Dispersion analysis of passive surface-wave noise generated during hydraulic-fracturing operations

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ABSTRACT

Surface-wave dispersion analysis is useful for estimating near-surface shear-wave velocity models, designing receiver arrays, and the suppression of surface waves. Here, we analyze whether passive seismic noise generated during hydraulic-fracturing operations can be used to extract surface-wave dispersion characteristics. Applying seismic interferometry to noise measurements, we extract surface waves by cross-correlating several minutes of passive records; this approach is distinct from previous studies that used hours or days of passive records for cross-correlation. For comparison, we also perform dispersion analysis for an

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active-source array that has some receivers in common with the passive array. The active and passive data show good agreement in the dispersive character of the fundamental-mode surface-waves. For the higher mode surface waves, however, active and passive data resolve the dispersive properties at different frequency ranges. To demonstrate one application of dispersion analysis, we invert the observed surface-wave dispersion characteristics to determine the near-surface, one-dimensional shear-wave velocity.

INTRODUCTION

Dispersion is defined as the frequency-dependence of velocities. Although body waves show dispersive character primarily due to the presence of intrinsic attenuation, surface waves show dispersion primarily due to near-surface vertical heterogeneity (Dobrin, 1951; Liner, 2012). Low-frequency surface waves penetrate deeper, sample higher velocities, and therefore travel faster. High-frequency surface waves, on the other hand, sense only the shallow near-surface and thereby travel at lower velocities.

Dispersion analysis can provide valuable information for acquisition design and suppression of surface-wave noise, and can also be used for inverting for near-surface velocity models. The dominant wavelength of surface waves computed from dispersion analysis can be used for designing receiver arrays that suppress these waves (Baeten et al., 2000; Draganov et al., 2009). Dispersive characteristics of surface waves also have long been used to infer near-surface shear-wave velocities, for estimating building responses to ground shaking caused by earthquakes (Borcherdt and Glassmoyer, 1992; Louie, 2001) or in crustal seismology to extract the shear-wave velocity model of the crust and upper mantle (Shapiro and Ritzwaller, 2002; Sabra et al., 2005).

Moreover, because dispersion is a distinguishable property of surface waves, understanding this property can provide a potential opportunity to suppress these waves (Forghani et al., 2013). In active seismic data, surface-wave noise suppression techniques are formulated in the frequency-wavenumber (Claerbout, 1985) or frequency-slowness domain (Hampson, 1986) to separate the surface waves from the body waves. For passive microseismic data acquired at the surface, however, the low signal-to-noise ratio of the body waves generated by microseismic events and the complex nature of surface-wave noise cause noise

suppression to be a significant challenge (Kochnev et al., 2007; Duncan and Eisner, 2010; Forghani et al., 2012, 2013).

Dispersion analysis of passive data is commonly applied to the passive noise generated from cultural activities, mostly road traffic (Park et al., 2007; Halliday et al., 2008). Here, we analyze whether passive energy observed during microseismic monitoring of hydraulic-fracturing operations can be used for surface-wave dispersion analysis.

Studies show that combined active- and passive-dispersion analysis provides broader frequency content of the dispersive surface waves, thereby resulting in a more complete analysis of these waves (Malovichko et al., 2005; Park et al., 2005, 2007; Halliday et al., 2008). For example, the combined active and passive surface-wave analysis by Park et al. (2005) resulted in better recognition of the surface-wave modes and more accurate estimation of the shear-wave velocity. Malovichko et al. (2005) and Park et al. (2007) used combined active and passive dispersion analysis for better estimation of near-surface soil properties.

Here, we analyze whether passive seismic noise generated during hydraulic-fracturing operations can be used to extract surface-wave dispersion characteristics and their correspondence with the dispersion characteristics of active surface-wave data. Hence, we extract dispersive characteristics of surface waves using both active and passive data. We use the combined active-passive dispersion curves to infer the one-dimensional (1-D) near-surface shear-wave velocity profile.

FIELD DATA DESCRIPTION

The datasets for this research were acquired over a Barnett Shale reservoir in the Greater Dallas area, prior to the start of a hydraulic-fracturing process. The energy observed in

the passive data is due to activities such as industrial pumps, engines, and trucks at the well-head area (Forghani-Arani et al., 2011). Figure 1 illustrates the receiver array used in this acquisition.

