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EXTRACTION OF REFLECTED WAVES FROM EARTHQUAKE MOTION RECORDS USING SEISMIC INTERFEROMETRY FOR S-WAVE VELOCITY PROFILING

S. Sugama(1), H. Miura(2)

(1) *Undergraduate Student, Hiroshima University, b161564@hiroshima-u.ac.jp*
(2) *Associate Professor, Hiroshima University, hmiura@hiroshima-u.ac.jp*

Abstract

Seismic interferometry techniques have been developed as an inexpensive and environmentally friendly method for exploring subsurface and crustal structures using ground motion records. Application of spectral whitening approach in the data processing was recently proposed by Oren and Nowack (2017). This technique mainly consists of spectral whitening for removing source and path effects, bandpass filtering and autocorrelation analysis in order to extract the information related to deep underground structures. The settings of parameters and applicability of the seismic interferometry method need to be more carefully discussed because the method has been applied at limited sites. In this study, we applied the seismic interferometry technique to the earthquake motion records observed at HRS013 and HRS018, the K-NET stations in Chugoku district, western Japan, to extract the reflected waves from strong impedance layers in the undergrounds. We compare the results of the autocorrelation analysis for the observation records to the theoretical values calculated from the Vs models at the stations. We confirmed that the reflected waves are successfully extracted by the analysis based on the parameters proposed by Chimoto and Yamanaka (2019), and the travel times of the predominant phases well agree with the theoretical travel time from the seismic bedrocks. Several bandpass filter ranges are examined to more clearly extract the reflected waves. The reflected waves are not clearly extracted when the filter range includes higher frequency components, even if it sufficiently covers the undulation frequencies. We found that the frequency range for 0.50-2.00 Hz in the bandpass filtering provide better results in detecting the reflected waves at the target stations.

Keywords: seismic interferometry, S-wave velocity structure, earthquake motion records, reflected wave

1. Introduction

It is important to identify accurate subsurface structures at earthquake motion observation stations for evaluating the site effects and predicting strong motions in future earthquakes. Due to the recent development of strong motion networks in Japan, many earthquake motion records have been collected. They have been widely used to evaluate the characteristics of ground motions and to investigate the site conditions. For example, at K-NET stations operated by National Research Institute for Earth Science and Disaster Resilience (NIED), earthquake motion records have been archived at over 1000 stations across the country since 1996. However, the deep underground structures at most of the observation stations including K-NET remain unclear because they have been rarely investigated. It is expected that subsurface structure at an observation station would be accurately explored only from earthquake motion records at the surface of the station.

Recently seismic interferometry techniques have been developed for exploring subsurface and crustal structures by many researchers [e.g., 1, 2]. These techniques are based on autocorrelation analysis of ground motion records at a single station or cross-correlation analysis of records observed at multiple stations. Previous studies revealed that information related to deep underground structures beneath the observation sites were correctly extracted from the autocorrelation/cross-correlation analyses without borehole records. Oren and Nowack [3] proposed a seismic interferometry technique to extract reflected waves from strong impedance layer in deep underground by autocorrelation analysis of ambient noise records at a single station using temporal sign-bit normalization, spectral whitening and bandpass filtering. They showed that source and path effects were removed from the records and the phases reflected from the deep underground layers were found in the autocorrelation functions by the proposed procedure. Chimoto and Yamanaka [4] also applied this technique to the strong motion records observed at KiK-net Narita, Chiba prefecture, Japan in order to optimize the S-wave velocity (Vs) structure model. They found that the reflected waves from the seismic bedrock in the autocorrelation functions obtained from the surface records. They also indicated that the setting of parameters for the bandpass filter range and smoothing window would be important to accurately extract the reflected waves.

The proposed technique would be useful for exploring deep underground structures from ground motion records at surface. Since the method has been applied at limited sites, and the applicability of the method needs to be discussed at different site conditions. In this study, we apply the seismic interferometry technique proposed by Oren and Nowack [3] to the earthquake motion records observed at K-NET stations in Chugoku district, western Japan where the deep underground Vs models were estimated by Miura et al. [5]. The frequency ranges in bandpass filtering used in the analysis is examined for accurately extracting the reflected waves.

