Assessing the reliability of low frequencies in geophone records

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Summary

The reliability of low frequencies is a crucial question for geophone records. An example is the data recorded for passive seismic studies using geophones paired with TEXAN miniature recorders, where the high resonance frequency of the geophones degrades the low-frequency waveforms and increases the ambiguity in phase picking. We have evaluated the reliability of such data from a mobile array of geophone-TEXAN pairs in central China. The frequency response of the geophones can be easily established using the Power Spectral Density Ratio (PSDR) between records of the geophone-TEXAN pairs and a broadband seismometer occupying the same sites. This method allows a quantification of the retrievable frequencies of short-period seismic data and a reliable spectral extension. For instance, the retrievable frequency band of the data recorded by 4.5-Hz geophones can be extended down to 0.3 Hz for regional M2.0 earthquakes in our study area, and down to 0.04 Hz for surface wave of a M6.2 teleseismic event in Indonesia. After applying an inverse filter within the retrievable frequency band, the quality of the data is improved significantly and matched well with the records of a nearby broadband permanent station. The new method is useful for assessing and extracting low-frequency information from geophone data.

Introduction

Geophones are widely used in both exploration seismology and solid earth seismology with a reliable quality and reasonable cost. The resonance frequencies of such short-period seismic sensors are typically around 10 Hz, and some are 4.5 Hz and 1 Hz. Those frequency ranges are sufficient for most active-source studies of sedimentary basins and upper crust where the main frequency is higher than 10 Hz. However, the targeted frequencies can be much lower for crustal-scale studies or monitoring microseismics. During the past decades the geophones have been used to study the regional seismic velocity structure using both active or passive sources (Nielsen and Thybo, 2009; Środa, Czuba, and Grad, et al. 2006; Majdański, Kozlovskaya, and Grad, et al., 2007; Malinowski, 2009; Nielsen and Thybo, 2009). In those studies only the high frequency information, such as 2 ~ 5 Hz (Środa, Czuba, and Grad, etal. 2006), is used for the regional seismic structure study. This frequency range is insufficient for studying regional structure or low-frequency seismic sources. For example, the seismograms of a M4.5 earthquake 100 km away may have a central frequency around 5 Hz and with significant energy at frequencies lower than 1 Hz (Clinton and Heaton, 2002). The analysis of the surface wave response of the regional quarry blast sources will need the frequency band from 0.2 Hz to 40 Hz (Yao and Dorman, 1992), and the source mechanism study needs the frequency band from 0.5 Hz to 2 Hz (Tan and Helmberger, 2007). Most importantly, acquiring the low frequencies is the key practical way to improve the frequency bandwidth and therefore seismic resolution (Knapp, 1990).

The two practical ways to extend the frequency bandwidth of seismic data are: improving the low-frequency response of the sensor and balancing the low frequencies during the processing. The former can be achieved through adding better types of circuits to extending the frequency response (Barzilai, 2002; Webb, Deaton, and Lemire, 2001). But those processes are too complex for practical acquisition. The balancing of the low frequencies through processing, such as by inverse filtering or deconvolution, is more convenient (Havskov and Alguacil, 2004; Scherbaum, 2001). However, the key for a successful inverse filtering is to determine the reliable frequency range for frequency balance. The inverse filter is actually the inverse of the frequency response of the sensor, which is normally given by the factory. But the full reliably invertible frequency range is not be given by the factory due to the nonlinear behavior for frequencies lower than the resonance frequency and the influence of the inherent noise of the instruments. One of the most commonly used methods analyzing the lowest reliable frequency is noise analysis with power spectral density (PSD), which estimates the lowest reliable frequency through the comparison between the PSD of the instrument and the New Noise Model suggested by Peterson (Peterson, 1993; Havskov and Alguacil, 2004; Havskov, 2007).

In this paper we device a new method for determining the lowest retrievable frequency of the geophone in the field, including the estimation of the reliable inverse filter and determination of the lowest retrievable frequency through a side-by-side comparison between the well calibrated broadband data and the geophone data. From 2007 to 2009, we carried out several field monitoring tests using different seismic sensors in Three Gorges Reservoir (TGR) region in central China. During those tests different kinds of seismic events are recorded, including teleseismic events (about 4,000 km offset), regional seismic events (about 500 km offset), local seismic events (10~100 km offset) and the quarry blasts (several kilometers offset). Through analysing data from those events, a reliable inverse filter is built to compensate for the low frequencies of the geophone data. Combining both the reliable inverse filter and the signal to noise ratio (SNR) analysis, we found that in a normal noise environment the reliable frequency range for the 4.5 Hz geophone can be extended to 0.3 Hz. This low-frequency limit agrees with the results of Havskov (2007), and is lower than the common thinking of 1 Hz (Havskov and Alguacil, 2004). Using records of the microseismic events in the TGR region, we will demonstrate the new way to determine the reliable frequency range of the short-period sensors, and to extend the frequency bandwidth of the short-period data. Therefore, if we need to acquire low-frequency data using geophones, we may add several broadband seismometers to occupy the sites as some of the geophones; this will facilitate a reliable recovery of the low frequencies.

