Comparison between active fault structure by time-reversal method and beachball

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Recently, authors constructed a dynamic model of an active fault based on time reversal principle of wave propagation. Then, it is shown that the beachball and the dynamic model are compared, and the azimuth of the obtained active fault was mutually corresponding. Dynamic model is constructed based on the time reversal principle of wave propagation. The P wave components of a seismic wave received at an observation point is cut out, and the wave is reversed timewise. The reversed signal is radiated on a propagation simulation, and the pulse formed at the source location, that is, time reversal pulse (TRP) is obtained. It is described as an example of the dynamic model for the earthquake that occurred in the central part of Suruga Bay in August, 2009. The clear orientation dependency existed in obtained TRPs. The frequency spectrum has changed greatly depending on the azimuth. The maximum amplitude frequency rises greatly as the azimuth moves from west to east and it has descended.
It is thought that the frequency rise in this case is done by a local speed mobile of a pressure source. The moving direction concentrated to Nishiizunishi, Kawazu, and Ito. The P waves received by these stations had a peculiar waveform. The head part of the received wave at Nishiizunishi has expanded. However, the received waves at Ito and Kawazu near Nishiizunishi ware usual waveforms. The head's growing in this manner occurs when the progression speed of a crack in an active fault becomes near the velocity of propagation. The pressure that occurs due to a crack is added cumulatively along with the speed mobile of the crack. That is, it is thought that a parametric effect was caused.
Nishiizunishi is the specific point that reflects the feature of this earthquake. The point where the narrow beam radiated from an active fault appears at surface of the earth is named a parametric spot (PS). The head of the pulse to which the head part observed at the PS expands is named a parametric head. The azimuth of the narrow beam radiated from an active fault is the azimuth of an active fault. Therefore, the azimuth of the PS is the azimuth of an active fault. The azimuth of the parametric spot of this earthquake is 86°. On the other hand, the azimuth by the beachball that the Meteorological Agency obtained is 71°. They are almost corresponding.
From the above studies, the dynamic model based on the time-reversal method is effective for the clarification of the quake characteristic of the active fault.

Keywords: Time reversal method, active fault vibration, beachball

Seismic audification and sonification for data exploration

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Seismograms are basic information for seismology. Seismologists usually check seismograms by visualization, i.e., plotting them on screen or paper. They must have another way: hearing sound made from seismograms, which is getting popular but mainly for outreach activities. We are trying to employ the seismo-sound for research. There are two ways to convert time-series data to sound: audification by interpreting the time-series data as an audio waveform; and sonification by assigning sound according to feature of the data such as instantaneous frequencies or amplitudes. We develop seismic audification and sonification methods to investigate what kind of information can be extracted by hearing the seismo-sound.
The first case study for our group is the 2011 Tohoku-oki earthquake using data from 116 of K-NET and KiK-net surface stations maintained by NIED. Since seismic records are, in general, at too low frequencies to hear, audification needs fast play in order to shift frequencies into the audible range. We synthesized audified seismograms from the 116 stations at 10 times faster than the actual speed. The sound is in an audible but low tone. From the sound we can feel the propagation of seismic waves all over Japan. In order to make the features of seismic waves clearer, we designed a sonification process to assign sounds according to the zero-crossing rate and amplitude in an audible frequency range. We set that the playback rate is 10, so that the length of the sound is around 40 s, enough short to listen. In addition we attempted not to make fearful sound, mainly for the purpose of outreach activity. The all data from 116 stations are played simultaneously with an appropriate time alignment.
The sonified sound allows us again feel the nationwide seismic wave propagation. The sound at the beginning is loud and at high pitch and getting small and at lower pitch. This feature reflects the geometrical spreading and the anelastic attenuation effects. Around 23 s after the onset of the sound, i.e., 230 s after the origin time, a high-pitch sound distinct from the overall propagation-like trend is heard. We searched for the origin of this high-pitch sound by sonifying seismograms from area to area, and found that this is from the Hida area in Gifu prefecture. The timing of the high-pitch sound is consistent with the origin time of a dynamically triggered event already reported [e.g., Uchide, SSA, 2011; Miyazawa, GRL, 2011; Ohmi et al., Zisin2, 2012].
The audification and sonification make it easier to observe changes and differences in frequencies as well as amplitudes for many stations at once. Our approach will be a powerful tool for detecting dynamically triggered events that radiate seismic waves at higher frequencies than those propagating for a long distance from a huge earthquake.
Acknowledgement: We used seismograms from K-NET and KiK-net maintained by NIED.