2. Data and Method

The earthquake motion data recorded at HRS013 and HRS018, K-NET stations in Hiroshima prefecture, Japan are analyzed because the deep underground Vs structures were estimated by Miura et al. [5]. Figure 1 shows the locations of these stations, epicenters and magnitude of the earthquakes. First, we collect earthquake motion records observed from 2001 to 2013. In order to exclude nonlinear response data, the records with peak ground acceleration (PGA) smaller than 150 gal are collected. Totally 64 records at HRS013 and 77 records at HRS018 are analyzed in this study.

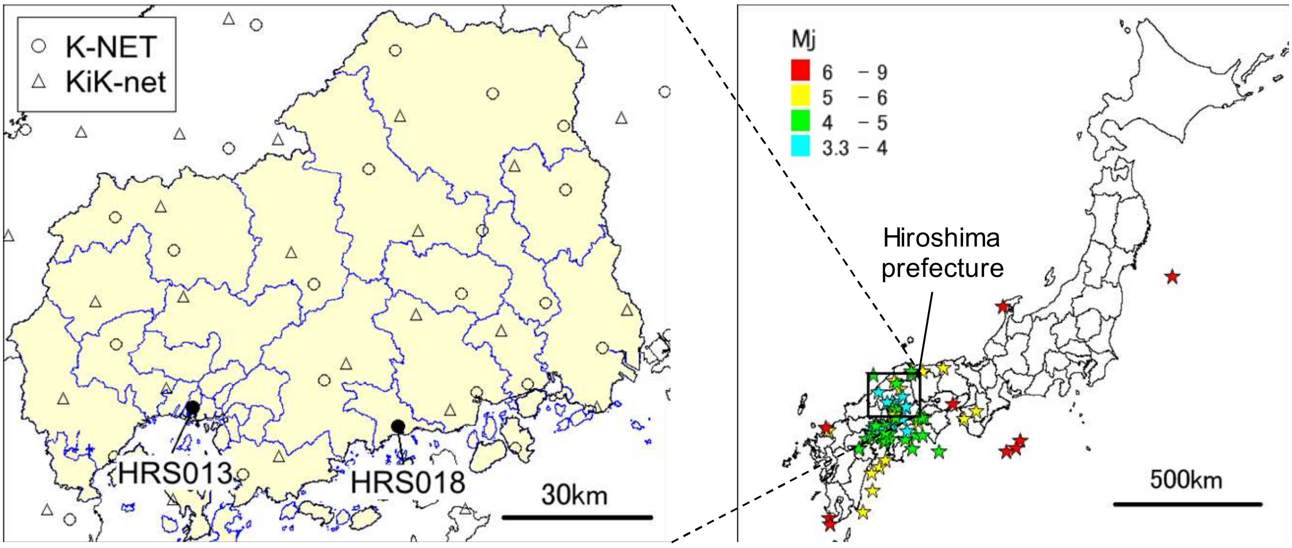

Fig.1 – Locations of target stations in Hiroshima prefecture (left). Locations of epicenters and magnitude of the earthquakes recorded at HRS013 and HRS018 (right).

Figure 2 shows the workflow of the seismic interferometry technique adopted in this study. This method consists of spectral whitening, bandpass filtering and calculation of autocorrelation functions in order to extract reflected phase from strong impedance layer beneath the station. For the initial pre-processing of the seismic data, original data is converted to ASCII format and baseline corrections are performed by removing mean values from the data. Cosine taper with 0.5 second width is then applied to the beginning and ending of the records to reduce the link effect in the Fourier transform. We calculate unsmoothed and smoothed Fourier amplitude spectra by the Parzen window with the bandwidth of 0.5 Hz. The spectral whitening is performed by calculating the ratio of the unsmoothed Fourier spectrum to the smoothed Fourier spectrum to remove frequency dependent source and path effect. The bandpass filtering is applied to the whitened spectra, and time-history data is obtained by inverse Fourier transform. Finally, autocorrelations are calculated for all the records and they are stacked to clearly identify the reflected waves from strong impedance layer of the underground.

