Retrieval of Rayleigh wave ellipticity from ambient vibration recordings- Introducing CVRD method

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ABSTRACT

Seismic noise is nowadays widely used in geophysics being easy and non-invasive techniques to characterize the subsoil structure. Different single and array methods have been introduced in this field to study seismic noise characteristics. RayDec as a single station method estimates the ellipticity curve of Rayleigh wave by stacking the time blocks of the signal with respect to the Random Decrement (RD) condition. In this study, we propose Vector Random Decrement (VRD) technique to obtain the ellipticity curve for a large number of stations recorded simultaneously in the array. The VRD technique benefits using vector triggering condition which forces every component of the array stations satisfy the common triggering points. We named the method as Common Vector Random Decrement (CVRD) technique in which common triggering points of all vertical components are used to determine the ellipticity curve of the array. In order to verify the method, an array data set is simulated. The synthetic and the real array data recorded in Ramsar site (North of Iran) are used to study the method. The results are compared with ones obtained from WaveDec array method. The CVRD method yields good performance in recognizing the singularities and right flank of fundamental mode of Rayleigh waves.

Keywords: Site effects, Seismic noise, Ellipticity curve, RayDec method, Vector random decrement (VRD) technique

INTRODUCTION

The estimation of site effects plays an important role in seismic hazard assessment studies. Site effect studies using seismic noise have become increasingly popular in recent years because of their simplicity, low cost, and non-destructively. Seismic noise wavefield investigation can be fulfilled by both single-station and array techniques. The classical H/V spectral ratio (Nakamura 1989) using a single-station ambient noise recording retrieves the shear wave velocity profile of the soil. More studies in recent years indicate that Love waves may contribute significantly to the measured H/V curves, and their contribution may also vary with frequency and time. RayDec method (Hobiger et al. 2009) is benefitting random decrement technique (Asmussen 1997) applying triggering condition on the vertical component and then stacking a large number of horizontal and vertical signals, which leads to emphasize more on Rayleigh waves with respect to Love and body waves in the ambient noise wavefield.

In this study, the VRD technique which was introduced by Asmussen (1997) and Ibrahim et al. (1998) is used to study the ellipticity curve of Rayleigh waves in an array of stations. The main idea of VRD is in using vector triggering conditions which forces each vertical component of array stations to satisfy based on a set of common points. We named the method as Common Vector Random Decrement (CVRD) technique to determine the ellipticity curve of the array. In this study, the synthetic array data is simulated to test the method. Besides, the real array data recorded in Ramsar (North of Iran) is used and the results of both data sets are compared with WaveDec array method. The Wave Decomposition (WaveDec) technique is based on maximum likelihood estimation of seismic wavefiled parameters in which the seismic wavefield is decomposed and wave parameters are iteratively re-estimated (Maranò et al. 2012). The results show that both methods succeed in retrieving the right flank of peak frequency. However, the peak frequency and the right flank are better determined by CVRD method.

Random Decrement technique

The random decrement (RD) technique was introduced at NASA during the late 60s and early 70s as an alternative approach to Fast Fourier Transformation (Cole, 1973). The underlying principle of RD lies in the estimation of the random decrement functions by averaging a large number of samples, for identical initial conditions (Asmussen et al. 1997). This method transforms the stochastic processes into RD functions. The time history of signal is monitored regarding the triggering condition and appropriate length of samples are detected and averaged. When the number of averages increases, the random parts of samples will eventually average out and to be negligible. The triggering conditions which are used in practice include level crossing, local extremum, positive point and zero crossing with a positive slope.

It is important to choose the proper triggering condition to control the convergence of RD estimations. Asmussen (1997), proposed that the optimal choice of triggering level is defined as the choice which minimizes the variance of the RD functions normalized to the triggering level. The single station RayDec method is introduced to determine the Rayleigh wave ellipticity curve based on RD technique (Hobiger et al. 2009). This technique represents the ellipticity curve of Rayleigh waves by minimizing the effect of love (SH) and body waves. The principle of the method is to estimate the energy level of averaging time segments of the filtered horizontal and vertical signals where the triggering points are selected.

Vector Random Decrement technique

Asmussen (1997) presented Vector Random Decrement (VRD) concept to apply for several measurements collected simultaneously. If the RD technique applies on the measurements individually, the processing time increases proportional to the number of measurements. The VRD technique reduces the estimation time without a significant loss of accuracy (Asmussen et al. 1997). The main difference between the RD and the VRD techniques according to Asmussen (1997) is due to using scalar or vector triggering conditions. A triggering point is detected if the stochastic vector process fulfilled individually formulated triggering conditions at any time.