[Figure 1 about here.]

The acquisition parameters of these datasets are summarized in Table 1. Note that the recording frequency range for the passive data (6-200 Hz) is broader than the one for the active data (6-30 Hz).

[Table 1 about here.]

DISPERSION ANALYSIS

Dispersion analysis of surface waves commonly involves transformation of the data from the time-offset domain to the frequency-wavenumber (Gabriels et al., 1987) or frequency-slowness domain (McMechan and Yedlin, 1981; Park et al., 1998, 1999; Xia et al., 2007). In our dispersion analysis, we follow the methodology of McMechan and Yedlin (1981) that involves applying two transformations to a common shot-gather. First, we apply the $\tau - p$ transform (also called slant-stack) to transform the data from the time-offset ($t - x$) to the $\tau - p$ domain, based on the following equation:

$$U(p, \tau) = \int_{-\infty}^{+\infty} U(x, t) dx = \int_{-\infty}^{+\infty} U(x, \tau + px) dx \quad (1)$$

(Claerbout, 1985; Stolt and Weglein, 2012), where $U(x, t)$ represents a recorded event at each receiver in the $t - x$ domain as a function of recording time (t) and source-receiver offset (x); $U(p, \tau)$ represents the event in the $\tau - p$ domain as a function of intercept with

the time axis (τ) and the slope or apparent slowness (p) of the event. Assuming a certain range of slopes and time-intercepts, this transformation can be obtained by summation of the receiver waveforms at each pair of slope (p) and time-intercept (τ). Because dispersion involves the velocities at which different surface-wave frequencies propagate, we convert the data from $\tau - p$ to $\tau - v$ domain, considering $v = 1/p$.

Second, we apply a 1-D temporal Fourier transform to transfer the data from $\tau - v$ to the velocity-frequency ($f - v$) domain. This transformation is described by:

$$U(v, \omega) = \int_{-\infty}^{+\infty} e^{i\omega\tau} U(v, \tau) d\tau, \quad (2)$$

where $U(v, \omega)$ represents the data in the velocity-frequency or dispersion domain; $\omega = 2\pi f$ denotes the angular frequency of the data.

DISPERSION ANALYSIS OF ACTIVE DATA

To extract surface-wave dispersion properties from the active data, we consider a shot gather recorded from the vibroseis source shown by the black star in Figure 1. In order to have a comparable dispersion analysis for active and passive data, we choose the location of the active source to be in the vicinity of the passive source location. Figure 2(a) illustrates the active shot gather recorded by the receiver array from this source. The early-arrival events with the smallest slope are possibly refraction events. Note in the shot gather that the different frequencies of surface waves correspond with different arrival times, which demonstrate the dispersive character of this wave.

Figure 2(b) shows the transformed data in the $\tau - v$ domain. The high-amplitude coherent events between 500 m/s and 1000 m/s represent the range of the phase velocities

for the fundamental mode surface wave. The low-amplitude coherent events between 1000 m/s and 2000 m/s may show the range of phase velocities for higher mode surface waves.

Next, we transform the data from the $\tau - v$ domain to the $f - v$ (dispersion) domain. In the dispersion domain (Figure 2(c)), we can see that the fundamental mode surface wave has frequency content in the range of 6-30 Hz and that it travels with a phase velocity of 550 m/sec to 850 m/sec. The dispersive characteristics of two higher-mode surface waves can also be seen but with weak amplitudes. Note that because of the limited frequency range of the vibroseis sweep (6-30 Hz), the frequency content of the active surface wave is limited to this range.

[Figure 2 about here.]

DISPERSION ANALYSIS OF PASSIVE DATA

The dispersion analysis technique that we apply to active data requires the data in the time domain to be in the form of a shot gather. Because the source of the passive data is uncontrolled, semi-continuous industrial noise, we do not have shot gathers as in active data. Therefore, we use passive seismic interferometry to extract pseudo-shot gathers from the passive data. In seismic interferometry, cross-correlation of two receiver recordings yields the response between the two receivers with one receiver becoming a pseudo-source (Wapenaar et al., 2010). Passive interferometry has been applied to ambient noise in both crustal (Shapiro et al., 2005; Gerstoft et al., 2006; Bensen et al., 2007) and exploration seismology (Miyazawa et al., 2008; Draganov et al., 2009).

