz compressional-wave geophones were placed every 0.6 m for a total spread length of 72 m and 120 channel records. Sources tested included various sized sledgehammers and a mechanical weight drop, each impacting appropriate sized striker plates. Source spacing was 2.4 m with source points extending off-end out to a distance equivalent to the maximum depth of investigation.

Figure 2. Field site, crew working, and semi parked on levee.

Results

To establish a general understanding of energy partitioning and model distribution we analyzed several representative complete shot records. At this stage most of the processing effort was focused on identifying the fundamental mode of the surface wave and separating it from higher modes and noise.

Next, an optimum trace-offset range was determined that would best image the target critical fundamental-mode energy (Ivanov et al., 2008), while maintaining as narrow a spread as possible for better horizontal resolution of the final 2-D V_s section.

The quality of fundamental-mode energy was appraised for six spread ranges starting with the closest (2-20 m), (fundamental mode and higher modes were blurred together), and concluding with the longest offset range 2-37 m (Ivanov et al., 2008). The 2-33 m offset range was estimated to be optimal for imaging and picking the fundamental-mode surface waves (Figure 3). Greater offsets were discarded to optimize the lateral resolution of the MASW survey 2-D V_s section.

Based on dispersion curve analysis the levee was principally interrogated by energy with frequencies above 25 Hz. The wavelength for 25 Hz Rayleigh Wave energy was roughly estimated to be 150(m/s)/25(Hz) = 6 m, which is a wavelength proposed to represent materials in the upper 3 m (using half-wavelength assumption; Song et al., 1989).

Furthermore, at 60 Hz the fundamental mode is at 120(m/s)/60(Hz) = 2 m wavelength = 1 m depth. Therefore, frequencies above 60 Hz would primarily provide information for the upper 1 m of the levee. Guided by previous observations the optimum spread selected for analysis was focused on fundamental-mode energy around and above 25 Hz.

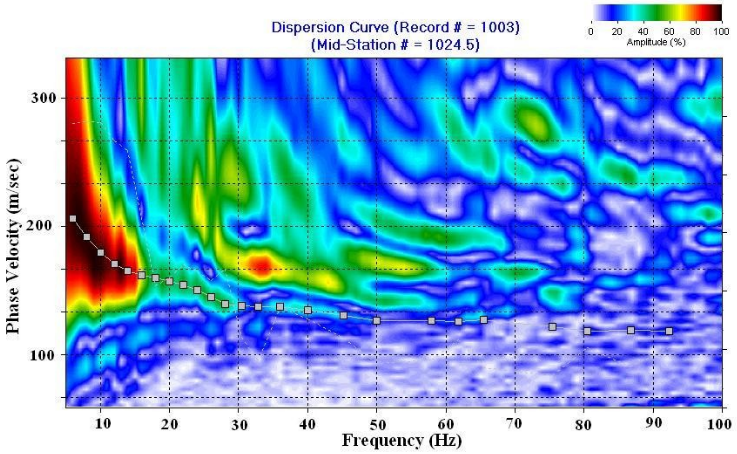

Figure 3. Dispersion curve estimated from a 2-33 m offset trace range.

Traditional MASW Processing

It was possible to estimate the fundamental-mode dispersion curve within a wide frequency range (Figure 3). Initially the dispersion curves were interpreted for all observed frequencies (6 to 80 Hz; Figure 3). Conventional inversion results provided a 2-D Vs image for depths down to 18 m (Figure 4).

