Selective-window processing for optimized surface wave imaging of passive data

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Summary

A selective-window processing technique successfully enhanced the fundamental-mode surface-wave trend that had was been previously affected by interference from off-line passive signals. Accurate interpretation of the fundamental mode trend is a critical step in surface-wave inversion. Misinterpretations can occur when higher mode surface waves overlap the fundamental mode or exhibit dominating energy amplitudes in the frequency-phase velocity domain. Since energy from multiple sources are commonly observed on passive data since they are commonly acquired using longer record times. In an effort to minimize contributions from off-line sources, a selective-window processing technique was implemented on a passive seismic dataset collected using a linear array. By manually selecting individual time windows from a given record, energy contributions from different surface wave modes were separated and focused to produce an enhanced fundamental mode trend. These enhanced surface wave trends led to optimized spread lengths for each gather and increased lateral resolution of the resulting 2-D shear-wave velocity profile.

Introduction

Due to the nature of ambient noise, off-line sources can interfere with the fundamental surface wave mode signal where the effects of higher modes or aliasing create discontinuous or low-amplitude trends. This can lead to misinterpretations of the fundamental mode and inaccurate velocity profiles (Zhang and Chan, 2003). Advanced pre-processing procedures such as dispersion-curve filtering (Park et al., 2002) or the high-resolution linear radon transform (Luo et al., 2008) can sometimes reduce the effects of these interfering waves, but such methods are not always adequate for passive datasets.

Since ambient noise sources produce energy in a more random fashion, longer acquisition times are used to maximize the opportunities for recording their occurrences. However, these longer acquisitions also increase the opportunity for recording off-line sources. For passive data acquisitions that utilize a linear array, off-line sources from multiple locations can greatly interfere with imaged surface wave dispersion trends. These off-line sources can appear in the frequency-phase velocity domain as aliasing, higher modes, or other artifacts that alter the appearance of the fundamental mode trend. If the direction of the propagating surface wave is not parallel to the alignment of the recording linear array, surface wave velocity will be recorded with “effective” or “apparent” dispersive characteristics (O’Neill and Matsuoka, 2005). Unless the effects of these interfering waves can be compensated for or removed, dispersion-curve picking will be challenging or performed inaccurately; especially as the complexity of the surveyed environment increases when higher modes may become more prevalent (O’Neill and Matsuoka, 2005). Additionally, mode interpretations with higher confidence can be performed if mode interference is minimized allowing for more accurate imaging of inverted velocities. To optimize contributions from recorded passive data, a selective-window processing technique was applied allowing a more qualitative analysis of surface wave energy. Results from this method were compared to the conventional phase-shift algorithm (Park et al., 1998) as well as a “black box” time-window splitting algorithm. The selective-window processing method produced a clearer, more coherent fundamental mode with improved lateral resolution of the final shear-wave velocity profile.

Data Acquisition and Processing

Nearby passing trains provided the passive seismic energy necessary for low-frequency surface wave imaging (<5 Hz). Passive seismic data were acquired overnight over a 12 hour period in consecutive 30-second records at a 2 ms sampling rate. Seismic data were collected using 4.5 Hz vertical geophones at 3 m spacing at a site in southcentral Kansas (Ivanov et al., 2013). This method can be summarized in five steps: (1) collect passive seismic data simultaneously using one or more 1D and a 2D receiver arrays, (2) select an optimal source file using both dispersion-curve images from 1D arrays and energy vs. azimuth angle images from the 2D array, (3) estimate optimal shorter spread size that meets desired project specifications (e.g., preserving lowest frequencies for maximum depth analysis) and extract as many as possible, short-spread records with varying spread mid-stations simulating roll-along data acquisition, (4) create dispersion-curve images from the short, rolling-along spreads and pick dispersion curves, (5) invert those picked curves for 1D and 2D Vs profiles.

Since the timing and quality of passive sources cannot be controlled during a survey, seismic records may contain multiple source signals or noise bursts that occur randomly and interfere with the fundamental mode surface wave. However, removing specific parts of the passive seismic wavefield can be more challenging than an equivalent processes for active seismic data processing where different wave types originate from the same point in time (i.e. time-zero). Therefore, quality control of these passive seismic records in the time domain is not sufficient.