In this study, we proposed the Common Vector Random Decrement (CVRD) technique to obtain the ellipticity curve of the array stations. The taken steps are as follows:

1) Finite Impulse Response (FIR) filter (such as hamming window) is applied on all three component recordings in the array.
2) A triggering condition which is considered here positive points is applied on each vertical component individually. In this case, the triggering points are detected where the signal lies between two previously defined positive lower and upper bounds.
3) In the following, among the retrieved triggering points of all vertical components, the common points should be selected. Because the vector triggering conditions force each vertical component to satisfy the common triggering points. It may cause a lower number of obtained triggering points and insufficient convergence. The basic VRD function assuming the array data with six stations is defined as:

$$\begin{bmatrix} D_{s1}(\tau) \\ D_{s2}(\tau) \\ \vdots \\ D_{s6}(\tau) \end{bmatrix} = E\left[\left(\begin{bmatrix} S_1(t+\tau) \\ S_2(t+\tau) \\ \vdots \\ S_6(t+\tau) \end{bmatrix} \middle| \; {T^v}_{S_1(t+\Delta t_1), S_2(t+\Delta t_2), \; \dots \; , S_6(t+\Delta t_6)} \right)\right], \quad (1)$$

where, $\mathrm{E}()$ refers to the mean value of stochastic process and The $\mathrm{T}^{v}$is denoted triggering conditions.

Asmussen (1997) proposed to use different possibilities in formulation of triggering condition by dividing the VRD function to some sets to control the convergence. The maximum number of sets with N station can be estimated as the lowest integer of $\frac{N}{2}$ (Asmussen et al. 1999). Then, two sets of VRD condition could be defined as:

$$ {T^v}_{S_1(t+\Delta t_1), S_2(t+\Delta t_2), S_3(t+\Delta t_3)} \; , \; {T^v}_{S_4(t+\Delta t_4), S_5(t+\Delta t_5), S_6(t+\Delta t_6)} \, , \quad (2)$$

Or alternatively three sets as:

$$T^{v}{}_{S_1(t+\Delta t_1),S_2(t+\Delta t_2)},\quad T^{v}{}_{S_3(t+\Delta t_3),S_4(t+\Delta t_4)},\ T^{v}{}_{S_5(t+\Delta t_5),S_6(t+\Delta t_6)}. \qquad (3)$$

4) The windows with the same length are extracted on all three components simultaneously wherever the common triggering points are detected. The 90^{o} phase shift which is typical of Rayleigh waves is applied on horizontal components.

5) The squared value of correlation function is defined as weighting factor for signals because the angle maximizes the correlation of horizontal and vertical components can still be weakly correlated.

6) The retrieved signals are stacked together and the ratio between the horizontal and vertical signals is estimated by analyzing the energy content of the vertical and horizontal stack. Finally, the obtained ellipticity curves of each station are averaged to assign common ellipticity curve for the array stations.

Datasets

In order to illustrate the application of CVRD technique on a large number of stations, an array data set is simulated. It includes the circular array of six stations regarding a complex velocity model with strong contrast (Figure 1a). The sources of seismic noise were approximated by surface or sub-surface forces with random force orientation and amplitude (Moczo and Kristek, 2002). The source time functions are considered as delta-like signals. The estimation of wavefield has been performed using the wavenumber-based method (Hisada 1995) for 1D horizontally layered structure. Besides, the real array data performed in 2013 using six CMG6TD Guralp seismometers at a site in Ramsar (North of Iran) is used. The length of the recording is 40 minutes with a sampling frequency of 100 Hz and the array aperture is near 15m. The layout of the simulated and real array data are depicted in Figure 1b and 1c.