Data acquisition and quality analysis

During September 2007 and June 2009, we conducted several seismic monitoring tests in a permanent seismic monitoring station (111.32E, 30.78N) in the central China. The permanent station has the Geodevice BBVS-60 broad-band seismometer with the flat frequency respond band from 60 s to 40 Hz and the self noise below USGS NLNM from 60 s to 10 Hz. Our seismic recording system employed was the single-channel RefTek 125 Texan recorder with a 4.5 Hz GS-11D single-component geophone. The broad-band seismometer and geophones are set on the same bed rock in a cave, where geophone is cemented by gypsum to enhance the coupling with the bed rock. The experiment involves several geophones inside the seismic monitoring cave (Figure 1).

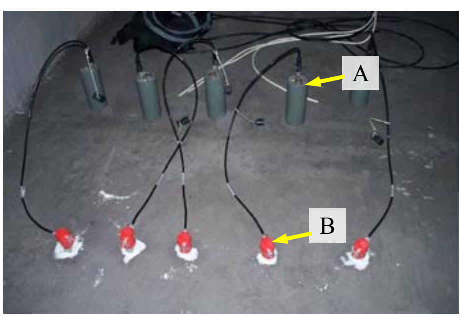

Figure 1. Picture of a recording test in a cave. Label A denotes a RefTek 125 recorder (TEXAN). Label B denotes the geophones coupled with the bedrock.

During the monitoring period several kinds of seismic events are recorded, such as teleseismic events ($d \sim 4000$km), regional seismic events (400 km $< d <$ 700km), local small earthquakes (10 km $< d <$ 200km), and manmade blasts ($d <$ 20km), where d represents the epicentral distance. Figure 2 shows the raw data and the power spectral density (PSD) of a M2.4 microseismic event in Three Gorges Reservoir (TGR) with hypocenter distance about 100 km. The upper panel shows the data recorded by the broadband seismometer and the lower one shows the data recorded by the geophone.

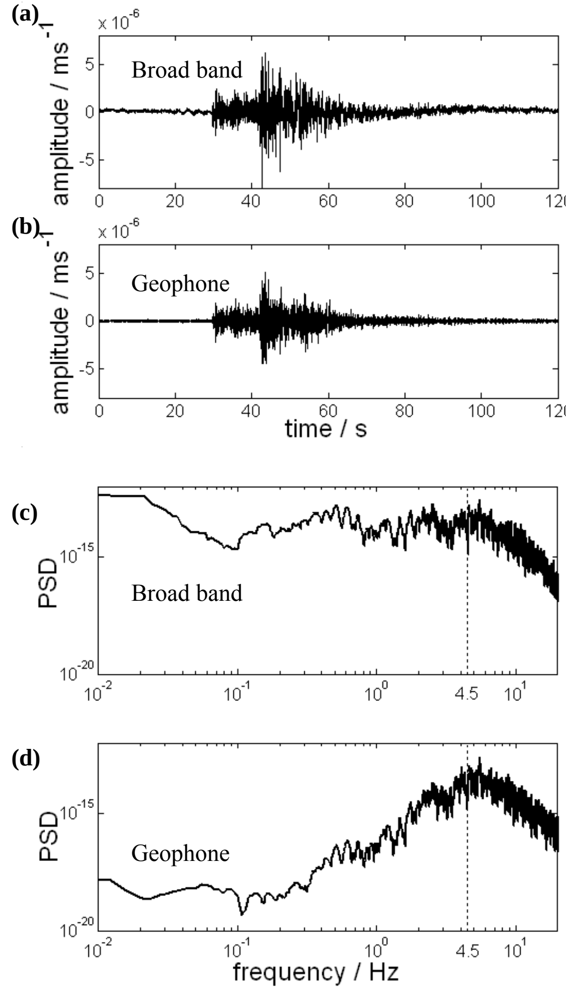

Figure 2. Raw data of the vertical component of a M2.4 event in Three Gorges Reservoir (TGR) recorded by (a) a broadband seismometer and (b) a geophone-TEXAN pair. (c) and (d) show the corresponding Power Spectral Density (PSD). The vertical dotted shows the location of 4.5 Hz.

Figure 2 shows that the microseismic event recorded by geophone has lower energy and lower frequency than that in broadband data recorded in Figure 2(a). The reason for this can be explained through the comparison between Figure 2(c) and Figure 2(d). This is mainly caused by the fact that the geophone distorts the seismic signal in low frequency range, and cannot response to the low frequency signal equally with high frequency signal. So we need to find the frequency response of the geophone and compensate its low frequency energy.