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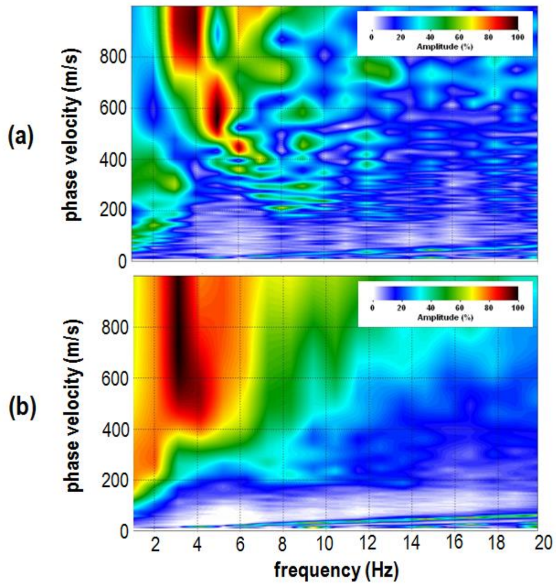

Figure 1. (a) Example overtone image produced using full 30-second record and (b) "black box" time-window split overtone image using 3-second records.

An automated time-window splitting procedure can be applied to evaluate data quality of source signals in the frequency-phase velocity domain (i.e. imaged overtone). This algorithm divides one record into shorter, evenly-timed windows and then transforms each window into a new overtone image. After these windowed overtone images are stacked, an RMS-error between the stacked and individual overtone image amplitudes is estimated; windows are then removed from a final stacked image if their RMS is greater than a specified criterion. Since this algorithm considers all amplitudes in a given window, high-amplitude wave types (i.e. higher modes, aliasing) can still dominate on the stacked overtone image and interfere with the fundamental mode trend compared to the conventional phase-shift imaging scheme (Figure 1). To optimize overtone imaging of passive data, windows should instead be removed based on signal quality, not quantity.

Selective-Window Processing

Instead of the previously mentioned "black box" time-window splitting procedure, a qualitative analysis of windowed overtone images was performed on passive seismic data; this analysis is referred to as selective-window processing method in this text. After a passive source file is selected (step two), shorter time windows are extracted from the 30-second record (e.g. 3-second records with a 1.5-second sliding window of overlap). Overtone images are produced for each of the 3-second records; then time

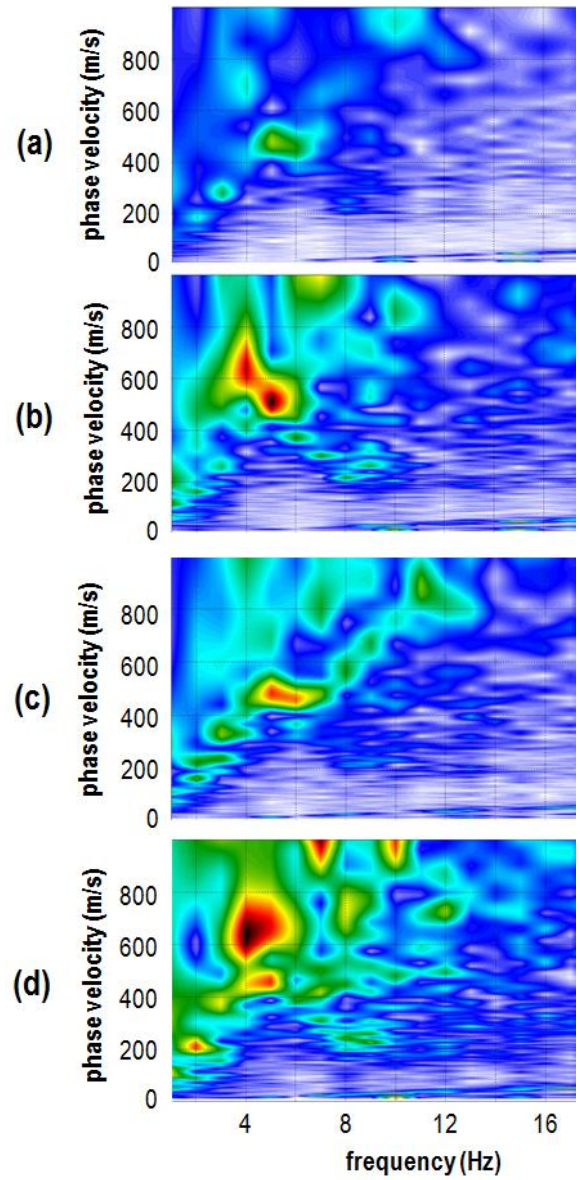

Figure 2. After selective-windowing has been performed on a 30-second record, windows are analyzed based on the energy amplitudes in the phase velocity-frequency domain. Different windows display varying levels of surface wave energy including (a) minimal signal, (b) high-amplitude low-frequency fundamental mode signal, (c) strong aliasing, and (d) incoherent surface-wave energy.

windows are manually selected and stacked to reconstruct a new overtone image. Each time window is considered for stacking based on the characteristics of the imaged dispersion energy.