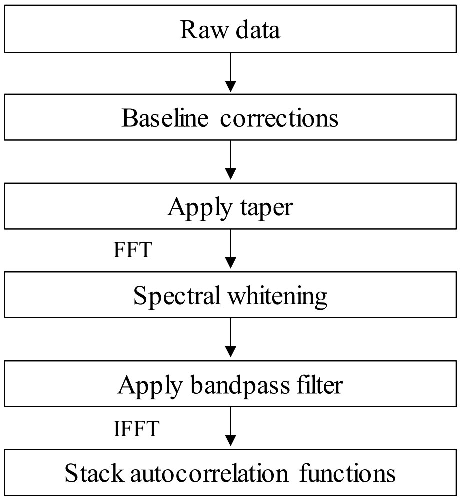

Fig.2 – Workflow of data processing.

Although seismic interferometry technique assumes vertical incident of S-waves below the stations [1], Chimoto and Yamanaka [4] showed that the autocorrelation functions for larger incident data were similar to those for smaller incident data. They also showed that autocorrelation functions calculated from whole parts of the records were not significantly different from those calculated from only S-wave parts of the records in the arrival times of the reflected waves. Therefore, we analyze whole parts for all the selected records.

At HRS013 and HRS018 stations, Miura et al. [5] already estimated the Vs structure models from the seismic bedrock (Vs=3000m/s) to surface by joint inversion technique of site amplification and receiver function obtained from earthquake motion data. These Vs models are shown in Table 1 and Fig.3. The densities of each layer (kg/m^3) are given from the Vs values (m/s) using Eq. (1).

$$\rho = 1400 + 670\sqrt{\frac{Vs}{1000}} \tag{1}$$

We compare the computed autocorrelation functions and theoretical values calculated from the estimated Vs models to discuss the relationship between reflected waves and underground structures.

Table 1 – Vs structure models of HRS013 (left) and HRS018 (right) estimated by Miura et al. [5]. Densities of each layer(kg/m^3) are given from the Vs values (m/s) using Eq. (1).

HRS013					HRS018				
Layer	Vs(m/s)	H(m)	Depth(m)	Density(kg/m^3)	Layer	Vs(m/s)	H(m)	Depth(m)	Density(kg/m^3)
1	93	2	2	1605	1	125	4	4	1637
2	153	30	32	1662	2	138	20	25	1649
3	360	18	50	1802	3	360	21	46	1802
4	681	24	74	1953	4	652	22	67	1941
5	1646	345	419	2259	5	1634	320	387	2257
6	2218	251	670	2398	6	2134	273	660	2379
7	3000	-	-	2560	7	3000	-	-	2560

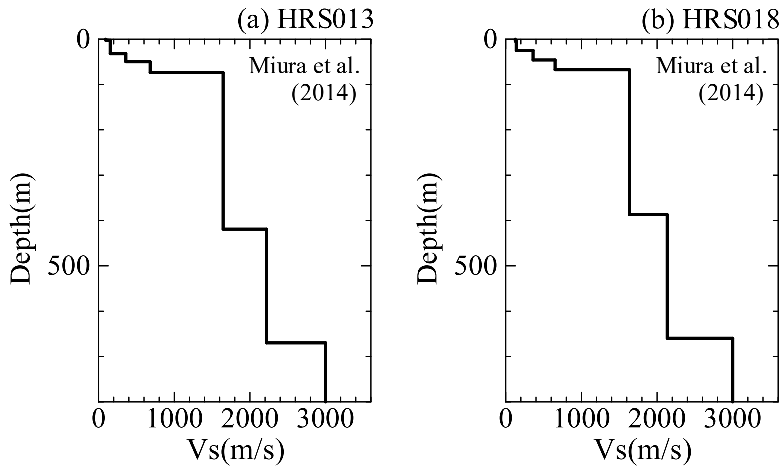

Fig.3 – Vs structure models estimated by Miura et al. [5]. (a) is a model of HRS013 (left). (b) is a model of HRS018 (right).