Keywords: Seismology, Audification, Sonification, The 2011 Tohoku-oki earthquake, Dynamic triggering of earthquakes

Estimation of the mantle structure with mutiple ScS phases by time-domain analysis

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In comparison of seismic waveform records or different parts of one record, researchers usually use a spectral approach with FFT, that is, records are compared in the frequency domain. Frequency-domain analyses are developed for stationary time serieses, but non-stationary wavelets with a finite record length are processed commonly in seismology. The Wiener filter is one of data processing schemes invented for such non-stationary signals, comparing two records directly in the time domain.

This study employs the Wiener filter approach to estimate the average seismic mantle structure with multiple ScS phases of a large deep earthquake in the west off Ogasawara Islands on 30 May 2015. We compared the results obtained by the time-domain Wiener-filter approach with those by a conventional spectral analysis in the frequency domain. We used seismograms recorded by F-net stations in the south of Japan islands, rotating them to obtain transverse component records for ScS and its related phases.

Each target wavelet (e.g., ScS and ScS2) in seismograms was recorded in a time window of 100-200 sec in our case. To exclude signals of other phases, we need to compare such data of a short record length. If we obtain the Fourier spectra of seismic waveform records and then compare them, any procedures to smooth the original waveform records are required, particularly to “taper” both ends of records. Such a procedure distorts the records, particularly amplitudes in a low frequency range although their phase information appears to be robust. As a result, the estimation of attenuation factors or Q values is degraded because of the use of amplitude spectra.

As an alternative approach, we considered one waveform record as an input time series and the other as an output one, and they are connected by a filter, which corresponds to a Wiener filter. The design of such a Wiener filter is based on a manner of least squares in errors. If the length of a least-square filter or the number of filter coefficients gets large, the error in the fit of the outcome of the input and the output becomes small. Nevertheless, a very long filter turns to be very unstable, usually with rapidly oscillatory characteristics. We found an optimal filter length based on the AIC (Akaike Information Criterion) parameter that indicates the trade-off between the size of errors and the number of filter parameters. The Wiener filter obtained in the above manner is then analyzed by the Fourier transform, which provided us with very reliable amplitude and phase differences between input and output time serieses (e.g., ScS and ScS2 phases) in a very wide frequency range. With the deep earthquake in the west off Ogasawara Islands, Q values at F-net stations in Japan along the Pacific Ocean were obtained to be 150 to 500 in a period range from 0.5 to 20 sec. Detail variations among stations, that is, fine lateral heterogeneous mantle Q structures can be discussed.

The present approach may be particularly useful with more than two waveform data similar to each other, when a cross correlation coefficient is utilized. With the use of a Wiener filter, we may detect a very small difference among waveforms in the study of temporal changes in seismograms.

Keywords: multiple ScS phases, velocity and attenuation structure of the mantle, time-domain analysis of seismic waveforms

Detection of converted phases from the upper mantle discontinuities using teleseismic body-wave microseisms

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<!--?xml version="1.0" encoding="UTF-8" standalone="no"?-->A seismological method using earthquakes is feasible for exploring the Earth’s deep interior. In ten years, seismic interferometry (SI) has been developed. Although, in the first stage, surface wave part was focussed, body wave part has been utilized in these years. For an appropriate reconstruction of Green's function by SI, equipartition of energy is required. However, the assumption is valid under only limited situations. Recent observations of teleseismic body-wave microseisms showed localized sources, which prevent from appropriate body wave retrievals using SI.