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Figure 2 represents four time window examples from one 30-second record. In Figure 2a, minimal information is observed, Figure 2b provides high-amplitude fundamental mode information from 4-5 Hz, Figure 2c is dominated by signal aliasing, and Figure 2d exhibits high-amplitude energy, but that energy is incoherent with high levels of noise that interfere with the fundamental mode. All time windows that exhibit coherent signal information are then stacked in the time-domain; time windows similar to Figure 2a, 2c, and 2d are not considered for further processing. After an optimal spread size is determined, a roll-along survey will be decimated and dispersion curves will be picked and inverted for velocity-depth profiles.

Results and Discussion

Selective-windowing was performed using 1000 ms, 2000 ms, 3000 ms, 5000 ms, and 10,000 ms time windows to evaluate how the window size affects the quality of the imaged surface wave energy. As a result, shorter time windows can separate different modes, but as windows continued to shorten, energy amplitudes became limited with decreasing signal coherency. Aliasing was prominent on time windows with 2,000 ms or less (Figure 3a, b), but as the window size increased, the level of noise contributing to the imaged energy increased (Figure 3d, e). The 3000 ms time window demonstrated optimized surface wave imaging with high-amplitude low-frequency information and minimized high-velocity, higher-frequency energy (Figure 3c).

After the window size is determined (i.e. 3,000 ms), a roll-along spread is decimated from the enhanced record. A 111 m spread was selected for processing before applying the selective-window processing scheme. Now that better surface wave mode separation was achieved, shorter spread sizes were analyzed to determine whether by shortening the spreads lengths any improvement in the lateral resolution of the final 2D image would be possible. It is commonly understood that lateral resolution increases as the spread length used for velocity inversion decreases since the area being averaged is smaller compared to longer spread sizes (Park et al., 2001; Mi et al., 2017).

For the same survey station, overtone images are shown in Figure 4 without selective-window processing (Figure 4a) compared to overtones where selective-window processing was applied (Figure 4b-e). Without selective windowing on a 111 m spread (Figure 4a), fundamental mode information was attenuated significantly such that an interpretation could not be made without additional investigation and interpretations from nearby station's dispersion information. However, when selective windowing was applied to the same dataset (i.e. 111 m spread), the fundamental mode trend was recovered with dominant, high-amplitude energy

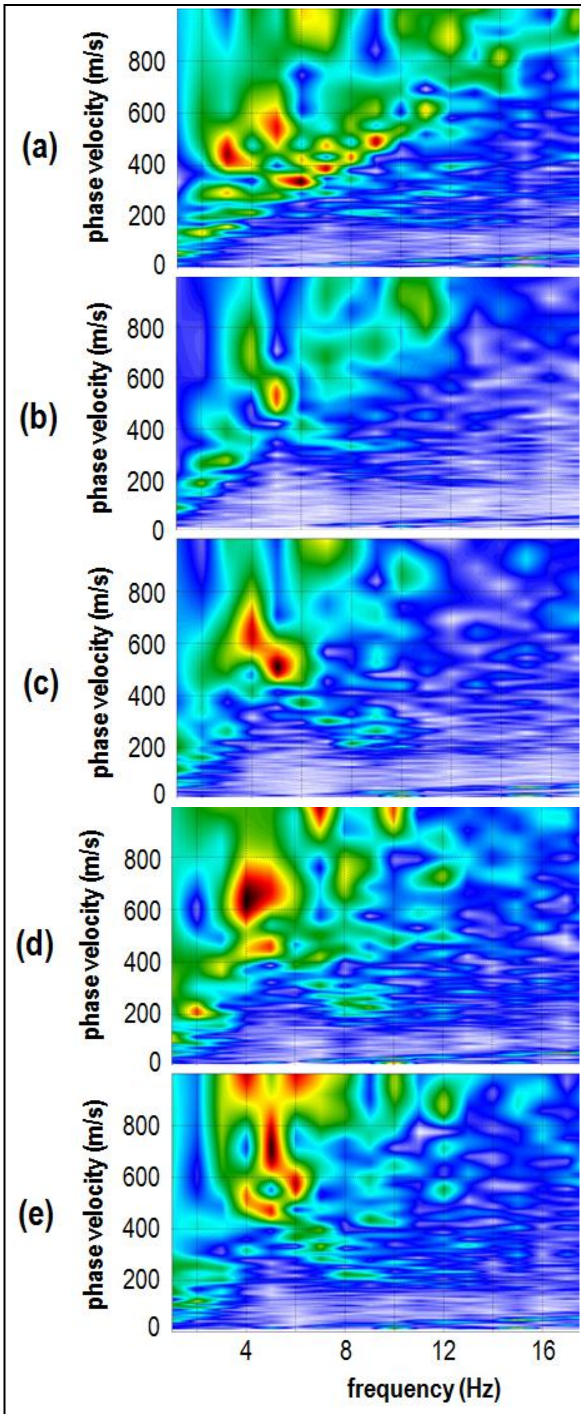

Figure 3. Selective-windowing using a (a) 1,000 ms, (b) 2,000 ms, (c) 3,000 ms, (d) 5,000 ms, and (e) 10,000 ms window.