Building the inverse filter using power spectral density ratio (PSDR)

Inverse filter (or called deconvolution) is a popular method to compensate the low frequency components of the geophone data (Havskov and Alguacil 2004; Scherbaum 2001). The most critical stage of this method is designing the inverse filter, which is the inversion of the frequency response of the instruments. Normally the frequency response curve is got from the instrument company, but those response curves only includes a small amount of the low frequency lower than the resonance frequency, such as 2 Hz for 4.5 Hz geophone. And also, the environment noises make another challenge to the application of the industrial response curve, such as the intrinsic noise or self-noise of geophone.

Normally the sensor self noise has significant influence on both the low frequency and the high frequency, as shown in Figure 3 (Scherbaum, 2001).

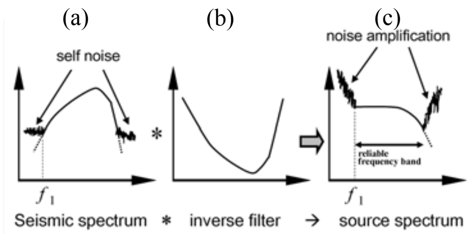

Figure 3. The intrinsic noise of the instrument degrades both the low- and high-frequencies when applying the inverse filter (Scherbaum 2001). The dashed line in the left panel represents the noise-free signal. f_1 and f_2 denote the corner frequencies.

The frequency response of the seismometer has two corner frequencies (low corner frequency f_1 and high corner frequency f_2 as shown in Figure 3(a)) which separate the response curve into the signal part from f_1 to f_2, and the noise part that outside of the signal part. Those two corner frequencies determine the frequency range of the inverse filter since the unlimited inverse filter will cause the noisy artifacts shown in Figure 3(c). Normally the influence of the high frequency noise can be removed by the low-pass filter for the regional seismic events with the main frequency lower than 10 Hz. But the influence of the low corner frequency can hardly be controlled before we know the low corner frequency. In this paper, the lower corner frequency will be determined through the analysis of the response of the instruments.

The response of the instrument is the ratio between the spectra of the instrument and the true ground motion. Since BBVS-60 has the flat response frequency and the low noise range both covering the frequency from 60 s to 10 Hz, we assume the broadband record represents the true ground motion, and then the ratio between the spectra of the geophone and the broadband seismometer represents the frequency response of the geophone. This method is reliable within the frequency range of the low SNR for broadband seismometer. So the inverse filter is determined by the inversion of this spectral ratio. The Fourier spectrum and the PSD are two kinds of spectra usually used in data processing. The Fourier spectrum represents the amplitude for each frequency components of the record, while the PSD describes the general frequency composition of the data in terms of spectral density of its mean square value (Bendat and Piersol, 1971). So the spectral ratio also has two versions, which are compared and shown in Figure 4.

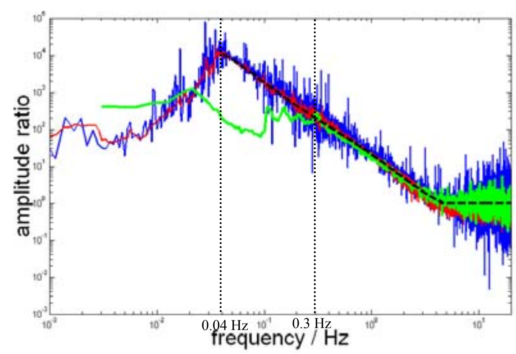

Figure 4. Inverse filter of the geophone (the dark dashed line) calculated by the Fourier spectral ratio (blue) and the square root of the PSDR for an Indonesian teleseismic event (red). The green curve shows the PSDR of a microseismic event in TGR (green). The vertical dotted line shows the frequency of 0.04 Hz and 0.3 Hz.

From Figure 4 we can see that the PSD ratio (PSDR) curve (red curve) is much smoother than the Fourier spectral ratio curve (blue curve). So the PSDR is more convenient to determine the inverse filter than the ratio of Fourier spectra. The inverse filter is estimated through a five-order polynomial fitting. The formula for the inverse filter ***F*** is

$$F^2 = \begin{cases} \exp[a \cdot \log(f)^5 + b \cdot \log(f)^4 + c \cdot \log(f)^3 + d \cdot \log(f)^2 \\ \quad + e \cdot \log(f) + g], \quad 0.04Hz \le f \le 4.5Hz \\ 1, \quad else \end{cases} , (1)$$

where f represents frequency; a = 0.0280, b = 0.1262, c = 0.0206, d = -0.3502, e = -4.0301, and g = 6.1232. One thing need to be mentioned is that this equation is used to retrieve low frequency of the GS-11D 4.5 Hz geophone. But this method is still suitable for determining the inverse filter of the other sensors. Normally the choice of the item in equation (1) is arbitrary. Here we choose five order polynomials to avoid the unstable oscillation caused by the higher order.