In this study, we have a different stradegy from SI for detections of converted phases from the upper mantle discontinuities. Using centroid locations of body-wave microseisms, we can apply a receiver function analysis as in an earthquake. The difficulty is that the signal is not transient but persistent. With a help of array analysis, we can infer source time function for the equivalent vertical single force at the centroid. Deconvolution of a slant stack time series of radial components by the source time function emphasizes P-SV conversion phases at upper mantle discontinuities beneath the stations. We apply this method for 779 Hi-net stations on Dec. 9th, 2014 when a weather bomb hit north Atlantic ocean. A preliminary analysis shows clear P660s. We will discuss the accuracy of the detected phases in a more quantitative manner.

Keywords: microseisms, ambient noise, array analysis

Estimation of seismic attenuation properties in eastern Hokkaido based on a diffusion-absorption model

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It is widely accepted that seismic coda waves are scattered waves with random phases generated by medium heterogeneities. We can often assume that the distribution of coda-wave energy is homogeneous and isotropic in space at large lapse times. However, it is reported that this assumption does not always hold at northeastern Honshu, Japan, where a volcanic front stretches from the north to the south. In order to interpret the observed spatial variation of coda-wave energy in the region, a diffusion-absorption model was proposed by Yoshimoto *et al.* (2006). This model consists of two half-spaces with different absorption coefficients, and the seismic energy density of each half-space satisfies the diffusion-absorption equation. In order to examine whether such a phenomenon is observed in other areas, we perform the similar analysis around the volcanic front in eastern Hokkaido, which runs central part of Hokkaido from the east to the west. We further investigate the spatial energy distribution of S-coda waves around the region and estimate the attenuation properties across the volcanic front based on the diffusion-absorption model.
We analyze seismograms of a local intermediate-depth event whose epicenter is located in the forearc, Tokachi region in Hokkaido. The hypocentral parameters obtained by Japan Meteorological Agency are 2 February 2013 23:17, 102km depth, and M6.5. We use seismograms recorded by 40 Hi-net stations in eastern Hokkaido, which are provided by the National Research Institute for Earth Science and Disaster Prevention. We apply bandpass filters of 2-4, 4-8, 8-16, and 16-32Hz to the three component velocity seismograms. We set seven time windows with a length of 5 sec for S-coda waves, and calculate the mean amplitudes of sum of squared three component velocity seismograms. We multiply them by the average density of the crust and upper mantle 3.0[g/cm^3] to obtain S-coda wave energy density.
We find the energy density in eastern Hokkaido is uniformly distributed in the forearc, while it decreases with the horizontal distance from the volcanic front in the backarc. Such spatial variation is similar to that observed in northeastern Honshu. It is revealed that the coda-wave energy in the backarc exponentially decreases with the distance. On the other hand, the coda-wave energy in the forearc is almost equally distributed in space, decreasing with the lapse times. In the backarc, the rate of the decrease is about two or three times larger than that in northern Honshu ((1.7-4.8)x10^{-2} [km^{-1}] at 2-32Hz) while the frequency dependence is approximately the same. Based on the diffusion-absorption model, the rate of the spatial decrease in the backarc is expressed by the square root of the ratio between the absorption coefficient and the diffusivity, while the rate of the temporal decrease in the forearc is expressed by the absorption coefficient. According to these relations, the intrinsic attenuation in the backarc is estimated to be larger than that in northeastern Honshu at all frequency bands by assuming the S-wave scattering coefficient of 0.01[km^{-1}]. In the forearc, intrinsic attenuation is smaller than that in the backarc, and the frequency dependence is estimated to be $Q_i^{-1} \propto f^{-1}$. We confirm that similar results can be obtained even for two other events.

Acknowledgments : We used the Hi-net data provided by the National Research Institute for Earth Science and Disaster Prevention, and JMA Unified Hypocenter Catalog provided by Japan Meteorological Agency in this study.