3. Results

Figure 4 shows four typical Fourier spectra of the earthquake motion records at HRS013. The figure includes unsmoothed and smoothed spectra, and whitened spectra. As proposed in Oren and Nowack [3], the interval of the peaks in the whitened spectra can be defined as undulation frequency. The undulation frequency is found approximately at 0.8 Hz. After applying the bandpass filtering with the band width of 0.5-2.0 Hz, the whitened time history is obtained by inverse Fourier transform. The autocorrelations are then calculated from the whitened time history, and are stacked for each horizontal component of the records. Figure 5 shows the shape of the bandpass filter used in this study. The four corner frequencies are given in the filtering. The filter range used in this process is discussed later.

Figure 6 shows the stacked autocorrelations at HRS013 and HRS018 for NS and EW components. There are two highlighted negative peaks in each panel of Fig.6. The predominant peaks are found at 1.31 s and 2.29 s in NS component of HRS013, and at 1.32 s and 2.29 s in EW component. The predominant peaks are found at 1.24 s and 2.03 s in NS component of HRS018, and at 1.23 s and 2.05 s in EW component. These peaks are considered to be the reflected waves from the boundary of the layers in the underground. In order to discuss the origin of the reflected waves, theoretical values of two-way travel times of S-waves and theoretical undulation frequencies are calculated for each layer boundary from the Vs models as shown in

Table 2. The detected travel times of the reflected waves around 1.2~1.3 s almost correspond to the travel times from the boundary between the 6th and the 7th layers. Since the 7th layers are the seismic bedrock with the Vs of 3000 m/s, the results indicate that the reflected waves are generated from the seismic bedrocks. Furthermore, the positive peaks at about 2.7 s in HRS013 and at around 2.5 s in HRS018 shown in Figs.6 can be considered to be the travel times of the multiple reflected waves between the seismic bedrock and surface.

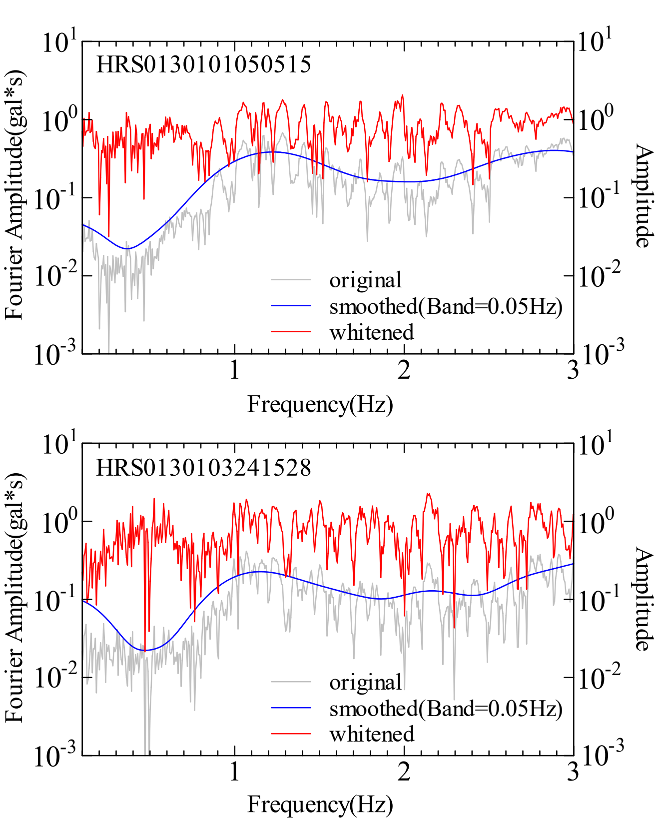

Fig.4 – Examples of Fourier amplitude spectrum for NS component of the earthquake motion records at HRS013.