In passive noise interferometry, the time-domain cross-correlation process is given by:

$$G(x_r, x_s, t_r - t_s) \propto \langle u(x_r, t_r) * u(x_s, -t_s) \rangle \quad (3)$$

(Snieder, 2004; Wapenaar, 2004; Wapenaar et al., 2010), where $u(x_r, t_r)$ is the recorded waveform at a receiver as a function of the receiver location (x_r) and the arrival time (t_r) of the waveform at that receiver; $u(x_s, t_s)$ is the recorded waveform at the pseudo-source as a function of the location of the pseudo-source (x_s) and the arrival time (t_s) of the event at that receiver; $G(x_r, x_s, t_r - t_s)$ is the extracted waveform that would be recorded at the receiver location x_r , if there were a source at the receiver location x_s ; $\langle \dots \rangle$ denotes ensemble time averaging (averaging over the whole time of the passive record) of the cross-correlation and can be estimated by average sum of a sufficiently long recording time. The cross-correlation extracts surface-wave arrival times, $t_r - t_s$, from the pseudo-source to every receiver in the array.

We apply the above cross-correlation method to the passive data recorded at the receivers in the central part of the array (gray area in Figure 1). A 2-sec time window of these passive data is shown in Figure 3. In order to have a proper comparison with the active dispersion analysis shown above, we choose the pseudo-source to be at the same location as the active source (shown by the black star in Figure 1).

[Figure 3 about here.]

In Equation 3, each cross-correlation in the ensemble is carried out on time windows spanning over 2-sec of the passive data. The choice of 2-sec windows is based on the estimation of the longest travel time for the surface wave to travel across the receiver array. Because the cross-correlation should be summed over a sufficiently long time, we choose

a 300-sec time interval for the summation, that involves summation of 2-sec moving time windows that are shifted by one sample. Figure 4(a) shows the pseudo-shot gather resulting from passive seismic interferometry. In the raw passive data (Figure 3), no obvious coherent arrivals are evident. However, after applying interferometry (Figure 4(a)) we can observe the extracted surface wave in the pseudo-shot gather.

As is done for active data, we transform the pseudo-shot gather in Figure 4(a) to the $\tau - v$ domain shown in Figure 4(b). The high-amplitude coherent events between 500 m/sec and 1000 m/sec correspond to the fundamental mode passive surface-wave. In this velocity range, the similarities between the $\tau - v$ domains of the active and passive data are clearly evident from Figures 2(b) and 4(b). However, in Figure 4(b) we observe high amplitude events within the velocity range 1000-2000 m/sec, which are absent in Figure 2(b). Also note some low amplitude scattered events at later time-intercepts that possibly correspond to the cross-term noise created by cross-correlation.

Thereafter, we apply the second transformation to the data—moving from the $\tau - v$ (Figure 2(b)) to the $f - v$ domain to obtain the dispersion image of the surface-wave (Figure 4(c)). It is noteworthy that by using only a few minutes of passive data in our dispersion analysis, we are able to extract well-resolved surface-wave dispersion curves. This observation differs from previous passive seismic studies that use hours or even days of passive data (Halliday et al., 2008; Draganov et al., 2009). We speculate we can use a shorter time interval because the large number of receivers included in the summation of the $\tau - p$ transform enhances the coherent surface-wave amplitude.

A comparison of the dispersion image of the passive data (Figure 4(c)) with that of the active data (Figure 2(c)) shows that both passive and active data demonstrate simi-

lar dispersive characteristics for the fundamental mode surface wave, although the active fundamental mode is better resolved. This might be the result of the lower signal-to-noise ratio in the passive data. For the higher-mode surface waves, active data lead to a better resolution for lower frequencies, and passive data resolve the dispersion better for higher frequencies. This might be related to the different frequency content of the passive (6-200 Hz) and active (6-30 Hz) data.