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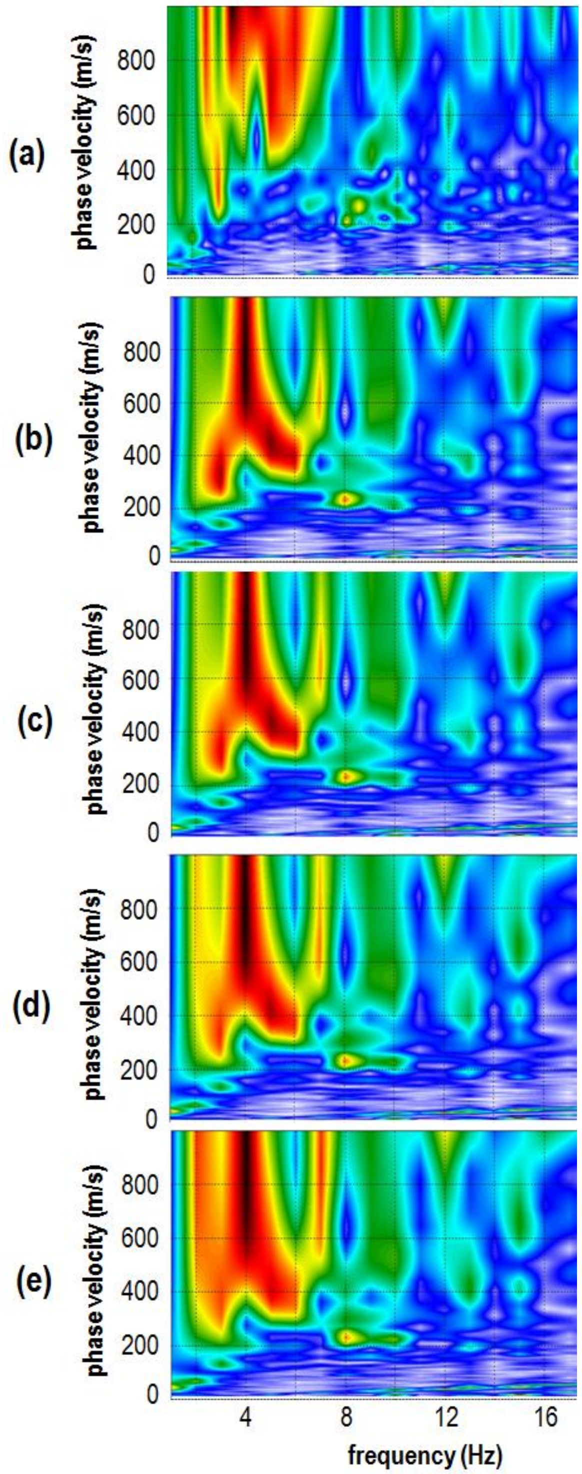

Figure 4. Overtone images produced using a (a) 111 m spread without selective-window processing compared to (b) 111 m, (c) 105 m, (d) 99 m, (e) 93 m spread sizes where selective-window processed was applied.

from 4-6 Hz and reduced interference effects from higher modes.

To produce this dataset, three 3000 ms windows were stacked focusing on energy specifically from the fundamental mode and attenuating higher mode energy. Other, shorter spreads that were analyzed including a 105 m, 99 m, and 93 m spread; a similar fundamental mode trend can be interpreted from each of the shorter spreads, but energy from low-velocity, low-frequency noise increased in amplitude with shorter spreads. Some lower-amplitude, higher mode data became more coherent as the spread length decreased, allowing interpretations of the fundamental mode in spite of the decreased signal-to-noise on the 93 m spread. Based on this investigation, this selective-window processing revealed a clearer fundamental mode dispersion trend with minimal contributions from higher mode energy and other coherent energies from possible off-line sources.

Conclusions

Surface wave modes were successfully separated using selective-window processing with contributions from isolated surface wave energy that was used more efficiently to produce more coherent fundamental mode trends with reduced artifacts from higher mode interference and aliasing. From a 30-second record, a 3-second time-window demonstrated optimal energy distribution in the frequency-phase velocity domain compared to other window sizes. If the time window was too narrow, surface wave energy became increasingly attenuated, while if the time window is too long, interference from other modes and sources interfered with the fundamental mode trend. When multiple time-windows are selected and stacked, contributions from higher modes and other interfering noise sources became reduced in the final overtone image.

Picked dispersion curves produced using this selective-window processing led to 2-D shear-wave velocity profiles with increased lateral resolution due to a shorter spread size that could be decimated while retaining coherent fundamental mode information. Based on these analyses on passive seismic data, this selective-window processing technique provided optimized overtone images with more coherent fundamental mode energy trends.

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