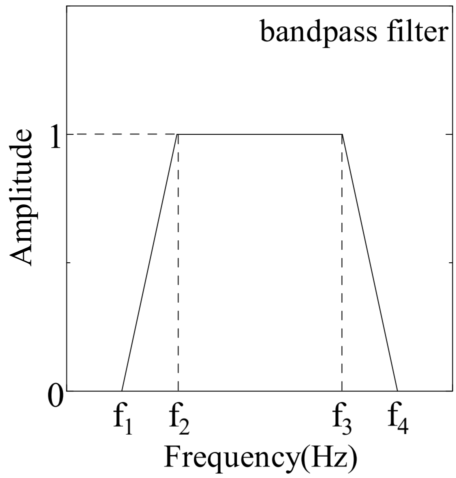

Fig.5 – The bandpass filter used in this study

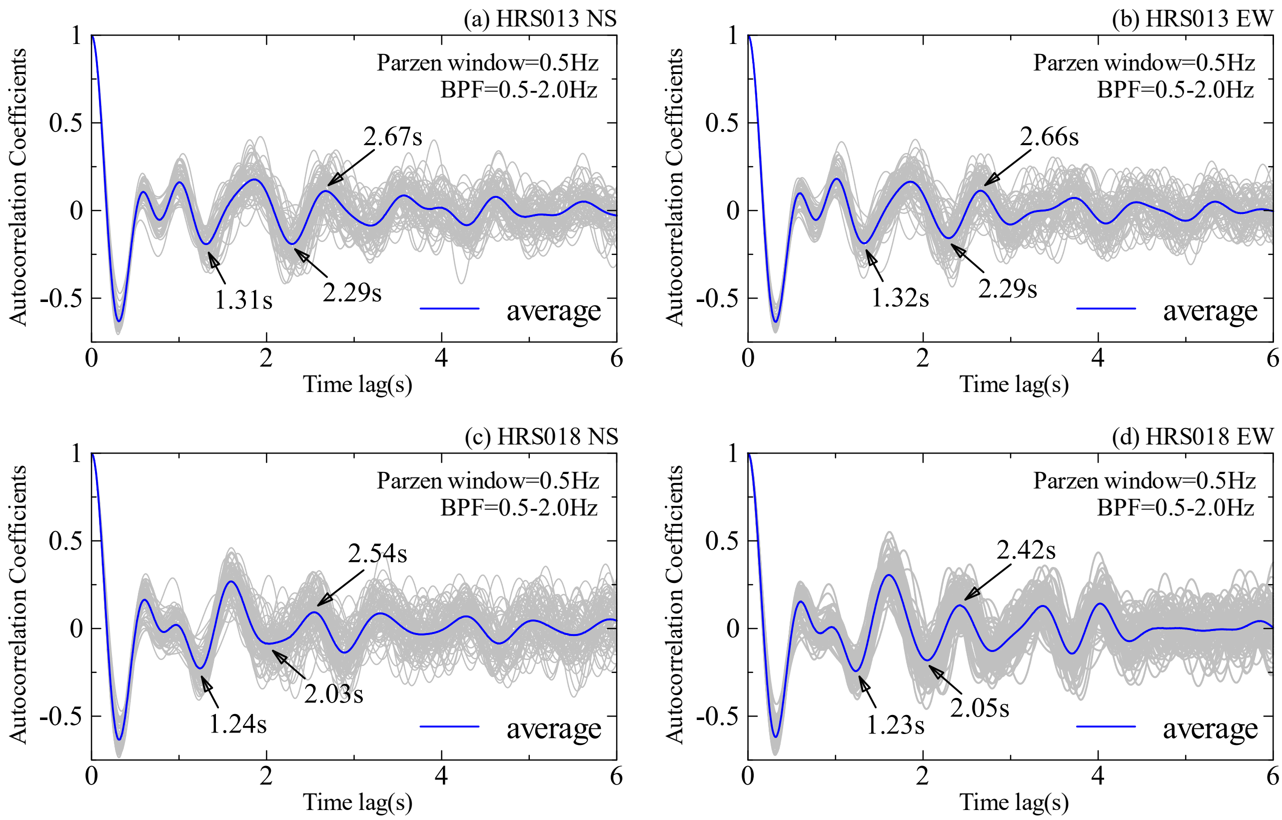

Fig.6 – Autocorrelations for each earthquake motion record of HRS013 and HRS018 are shown with gray color and their stacked waveform is shown with blue color. (a) shows autocorrelations of HRS013 records for NS components (left top). (b) shows autocorrelations of HRS013 records for EW components (right top). (c) shows autocorrelations of HRS018 records for NS components (left bottom). (d) shows autocorrelations of HRS018 records for EW components (right bottom).

