3D Wave-Mode Separation for Elastic Time-Reverse Imaging

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ABSTRACT

Most near-surface seismic analysis methods assume that the input data are comprised of body-wave arrivals and that the often-dominant surface-wave energy has been successfully mitigated through judicious data preprocessing. However, some recently developing seismic elastic imaging approaches, including elastic time-reverse imaging (E-TRI), instead use backscattered surface-wave energy as signal rather than noise. Originally developed for microseismic event location, E-TRI has been adapted for use in near-surface active-source seismic investigations, and surface-wave scatterer detection. Similarly to elastic reverse time migration (E-RTM), E-TRI is an elastic full-wavefield migration method that uses two time-reversed elastic wavefields and applies an imaging condition (e.g., cross-correlation, energy norm, or deconvolution) to stack correlated energy to generate an interpretable image. However, unlike RTM, active-source E-TRI uses recorded elastic data partitioned into (1) an outward-propagating transmission and (2) an inward-propagating backscattered wavefields to focus energy at subsurface scatterer locations. E-TRI has already proven useful for detecting small-scale anomalies in near surface scenarios but issues arose when processing data at frequencies above 25 Hz, below the expected dominant frequency range.

While E-TRI and related near-surface seismic analysis methods have been developed for surface-wave dominated data, most still assume that the surface-wave data contain only the fundamental Rayleigh- (or Love)-wave mode, implying each phase velocity uniquely correlates to an individual frequency. However, the near-surface velocity structure frequently generates surface-wave data with more than a single mode, and therefore a non-unique phase velocity-frequency relationship. In particular, multi-mode surface wave data are commonly associated with near-surface geological layering, particularly where a low-velocity layer lies between faster layers. In these scenarios, it can be injudicious to assume single modal data, which can lead to cross-mode contamination, reduced data coherency, imaging artifacts, and lower overall signal-to-noise ratios.

One straightforward method to avoid such mode interference is to isolate the fundamental mode (R_0) by bandpassing the data to below the frequency at which the first higher-order mode (R_1) arrives; however, such a processing approach can remove useful wavefield components and limit detection of smaller-scale anomalies at shorter wavelengths. Alternatively, one can use a velocity-based dip filter to separate interfering modes, increasing the continuous frequency range each single-mode estimate contains and reducing cross mode overlap.

A 3D field data test was used for this study, featuring a meter scale void anomaly erected at about 10 m depth within a complex layered earth. Multiple overlapping wave-modes required previous bandpassing below 25 Hz, the frequency where R_1 arrives, to produce a coherent image. While fundamental-mode separation previously enhanced coherency in the fundamental mode of the transverse component, Rayleigh-wave amplitudes in the vertical component were stronger in the higher-order mode component at higher frequencies (Figure 1a). Similarly, the fundamental mode alone was less sensitive closer to the void position. We therefore seek to explore migrating both modes simultaneously. This process involves performing wave-mode separation with velocity-dip filtering followed by transmitted and scattered wavefield separation via $f-k$ domain muting, leaving four different data subsets for using in E-TRI analysis containing the transmitted and backscattered fundamental (T_0 and B_0) and first-order (T_1 and B_1) Rayleigh wave modes. Figure 1b-e presents the 3-D E-TRI results for for different subset combinations. As expected, migrating the fundamental mode alone (T_0+B_0) (Figure 1b) yields a lower signal-to-noise ratio compared to the first-order mode (T_1+B_1) (Figure 1c), which also provides improved depth constraints at the expense of additional artifacts. When the two modes are migrated in combination (T_0+B_1 and T_1+B_0), the depth estimates and artifacts begin to focus more accurately near the void's true location at the center of the array. This study demonstrates that applying wave mode separation to near-surface data can markedly enhance image coherency, offering a practical improvement for near-surface imaging workflows.

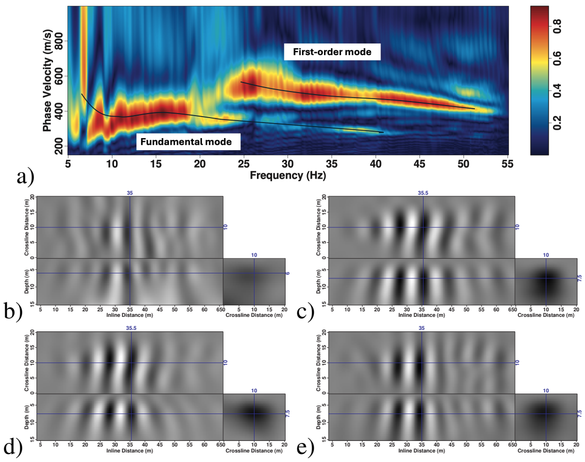

Figure 1: (a) Dispersion panel showing representative R_0 and R_1 modes. 3-D E-TRI images showing the void buried at 10 m depth at the 35 m point in the array computed with the following subset combinations: (b) T_0+B_0, (c) T_1+B_1, (d) T_0+B_1, and (e) T_1+B_0.

ACKNOWLEDGMENTS

We thank Dr. Steve Sloan and the U.S. Army Corps of Engineers for providing the 3-D seismic dataset. This work is supported by the Consortium Project on Seismic Inverse Methods for Complex Structures at the Center for Wave Phenomena (CWP). We acknowledge the Mines Research Computing for providing access to the Wendian HPC resources.