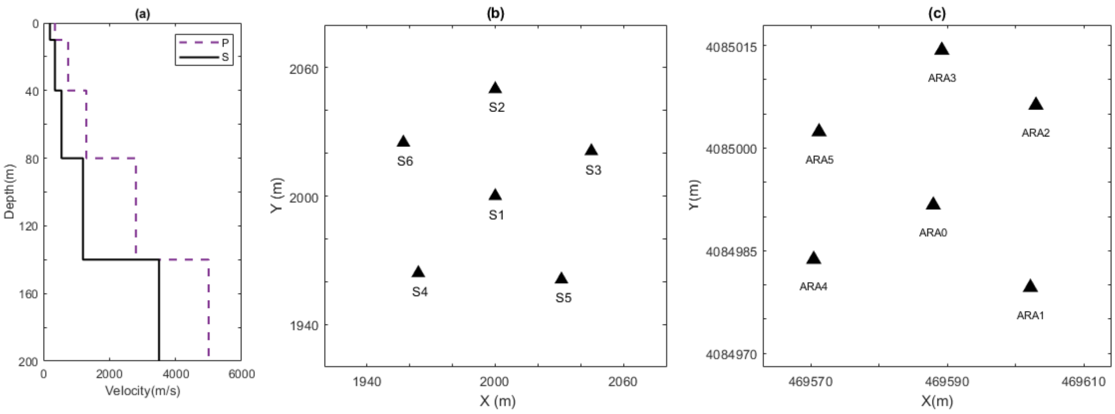

Figure 1. a) The compressional and shear wave velocity profiles and b) the array layout of simulated data and also c) the array layout of Ramsar array data.

Application of CVRD method

The CVRD method is applied on synthetic and real datasets discussed above and the results are compared with ones obtained from WaveDec array method. In the case of synthetic data, the CVRD and WaveDec display a good accordance in obtaining right flank of peak frequency in comparison with theoretical model (Figure 2a). However, the ellipticity peak and the amplitude are clearly identified via CVRD. The left flank is slightly overestimated by CVRD while the other method fail to recognize it. Using Ramsar array data, both methods yield the same results in estimating right flank of peak frequency and the trough frequency according to Figure 2b. CVRD shows a good performance at whole studied frequency range especially in obtaining the peak frequency and the left and right flank.

It is deduced that the singularities and the flanks of peak frequency of fundamental model of Rayleigh wave are realized well by CVRD in comparison with WaveDec array method.

Considering the importance of the right flank of the ellipticity peak in carrying valuable information on the underground structure, the CVRD method is recommended.

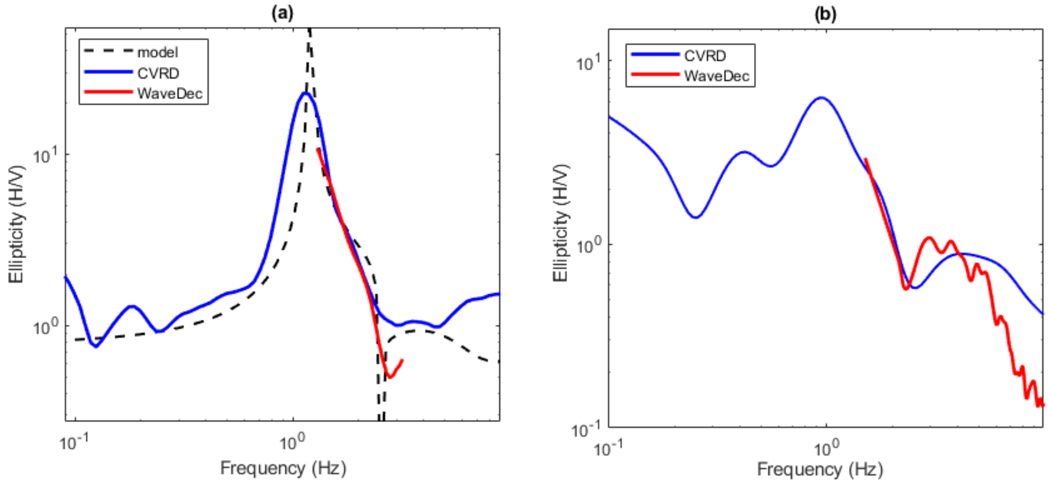

Figure 2. Comparing the ellipticity curves deduced via CVRD and WaveDec for a) synthetic array data with the theoretical fundamental model and, b) real data recorded in Ramsar site.

CONCLUSION(S)

In this study, we have presented the CVRD method to estimate Rayleigh wave ellipticity curves for an array of seismic stations based on vector random decrement technique. The main idea of VRD is in using vector triggering conditions which forces each vertical component of array stations to satisfy based on a set of common points. The common triggering points are determined in the processing of vector random decrement technique. The method is verified on synthetic and real array data and also the results are compared with ones obtained by WaveDec array method. The CVRD succeeds in recognizing the singularities and the flanks of fundamental mode of Rayleigh wave ellipticity curve.

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