Figure 4 also shows that there are two splitting points at 0.04 Hz and 0.3 Hz on the PSDR curve of the teleseismic event and the microseismic event respectively. This tells us the lowest retrievable frequencies for those two seismic events, i.e. the lower corner frequency f_1 in Figure 3, are respectively 0.04 Hz and 0.3 Hz. The frequency range lower than the splitting point of the PSDR means that the geophone fails to record the true ground motion, which is the result of the influence of the high intrinsic noise level of geophone at low frequency. Then combining both the inverse filter function and the lowest retrievable frequency we can determine the inverse filter for retrieving the low frequency of the geophone.

Recovering the low frequency for a regional array data

For regional earthquake study, the 2D profile is often used to identify the Moho reflection and estimate the underground velocity through tomography. Figure 5(a) shows an example of a 2D profile for the same M2.4 event in TGR region with that shown in Figure 2. In this profile we can hardly recognize the reflection and surface wave. After applying the inverse filter shown in Figure 4, both the surface waves and the deep reflection waves are improved, which is shown in Figure 5(b).

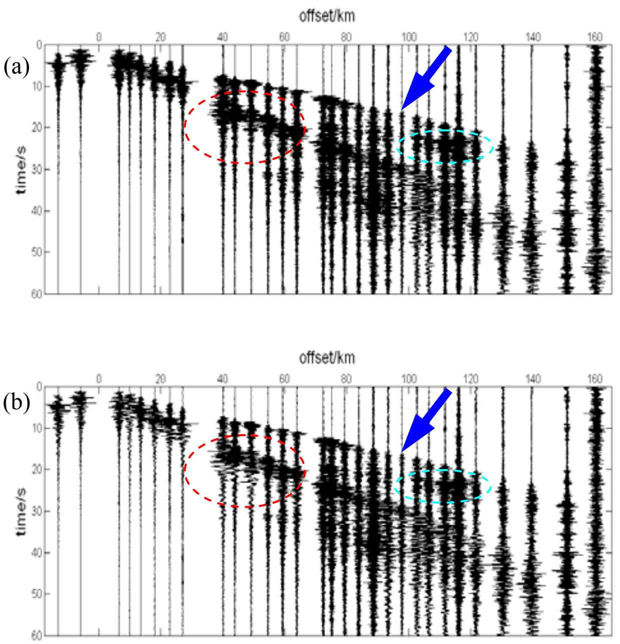

Figure 5. The improvement of the original profile through inverse filter. (a) The original data profile, (b) The improved profile with recovered low-frequencies.

In Figure 5, the lowest retrievable frequency is chosen as 0.3 Hz. For the higher SNR in the field the retrievable frequency range of the geophone will be wider. To show the detail of the improvement, one channel, shown by blue arrow in Figure 5, is chosen to do the comparison with the broadband data. The comparison results are shown in Figure 6, in which the retrieved first arrival waveform (red curve in Figure 6b) shows better match with the broadband record (blue curve in Figure 6) comparing with the raw data of geophone (red curve in Figure 6a).

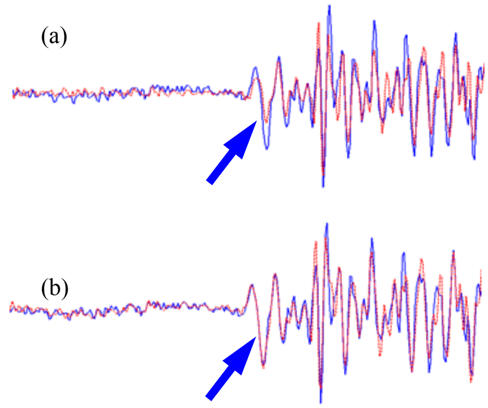

Figure 6. The comparison of first-arrival waveform of the raw data (a) and the retrieved result (b) of the local seismic events. The distance between source and receiver is about 100 km. (a) Comparison between the raw geophone data (red dotted line) and the broadband data (blue solid line); (b) Comparison between the recovered geophone data (red dotted line) and the broadband data (blue solid line).

Conclusions

Inverse filtering is an effective way to compensate for the low frequency energy of seismic data. Two necessary steps in inverse filtering are estimating the stable inverse filter and determining the lowest limit of reliable frequencies. In this study both the inverse filter and the lowest retrievable frequency are estimated through the analysis of the power spectral density ratio (PSDR). The estimated lowest retrievable frequency for the GS-11D geophone is 0.3 Hz for local microseismic events, which as agrees with the noise analysis result. This is a reliable way to design the inverse filter with variable environments and different noise levels. This PSDR method is applicable for other short-period sensors and will be useful for extracting more information through extending the low-frequency range of the short-period seismic data, such as that recorded by geophone-TEXAN instruments.

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