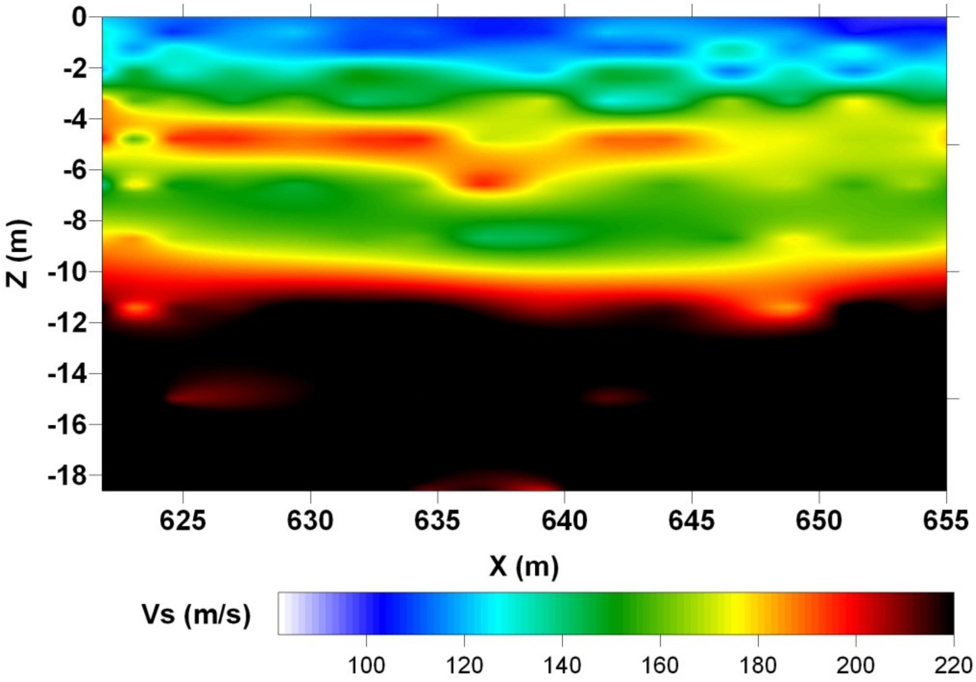

Figure 4. MASW Vs estimates using a deep 10-layer depth model.

These results provided important guidance and information about the overall structure and characteristics of the sediments within the levee, foundation, and the majority of the unconsolidated sediments above bedrock. However, resolution of the upper 3 m or so, which represented the levees did not meet the objectives of the survey.

Levee focused MASW Processing

To better focus and control the MASW method on the levees themselves we tested various inversion parameters using different models. We were specifically looking for parameters that resulted in the optimum and realistic image of the levee. Using a shallower depth model consisting of the same number of layers as the deep model (i.e., 10), but half space constrained at 7 m depth, provided more details for the upper 3 m (Figure 5).

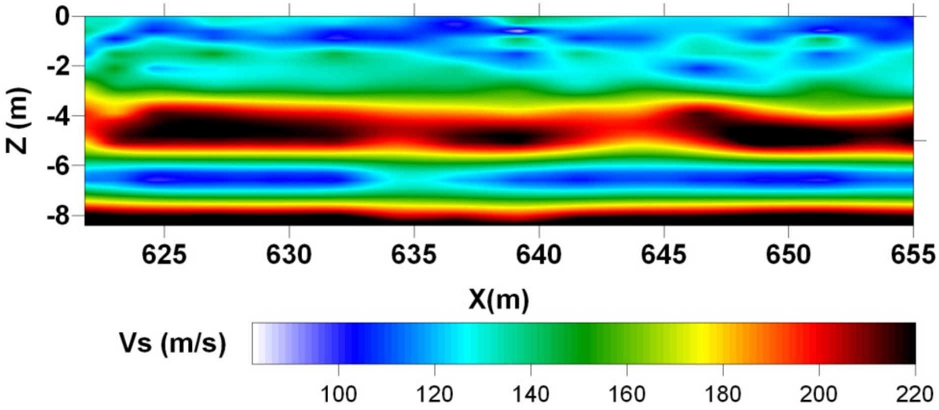

Figure 5. MASW Vs estimates using a shallow 10-layer depth model.

However, the inversion model did not provide deep enough layers that would match the low frequency range (7 – 10 Hz) of the observed dispersion curves. This lack of deeper layers caused instability (extreme high and low values at 4.5 and 6.5 m) compared to inversions using a deep model that matched the frequency range (Figure 4). In search of a more reliable solution, the high-velocity gradient of the dispersion curves for frequencies below 11 Hz was removed, Frequencies this low are likely influenced by the high-velocity (> 210 m/s) part of the section below 9 m (Figure 4). Without these low frequency estimates the new dispersion-curve frequency range matched the shallow inversion model with a half space at 7 m. With this more depth-constrained approach the inversion model focused on the shallower portion of the line and provided a much better image of the internal characteristics of the levee (Figure 6) in comparison with inversion result using a deep model (Figure 2).