The pseudo-source location for the above analysis (black star in Figure 1) is chosen based on the analysis by Forghani-Arani et al. (2011) who located the surface noise across the receiver array. To investigate the importance of the pseudo-source location in this dispersion analysis, next we choose a pseudo-source far from the noisy location in the array (white star in Figure 1). Figure 5(a) shows the corresponding pseudo-shot gather for this pseudo-source. Note that for this pseudo-source, the surface-wave retrieval is not successful. The reason for this will be clarified in the discussion section. Also, the $\tau-v$ and $f-v$ images of this pseudo-shot gather (as shown in Figures 5(b) and 5(c), respectively) do not extract the surface-wave dispersive properties, except a small part of the fundamental mode. This observation shows that in this study the pseudo-source location is critical for a successful passive-seismic dispersion analysis.

Surface-wave dispersion measurements obtained from active and passive data show markedly different frequency content. Therefore, using the two datasets one can achieve broader and more resolved dispersive characteristics of the surface waves.

[Figure 4 about here.]

[Figure 5 about here.]

INVERSION FOR SHEAR-WAVE VELOCITY

To extract the shear-wave velocity models from the dispersion curves, we use the GEOPSY software developed by Wathelet (2005). This software uses a direct search method that is based on the neighborhood algorithm (Sambridge, 1999). The algorithm generates several thousand Earth models and calculates their corresponding dispersion curves using the propagator-matrix method for a horizontal multi-layered media (Gilbert and Backus, 1966; Aki and Richards, 2002). During the generation of the models, misfit values which represent the distance between the calculated dispersion curves and the observed dispersion curves are estimated (Wathelet, 2005, 2008). The shear-wave velocity models with the minimum misfit values are then chosen as the acceptable models.

Here, we use the dispersion curves that are obtained by our dispersion analysis (shown in Figure 6(a) as black curves) as inputs to the inversion algorithm. Note that these curves are combined passive and active dispersion curves. Inserting these dispersion curves in the inversion algorithm, we obtain the shear-wave velocity models as shown in Figure 6(b). The most acceptable models are those with the lowest misfit values (shown in red). The uncertainty (observed as the breadth of scattering of the acceptable models) deeper than 55 m increases with depth. This indicates that due to the lack of dispersion values at low frequencies (< 6 Hz) the shear-wave velocities are not well-constrained by the dispersion curves (Lomax and Snieder, 1994). The predicted (calculated) dispersion curves from the shear-wave velocity models that are shown in Figure 6(a) are in reasonable agreement with the observed curves.

Note that mode number identification is critical for the inversion process and that identification of the higher mode can be particularly challenging and requires prior knowledge of

the near-surface structure (Wathelet, 2005). However, because we do not have prior information about the near surface at our study area we use a trial-and-error approach, where we assign a certain number to each mode. Based on that mode number we invert for the shear-wave velocity. We then predict the dispersion curve from the shear-wave velocity profile using forward modeling. The mode number that estimates the closest predicted dispersion curve to the observed dispersion curve is considered to be the correct mode number.

[Figure 6 about here.]

DISCUSSION

We showed that the choice of the pseudo-source location in passive dispersion analysis is important for the successful retrieval of surface waves and their dispersion properties. A pseudo-source close to the source of the passive noise yielded a good quality shot gather. On the other hand, when the chosen pseudo-source location was far away from the passive-noise source, the quality of the pseudo-shot gather decreased substantially. Here we discuss the reason for this observation.

In interferometry, sources within the stationary phase zones (Fresnel zones) have the maximum contribution to the retrieval of a signal between two receivers (Snieder, 2004). In the extraction of the direct surface waves between any given pair of pseudo-source and receiver in a homogeneous medium, these stationary sources lie on or in the vicinity of the line that connects the pseudo-source and the receiver (Snieder, 2004; Snieder et al., 2006). When the pseudo-source is selected near the passive-noise sources, the direct surface waves can be extracted by cross-correlation for a wide range of receivers in the array as is schematically illustrated in Figure 7(a). On the other hand, for a distant pseudo-source,

the direct surface waves can be retrieved only for a narrow range of receivers (shown in Figure 7(b)). As a result, the dispersion curves are more pronounced and better resolved for pseudo-sources proximal to the passive noise sources than for distant ones.

