Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)
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SSS023-P21 Room:Convention Hall Time:May 24 16:15-18:45

Estimation of Complex Spectral Ratio of Surface and Borehole Seismometry and Numerical Tests

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I compared 4 estimation methods of complex spectral ratios from seismic vertical array records and the results of numerical tests of noise-added synthetic records by these methods. Phase difference spectra are useful to identify velocity and attenuation structure using the spectral ratios. Examined estimation methods are two least-square approaches (H_1 and H_2), a geometrical mean of H_1 and H_2 (H_3), and geometrical mean of the Fourier spectra (H_G). These methods are different ways of assumption of noise.

The two least-square approaches assume that one of the surface or borehole records (y(f) and x(f) in the frequency domain, respectively) includes noise and the other one is noise-free. The least-square solution of the observational equation that is assumed that surface record y(f) includes noise is $H_1=C_{xy}(f)/S_{xx}(f)$, where C_{xy} is the ensemble mean of the cross spectra of x(f) and y(f) and S_{xx} is the one of the power spectra of x(f). The solution that borehole records includes noise is $H_2=S_{yy}(f)/C_{yx}(f)$, where S_{yy} is the ensemble mean of the power spectra of y(f). Phase difference spectra of H_1 and H_2 are identical.

The effects of the noise are shown in the expected value. The noise is no effects on the expected value of C_{xy}. This causes that the phase differences are expected to be robust. The expected values of S_{xx} and S_{yy} are affected by the variance of the noise of x(f) and y(f), respectively. This indicates that the H_1 and H_2 are different for the same x(f) and y(f).

I applied these 4 methods to estimate the spectral ratios of the spectra of noise-added synthetic surface and borehole records. The noise-free surface and borehole synthetic records were calculated with the exact transfer function of the vertically incident plain wave in the homogeneous medium with the surface. I made noise-added synthetic records by adding 20 different white noise on the noise-free synthetic records.

Stacked spectral ratios were calculated by the 4 methods. Mean values of cross and power spectra of the 20 pairs of noise-added synthetics were calculated. H_1, H_2, and H_3 were calculated from the mean values. H_G were calculated with geometrical mean of the spectral ratios of the Fourier spectra y(f)/x(f). The result of H_1 indicates small error in the frequencies between peaks of the exact transfer function, whereas, at the peak frequency of the transfer function, H_1 underestimates the peaks due to the noise in the borehole records. H_2 indicates clear peaks, whereas it overestimate the valleys. H_3 are the geometrical mean value that is robust, but indicates unclear peak compared with H_2. H_G are close to H_3. Phase difference spectra of H_1 and H_2 are very close to the exact transfer function.

Smoothed spectra of noise-free synthetic spectra are very similar to the stacked spectra. H_1, H_2 and H_3 were calculated from smoothed cross and power spectra. H_G are the geometrical mean of the spectral ratios of the smoothed Fourier spectra x(f) and y(f). Parzen window was used as a smoothing window. The spectra applied both of stacking and smoothing also results similar to the stacked spectra.

Keywords: seismic vertical array, complex spectral ratio, transfer function