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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 suppressing 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 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 an application of dispersion analysis, we invert the observed surface-wave dispersion characteristics to determine the near-surface, one-dimensional shear-wave velocity.

1. 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 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 (Sabra et al., 2005; Shapiro and Ritzwaller, 2002).

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 (Duncan and Eisner, 2010; Forghani et al., 2012, 2013; Kochnev et al., 2007).

Dispersion analysis of passive data is commonly applied to the passive noise generated from cultural activities, mostly road traffic (Halliday et al., 2008; Park et al., 2007). 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 analyses provide broader frequency content of the dispersive surface waves, thereby resulting in a more complete analysis of these waves (Halliday et al., 2008; Malovichko et al., 2005; Park et al., 2005, 2007).

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For example, the combined active and passive surface-wave analyses 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 analyses 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.

2. 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).

Fig. 1 illustrates the receiver array used in this acquisition.

The acquisition parameters of these datasets are summarized in Table 1. Note that the recording frequency range for the passive data (6200 Hz) is broader than the one for the active data (6-30 Hz).

3. 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:

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

(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 the 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 $v = 1/p$.

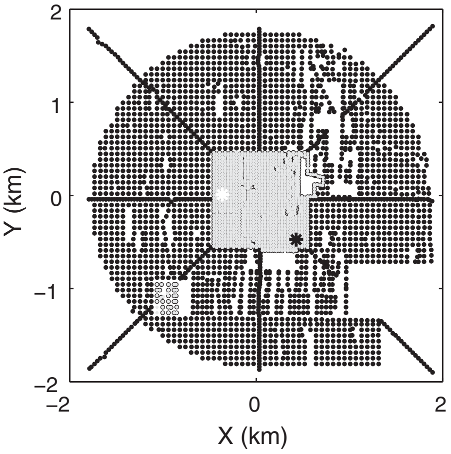

Fig. 1. Map view of the receiver array used to acquire the active and passive data; Black (outer array) and gray (central array) dots represent the receivers used for active records and gray dots indicate the receivers used for passive records. The black star represents the location of the active shot 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.

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

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:

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

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.

4. 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 Fig. 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. Fig. 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.

Fig. 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 (Fig. 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/s to 850 m/s. 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.

5. 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).