[Figure 7 about here.]

Surface-wave dispersion might potentially be exploited to separate surface waves from body waves. For example, in the passive dispersion domain (Figure 4(c)) surgical removal of the surface-wave dispersion curves and a transformation of the rest of the data back to the time-offset domain, might yield the body waves free from the surface-wave noise. Another approach is to apply a velocity or slowness filter to the passive data. Because from the $\tau - v$ domain (Figure 4(b)) we can find the range of surface-wave velocities, we apply a $\tau - v$ or $\tau - p$ transform to the passive data excluding the range of surface-wave velocities or slownesses. Thereafter, by applying the inverse $\tau - v$ or $\tau - p$ transform we might be able to retrieve only the body waves in the time-offset domain. Forghani et al. (2013) show the effectiveness of using the $\tau - p$ transform in suppressing the surface-wave noise in surface microseismic data.

The aim of this work is to analyze whether passive seismic noise generated during hydraulic fracturing operations can be used to extract surface-wave dispersion characteristics. To demonstrate one of the applications of the dispersion analysis, we performed the dispersion-curve inversion for which we only used one pseudo-shot gather and extracted the 1-D shear-wave velocity profile. To obtain a more detailed velocity model, pseudo-shot gathers can be generated for every receiver location followed by inversion of the dispersion curve to yield a 3D shear-wave velocity structure of the subsurface. It might be more accurate to sort the pseudo-shot gathers into CMP gathers and perform dispersion-curve

inversion on the individual CMP gathers. Since near-surface velocities can be azimuthally anisotropic, one could perform the same analysis for data from different azimuthal sectors to yield a 3D distribution of shear-wave velocity and its azimuthal anisotropy.

CONCLUSIONS

Here, we performed a combined active and passive dispersion analysis to extract and analyze the dispersive characteristics of surface waves. The passive data used here were generated from various operations during hydraulic fracturing of a tight gas reservoir. Pseudo-shot gathers extracted from the passive data using interferometry were of better quality when the pseudo-source location was close to the passive noise sources.

The dispersion character of the fundamental mode is observed to be the same for both the active and passive data. However, for the higher-mode surface waves, passive and active data yield dispersion behaviors at different frequency ranges. Combining the passive and active dispersion analysis, we obtained surface-wave properties within a broader frequency band. We inverted the combined passive and active dispersion curves and obtained a range of acceptable near-surface 1-D shear-wave velocity models.

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LIST OF FIGURES

1 Map view of the receiver array used to acquire the active and passive data; Black (outer array) and gray (central array) dots represent the receivers used for active records and gray dots indicate the receivers used for passive records. The black star represents the location of the active shot used in this study, and the white star represents the location of the receiver used as a pseudo-source in one of the cross-correlation examples.

2 (a) Active shot-gather recorded from the active source location shown by the black star in Figure 1. Note the fundamental and higher-mode surface-wave arrivals that are marked with black and white arrows, respectively. (b) $\tau - p$ image of the shot-gather in Figure 2(a). (c) Dispersion image of the active data obtained by applying 1-D Fourier transform to Figure 2(b). Note that although the frequency content of the active data is 6-30 Hz (Table 1), for comparison with the dispersion image of passive data, the dispersion image is illustrated up to the 100 Hz frequency. In (b) and (c) the colors represent the stack amplitude in $\tau - v$ and dispersion domain, respectively.

3 Plot of two seconds of the raw passive data. This is our starting point for the further analyses.

4 (a) Pseudo-shot gather obtained by cross-correlation of receivers with the pseudo-source shown by the black star in Figure 1. (b) $\tau - v$ image of the pseudo-shot gather in Figure 4(a). (c) Dispersion image of the passive data obtained by applying 1-D Fourier transform to the $\tau - v$ image in Figure 4(b). Note that although the frequency content of the passive data is 6-200 Hz (Table 1), because the frequencies above 100 Hz have very low amplitudes, the dispersion image is illustrated up to the 100 Hz frequency. In (b) and (c) the colors represent the stack amplitude in $\tau - v$ and dispersion domain, respectively.