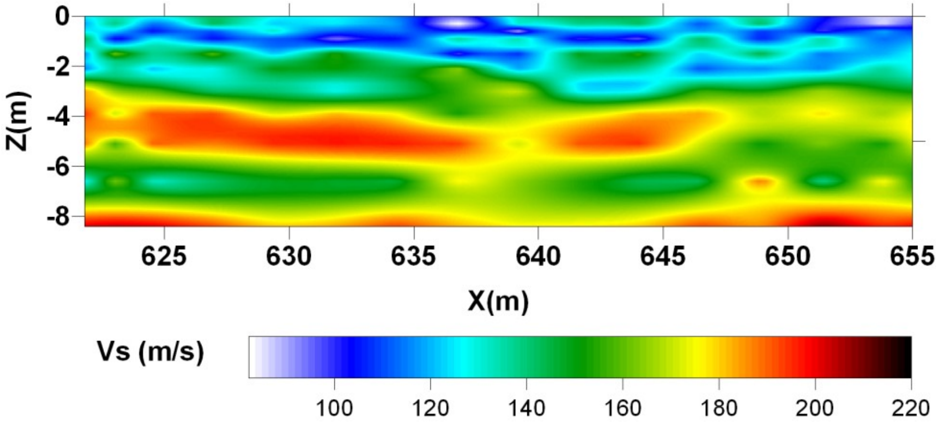

Figure 6. MASW Vs estimates using a shallow 10-layer depth model.

As well, in comparison with inversion results from using the same shallow model and dispersion curves containing lower (6-10 Hz) frequencies (Figure 5) the shallow-focused inversion (Figure 6) provided a better image of the levee core and lacked the extreme values. The levee body can be observed as a high V_s anomaly in the depth range 0-3 m on the 2D V_s images. The base of the levee is also well imaged.

Conclusions

The MASW method proved to be a useful tool for assessment of levees after tuning the inversion through the use of a shallower depth model and avoiding low-frequency dispersion-curve estimates and therefore a deeper model. The main value to be extracted from our work is the demonstration of a practical approach to improving shallow focusing and resolution without increasing the number model parameters (number layers), which could represent risk for inversion instabilities.

The improved shallow image and the image from traditional processing can be used to integrate for a combined final image. Similar results could probably be achieved by using a greater number of layers and specific type and weight of regularization. However, finding appropriate regularization parameters can be a difficult and time-consuming task from practical perspective. Thus, this suggested technique is an efficient practical approach for improving the resolution of the top half or third of the MASW 2D V_s section.

This approach provided useful results at all levee sites, identifying anomalous zones either within the levee or beneath the levee consistent with ground truth. Therefore, the MASW survey achieved the goals of identifying zones with structural deficiencies and failure potential.

Acknowledgments

Support and assistance from the U.S. Section of the International Boundary and Water Commission is greatly appreciated and without which this research would not have been possible. Permission to publish this paper was granted by the Commissioner, U.S. Section of the International Boundary and Water Commission, and by the Director, Geotechnical and Structures Laboratory, Engineer Research and Development Center.

References

Ivanov, J., R.D. Miller, G. Tsoflias, 2008, Some practical aspects of MASW analysis and processing: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2008), Philadelphia, Pennsylvania, April 6-10, 21, No. 1, 1186-1198.

Ivanov, J., Miller, R.D., Stimac N., Ballard R.F., Dunbar, J.B., and Smullen, S., 2006, Time-lapse seismic study of levees in southern New Mexico: 76th Annual International Meeting, SEG, Expanded Abstracts, 3255-3258.

Meju, M. A., 1994, Biased estimation: a simple framework for inversion and uncertainty analysis with prior information: Geophysical Journal International, 119, 521-528.

Miller, R. D., Xia, J., Park, C. B., and Ivanov, J.M., 1999a, Multichannel analysis of surfaces waves to map bedrock: Leading Edge, 18, 1392-1396.

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, Technical Program with Biographies, SEG, 59th Annual Meeting, Dallas, Texas. 509-512.