4. Discussion

We examine several different filter ranges in the bandpass filtering to more clearly extract the reflected waves. According to Oren and Nowack [3], the undulation frequency of the spectrum is inversely related to the two-way travel time of reflected waves. At the stations where the bedrock depths are relatively shallower compared to the KiK-net Narita discussed in Chimoto and Yamanaka [4], the travel time of reflected waves between the ground surface and the seismic bedrock is expected to be smaller, consequently, the undulation frequency to be larger. At HRS013 and HRS018, the undulation frequencies of reflected waves from deep layer boundaries is about 0.80-1.05Hz as shown in Table 2. In order to extract distinct reflected waves, the range of bandpass filter should cover several undulation frequencies.

Table 3 show seven cases of the bandpass filter ranges analyzed in this study. Four frequencies, f1, f2, f3 and f4 indicate the four corner frequencies shown in Fig. 5. We calculate the autocorrelations for NS components of the records of HRS013 for each case. Figure 7 shows the stacked autocorrelations for each range of the bandpass filter. Figure 7(a) includes the stacked autocorrelations with the filter ranges of Case 1-3. It appears that the peaks of stacked autocorrelation become unclear when the filter includes higher frequency components, although the wider filter range fully covers the undulation frequencies. The similar characteristics are found in Fig. 7(b) that includes the filter ranges of Case 4-7. Theoretically, the filtering range should include higher frequencies such as Case 2 and 3 in detecting reflected waves from shallower seismic bedrocks such as HRS013 and HRS018 (Chimoto and Yamanaka [4]).

Table 2 – Impedance ratios, two-way travel-times and undulation frequencies for each layer boundary calculated from Vs structure models of Miura et al. [5]. HRS013 (top) and HRS018 (bottom).

HRS013			
Layer boundary	Impedance ratio	Two-way travel time(s)	Undulation frequency(Hz)
1st & 2nd	0.59	0.05	19.87
2nd & 3rd	0.39	0.44	2.27
3rd & 4th	0.49	0.54	1.86
4th & 5th	0.36	0.61	1.64
5th & 6th	0.70	1.03	0.97
6th & 7th	0.69	1.25	0.80

HRS018			
Layer boundary	Impedance ratio	Two-way travel time(s)	Undulation frequency(Hz)
1st & 2nd	0.90	0.07	14.26
2nd & 3rd	0.35	0.36	2.75
3rd & 4th	0.51	0.48	2.08
4th & 5th	0.34	0.55	1.83
5th & 6th	0.73	0.94	1.07
6th & 7th	0.66	1.19	0.84

However, the results show that the amplitudes of the autocorrelations become smaller when the filtering range shifts higher frequency zone. One of the reasons for such smaller amplitudes in higher frequency would be that the seismic waves in higher frequency are contaminated by high frequency scattering during the propagation to the surface. Considering these results, the bandpass filtering with the range of 0.5-2.0 Hz provide predominant peaks in the autocorrelations of the record at HRS013 and HRS018.

Table 3 – The filter ranges used in this study.

