Rayleigh-wave group velocity in Japan revealed from the cross-correlation analysis of microseisms excited by typhoons

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ABSTRACT

Cross-correlation analysis of microseisms has been recently recognized as a new method to measure the group velocity of Rayleigh waves and is used for the velocity tomography in various areas in the world. We note that microseisms are mostly excited by oceanic waves and the propagation direction of microseisms observed on land is usually unilateral; however, the necessary condition of this method is theoretically the establishment of an equi-partition state, that is, an isotropic distribution of microseism propagations. There have been few studies which paid attention to this condition for the practical analysis yet. In the cross-correlation analysis, it is ideal that each station pair is isotropically surrounded by seismic noise sources. In order to realize an idealized condition, here, we select records of microseisms in four periods of different weather conditions: three typhoons and one low pressure area are located at different positions surrounding Japan Island. Microseisms registered by 709 short-period seismic stations of Hi-net distributed in Japan are used for the analysis, where a time window of 36-48 hour length is long enough for stable measurement in each period. From the cross-correlation analysis, we find a good correlation between the location of the center of typhoon and the propagation direction of microseisms for periods over 4-16 s; however, we recognize that microseisms of 2-4 s periods are generated from the nearest coast. By stacking all the microseisms recorded for the four different periods, we obtain reliable group velocities of Rayleigh waves, which show normal dispersion. We further apply the tomography technique to group velocities for station pairs in order to obtain a 2D velocity distribution in Japan. The results well reflect the geological structure of each area. For example in the 4-8 s period band, granitic mountain areas show high velocities near 3 km/s while the Kanto plain shows low velocities near or under 1 km/s reflecting thick deposits.

KEY WORDS: Cross-correlation analysis, microseisms, typhoon, Rayleigh waves, group velocity, equipartition.

INTRODUCTION

For imaging the velocity structure of the Earth, active sources or natural earthquakes have been commonly used in seismology; however, a new technique using microseisms was proposed. The original idea is based on the fact that a coherent part of microseisms observed at two points could be retrieved from the average of the cross-correlation functions (CCFs) over long time if many microseism sources are isotropically distributed in space [Snieder, 2004; Wapenaar et al., 2004; Sánchez-Sesma and Campillo, 2006]. Cross-correlation analysis for retrieving a Green function has been emphasized in several fields of wave physics including acoustics, helioseismology, geophysical exploration, and seismology.

Several studies showed that the group velocities of Rayleigh waves were successfully retrieved from the averaged CCFs calculated from microseisms or coda waves of local earthquakes [e.g. Campillo and Paul (2003), Sabra et al. (2005a), Shapiro et al., (2005)]; however, most of their resultant averaged CCFs are asymmetrical in the time domain. From the analyses in California, Sabra et al. (2005b) reported that the CCFs for station pairs parallel to the coast line became symmetric but those became asymmetrical for station pairs perpendicular to the coast line. It simply reflects that microseisms propagate from the ocean to the inland since most of their mechanical sources are oceanic waves. Therefore, even if we use sufficiently long time records of microseisms for the CCF analysis, generally, propagation directions of microseisms could not be isotropic.

We note that Japan Island is surrounded by the

Figure 1. Distribution of Hi-net stations (small circles) in Japan, and typhoons (stars) with paths (broken lines) and a low pressure area (a closed circle). The inserted map shows the north of central Japan.
Pacific Ocean and the Japan Sea, and typhoons and low pressure areas pass over these seas. As main sources of microseisms, they control the propagation direction of microseisms. If we carefully select observation periods having different locations of typhoons and low pressure areas surrounding Japan Island, we are able to establish an idealized condition on the isotropy of microseism propagation directions. Paying attention to the isotropy condition, we carry out the CCF analysis for the estimation of Rayleigh-wave group velocities in Japan.

DATA

Vertical-component velocity records of microseisms registered by 709 stations of Hi-net are used for the analysis. At each station, a velocity-type seismometer of a natural period of 1 Hz is installed at the bottom of a borehole. Figure 1 shows the distribution of these stations by small circles. After the deconvolution of the system response, applying band-pass filters of 2-4 s, 4-8 s and 8-16 s periods, we convert them to one bit signals in order to weaken effects of active seismic sources or artificial sources. Each station data is divided into time windows of 360s length, and a CCF is calculated for every time window. Then, CCFs are averaged over the whole data. Rayleigh wave's travel time for a station pair is picked up from the envelope of the averaged CCFs, which is produced by using the Hilbert transform. The station separation over the travel time can be interpreted as the group velocity of Rayleigh waves.

Using the maximum value of the averaged CCF as a signal value and the average of the averaged CCF over time lags of 150~200 s and -150 ~ -200 s as a noise value, we define the S/N ratio. As an example, Figure 2 shows how the S/N ratio increases as the data length increases for the 4-8 s band at a station-pair (N.SYKH-N.TMAH) of a 25.7 km separation. The gradient of the curve is large for the first 10 hours; however, it is gradually saturated after 20 hours. The time dependence of S/N ratio is nearly proportional to the square root of the data length, which is similar to that reported in California [Sabra et al. (2005a)]. We find 36 hours are enough to obtain a stable measure of averaged CCFs.