5 (a) Pseudo-shot gather obtained by cross-correlation of receivers with the pseudo-source shown by the white star in Figure 1. (b) $\tau - v$ image of Figure 5(a). (c) Dispersion image of the passive data obtained by applying 1-D Fourier transform to Figure 5(b). In (b) and (c) the colors represent the stack amplitude in $\tau - v$ and dispersion domain, respectively.

6 (a) Observed dispersion curves (shown in black) used to invert for shear-wave velocity and predicted dispersion curves with high-misfit values (green) and low-misfit values (red); (b) Acceptable shear-wave velocity models with high-misfit values (green) and low-misfit values (red).

7 Schematic of the receiver zone (blue shade) in which surface waves are extracted by interferometry from the passive noise sources in the red ellipse area; the pseudo-source (large black star) is located (a) close to the noise sources and (b) far from the noise sources. Black dots indicate the rest of receivers in the array for which surface waves could not be extracted.

Figure 1: Map view of the receiver array used to acquire the active and passive data; Black (outer array) and gray (central array) dots represent the receivers used for active records and gray dots indicate the receivers used for passive records. The black star represents the location of the active shot used in this study, and the white star represents the location of the receiver used as a pseudo-source in one of the cross-correlation examples.

Figure 2: (a) Active shot-gather recorded from the active source location shown by the black star in Figure 1. Note the fundamental and higher-mode surface-wave arrivals that are marked with black and white arrows, respectively. (b) $\tau - p$ image of the shot-gather in Figure 2(a). (c) Dispersion image of the active data obtained by applying 1-D Fourier transform to Figure 2(b). Note that although the frequency content of the active data is 6-30 Hz (Table 1), for comparison with the dispersion image of passive data, the dispersion image is illustrated up to the 100 Hz frequency. In (b) and (c) the colors represent the stack amplitude in $\tau - v$ and dispersion domain, respectively.

Figure 3: Plot of two seconds of the raw passive data. This is our starting point for the further analyses.

Figure 4: (a) Pseudo-shot gather obtained by cross-correlation of receivers with the pseudo-source shown by the black star in Figure 1. (b) $\tau - v$ image of the pseudo-shot gather in Figure 4(a). (c) Dispersion image of the passive data obtained by applying 1-D Fourier transform to the $\tau - v$ image in Figure 4(b). Note that although the frequency content of the passive data is 6-200 Hz (Table 1), because the frequencies above 100 Hz have very low amplitudes, the dispersion image is illustrated up to the 100 Hz frequency. In (b) and (c) the colors represent the stack amplitude in $\tau - v$ and dispersion domain, respectively.

Figure 5: (a) Pseudo-shot gather obtained by cross-correlation of receivers with the pseudo-source shown by the white star in Figure 1. (b) $\tau-v$ image of Figure 5(a). (c) Dispersion image of the passive data obtained by applying 1-D Fourier transform to Figure 5(b). In (b) and (c) the colors represent the stack amplitude in $\tau-v$ and dispersion domain, respectively.

Figure 6: (a) Observed dispersion curves (shown in black) used to invert for shear-wave velocity and predicted dispersion curves with high-misfit values (green) and low-misfit values (red); (b) Acceptable shear-wave velocity models with high-misfit values (green) and low-misfit values (red).

Figure 7: Schematic of the receiver zone (blue shade) in which surface waves are extracted by interferometry from the passive noise sources in the red ellipse area; the pseudo-source (large black star) is located (a) close to the noise sources and (b) far from the noise sources. Black dots indicate the rest of receivers in the array for which surface waves could not be extracted.

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- 1 Survey parameters

Table 1: Survey parameters

Sampling Rate	2 ms
Frequency Range (active data)	6-30 Hz
Frequency Range (passive data)	6-200 Hz
Number of Receivers (Central array)	1197
Number of Receivers (Outer array)	3871
Receiver Interval (Central array)	30 m
Receiver Interval (Outer array)	60 m
Receiver Component	Vertical