Ranges of bandpass filter (Hz)				
Case	f1	f2	f3	f4
1	0.40	0.50	2.00	2.50
2	0.40	0.50	2.50	3.00
3	0.40	0.50	3.00	3.50
4	0.05	0.10	1.50	1.75
5	0.05	0.10	2.00	2.50
6	0.05	0.10	2.50	3.00
7	0.05	0.10	3.00	3.50

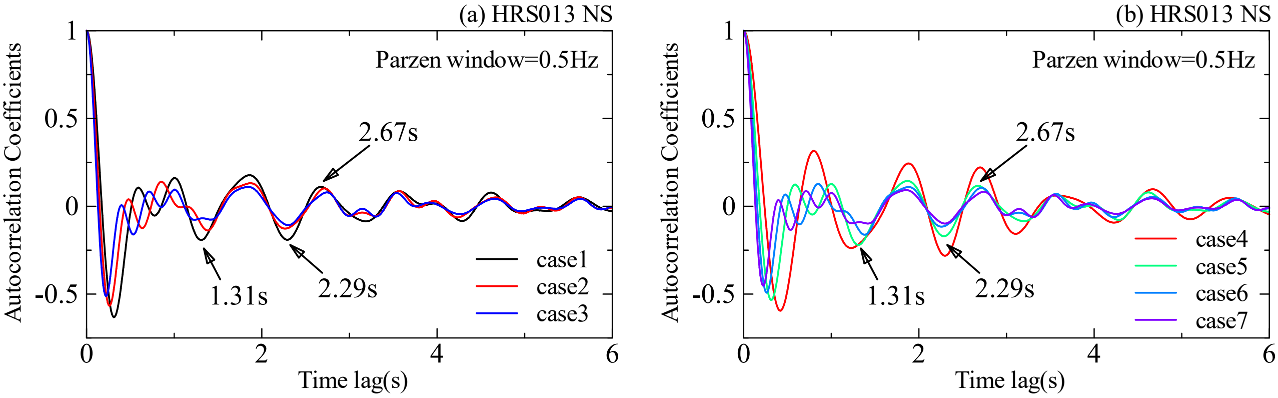

Fig.7 – Stacked autocorrelations for each bandpass filter range (as shown in Table 3). The autocorrelations were calculated for NS components of the record of HRS013. (a) shows the stacked autocorrelations with the filter ranges of Case 1-3 (left panel). (b) shows the stacked autocorrelations with the filter ranges of Case 4-7 (right panel).

5. Conclusions

The seismic interferometry technique proposed by Oren and Nowack [3] was applied to the earthquake motion records of K-NET in Chugoku district, western Japan. The reflected waves were successfully extracted by the parameters proposed by Chimoto and Yamanaka [4] even at the different site conditions. We confirmed that the travel times of the reflected waves almost correspond to the theoretical travel times from the seismic bedrocks, indicating that the reflected waves were generated from the seismic bedrocks. Also, we examined various bandpass filter range to more clearly extract the reflected waves. It was found that the reflected waves are not clearly extracted when the filter range includes higher frequency components. The range of the bandpass filtering for 0.5-2.0 Hz provided clearer peaks in the autocorrelation than other bandwidths.

6. Acknowledgements

Earthquake motion records observed at the K-NET stations operated by National Research Institute for Earth Science and Disaster Resilience were used in this study.

7. References

[1] Claerbout, J. F. (1968): Synthesis of a layered medium from its acoustic transmission response, *Geophysics*, **33**(2), 264-269.

[2] Nakahara, H. (2015): Auto correlation analysis of coda waves from local earthquakes for detecting temporal changes in shallow subsurface structures: the 2011 Tohoku-Oki, Japan earthquake. *Pure Appl. Geophys.*, 172, 213-224.

[3] Oren, C. and Nowack, R. L. (2017): Seismic body-wave interferometry using noise autocorrelation for crustal structure, *Geophys. J. Int.*, **208**, 321-332.

[4] Chimoto, K. and Yamanaka, H. (2019): S-Wave velocity structure exploration of sedimentary layers using seismic interferometry on strong motion records, *Explor. Geophys.* 50: 625-633

[5] Miura, H., Manabe, R., Kanno, T., and Abiru, T. (2014): Estimation of S-Wave Velocity Structure Model by Joint Inversion of Site Amplification Factor and Receiver Function, *J. JAEE*, **14**, 31-49 (in Japanese with English Abstract).