In the cross-correlation analysis, it is ideal that each station pair is isotropically surrounded by microseisms’ sources; however, oceanic waves in the Pacific Ocean are especially strong in microseisms’ sources for the case of Japan. Even though the duration of the observation period is elongated, the propagation of microseisms is unilateral and it is difficult to establish the idealized situation.

Here, in order to establish the idealized condition for the CCF analysis as possible as we can, we select records of microseisms in four periods corresponding to different weather conditions controlled by the locations of typhoons and a low pressure area surrounding Japan Island as follows: period I, a typhoon on the Japan Sea (36 hours from 0 h, Sep. 12, 2003); period II, a typhoon on the Japan Sea (48 hours from 0 h, Sep. 6, 2005); period III, a low pressure area on the Pacific Ocean (36 hours from 0 h, Apr. 16, 2005); and period IV, a typhoon on the Pacific Ocean (48 hours from 0 h, Sep. 26, 2005). Their locations and paths are shown in Figure 1. Power spectra of microseisms are stronger in the western part of Japan during periods I and II while in the eastern part during periods III and IV.

EFFECTS OF TYPHOON

Selecting data from several stations in the north of central Japan, we carefully examine averaged CCFs in two different weather condition periods II and IV. This area faces on the Japan Sea as shown in the inset of Figure 1, and averaged CCFs in this area are shown in Figure 3, where distance is measured from the reference station N.SYKH and positive lag time means the wave propagation from other stations to reference station, namely westward propagation. Rayleigh wave packets are clearly seen in the averaged CCFs in each period band. We find the propagation of Rayleigh waves is eastward and westward in periods II and IV, respectively for both 4-8 s and 8-16 s period bands. It means that there must be microseisms’ sources excited by the typhoon location. But, in the 2-4s period band, the averaged CCFs show eastward propagation not only in period II but also in period IV, namely the eastward propagation is always predominant irrespective of the weather condition. Microseisms over 4 s period are strongly controlled by the typhoon location even if it is far from the land. But in the 2-4 s period band, microseisms are mostly generated near the coast face to the Japan Sea, that is, the isotropic condition is not perfect.

GROUP VELOCITY OF RAYLEIGH WAVES

We calculated CCFs averaged over four different periods, 168 hours in total, for station pairs with a separation less than 100 km. The total number of these station pairs is 14632; however, we do not use all the station pairs for
the following inversion analysis. First, taking the threshold value of the S/N ratio to be 6.0, we select averaged CCFs showing clear wavelets. We note that the averaged CCF of some station pairs parallel to a coastline shows a very clear wavelet having an extremely fast apparent velocity. Secondly, we set a limitation of Rayleigh-wave group velocity range to be larger than 0.5 km/s and smaller than 4.0 km/s to eliminate data showing extreme velocities. Applying these two criteria to all the data, we select 8308 station pairs in the 2-4 s period band, 11222 in the 4-8 s period band and 11299 in the 8-16 s period bands. Finally we obtain Rayleigh wave travel times for each station pair, which show normal dispersion.

Now, we apply the velocity tomography technique to station pairs' travel times. The ray path of Rayleigh wave between station pairs is assumed to be a straight line in order to make the inversion problem simple linear equations. Dividing all the study area into grids of 0.5×0.5 degree, we estimate the Rayleigh-wave group velocity in each grid. Shifting each grid with 0.25 degree to four different directions and averaging over the estimated group velocities over the four grids, we finally obtain smoothed group velocity for every 0.25×0.25 degree grids.

Figure 4 shows resultant velocity inversion maps for three period bands, where the group velocity is shown by gray scale. Each map shows only grids having the diagonal component of the resolution matrix larger than 0.8. Spatial differences of Rayleigh-wave group velocity are more noticeable in 2-4 s and 4-8 s than in 8-16 s reflecting several similarities with geological characteristics. High velocities near 3 km/s mainly appear in granitic mountainous zones, for example the Chugoku, Kitakami and Abukuma mountains. Low velocities appear in the Kanto and Nobi plains having thick deposits. The velocity is under 1 km/s in the Kanto plain. We also find a negative correlation between the resultant group velocity and the distribution of seismic intensity anomalies revealed from geological conditions since Rayleigh wave group velocity is sensitive to soft deposits (see http://www.bousai.go.jp/oshirase/h17/yureyasusa/zenkoku.pdf).

CONCLUSION

In the cross-correlation function analysis for Rayleigh-wave group velocities, the isotropic distribution of microseism propagation directions is necessary; however, it is not sufficient to elongate simply the observation period. Here we proposed to use different observation periods depending on the locations of typhoons and low pressure areas surrounding Japan Island to establish such an idealized condition. Using microseism data registered during four different weather conditions, we carried out the cross-correlation function analysis. Typhoons have strong effects on the propagation direction of microseisms for periods over 4 s while microseisms in the 2-4 s period band are mostly generated near the nearest coast. By stacking all the microseisms recorded for the four different periods, we obtain reliable group velocities of Rayleigh waves at each station pair for 2-4 s, 4-8 s and 8-16 s period bands, which show normal dispersion. Using the tomography technique, we obtained a distribution of Rayleigh wave group velocities in Japan, which shows normal dispersion and well reflects the geological structure of each area. Granitic mountainous areas show high velocities and plains show low velocities reflecting thick sedimentary deposits.

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REFERENCES


**Figure 4.** Group velocity distribution of Rayleigh waves for three period bands (a-c), where the grid size is 0.25x0.25 in degree.