Keywords: diffusion, attenuation, coda-wave, volcanic front

Development of trans-dimensional waveform inversion to estimate 1D layered underground structure model

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Some previous studies tried to estimate 1D layered underground structure models based on the waveform modeling of small events (e.g., Ichinose et al. 2003; Kakehi 2004; Asano and Iwata 2009) to obtain reliable Green’s functions used in earthquake source inversions. In this study, we develop a new approach of the estimation of 1D structure model from waveform data using the reversible jump Markov chain Monte Carlo (rjMCMC) method (Green 1995). The trans-dimensional inversion using the rjMCMC method has recently found applications in geophysics (e.g. Malinverno 2002; Agostinetti and Malinverno 2010; Bodin et al. 2012; Dettmer et al. 2014; Hawkins and Sambridge 2015). In the rjMCMC method, the number of model parameters is one of the variables in the inverse problem, and therefore the parsimony of the solution can be determined by data and is not imposed by user (Gallagher et al. 2009; Agostinetti and Malinverno 2010). Because in this method there is no necessity of strong prior information (e.g. layer number and initial structure model), the flexibility of the proposed approach in this study is expected to be high. Another advantage is that ensembles of models produced by the MCMC approach are useful for the estimation of model uncertainties. The uncertainty information of structure model could be used in the introduction of synthetic errors to source inversions as the uncertainties of Green’s functions.
The geometry of layers is described by a variable number of Voronoi nuclei (e.g. Bodin et al. 2012). For simplification, errors of the observation equation are assumed to follow a Gaussian distribution and be independent from each other. Unknown parameters are the number of layers, thickness of each layer, Vs of each layer, and hyper-parameter which represents the scale factor of the errors. Vp and density of each layer are calculated from Vs by the empirical relations of Brocher (2005). The attenuation characteristics (Qp, Qs) are calculated from Vs following the procedures of Kawabe and Kamae (2008) and Koketsu et al. (2009). Synthetic waveforms are calculated using the discrete wavenumber method (Bouchon 1981) and the reflection/transmission matrix method (Kennett and Kerry 1979). In the trans-dimensional sampling of structure models, we use the parallel tempering algorithm (e.g. Sambridge 2013) to improve the efficiency of the probabilistic sampling and the search range of parameter space.
In this presentation, we will show the results of the applications of the newly developed approach to synthetics and real data to show the validation and usefulness.

Keywords: Trans-dimensional waveform inversion, Estimation of 1D structure model, Reversible jump MCMC method

Property of the seismic-wave propagation in subduction zone studied by large-scale simulation and adjoint kernels

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At the subduction zones, such as the Japan trench, the Nankai trough and the Ryukyu Islands, the propagation of the seismic-waves are affected by the strong lateral heterogeneities [1]. Such effects must be considered in generating the synthetic waveforms for the analyses of earthquake sources and structural heterogeneities. In the previous presentation [2], by using a 3D structure model for the northeastern Japan (including Japan trench) and by using finite-difference simulations, we showed that the observed surface-waves with a period band of 12-40 s were well reproduced by the synthetics while for periods shorter than around 10 s the misfit between the observed and synthetic waveforms were large. In order to improve the structure model for the short-period waves we need to understand the properties of the wave propagation through the heterogeneous media. Thus, in this paper, as a continuation of the project [2], we study the property of the wave propagation in term of the adjoint kernels [3-6] which represent how the waves sample the different part of the structure. As an example, we use the same 3D structure model (Japan trench) and the same shallow suboceanic earthquake whose epicenter is only about 50 km landward from the trench (2003/11/1, Mw5.8) as those of [2]. We apply a GPU-accelerated finite-difference program developed by ourselves [7,8] and use the TSUBAME-2.5 supercomputer in Tokyo Institute of Technology. As in [6] the adjoint kernels are computed by using two wave-fields: one propagates from the source point and the other from the station point. We selected a KiK-net station, Yamada (IWTH21 in Iwate) as the preliminary example. The horizontal slice of the resultant rigidity kernel at near the source depth (11 km) and at period of 12.80 s shows nearly symmetric pattern with respect to the straight line (i.e., great circle path) connecting the source and the receiver positions projected onto the plane of the slice. Thus, for this period, the distortion of the wave propagation path is weak: the required perturbations in material parameters would be applied mainly to those along and near the great circle path to improve the structure. The rigidity kernel at period of 7.31 s, however, shows distorted pattern that represents complicated wave propagation such as bending and scattering. This result indicates that perturbations just along the great circle path would not be enough to improve the structure for short period waves. We will consider more kernels computed for the Japan trench and the Ryukyu Islands. This project is partially supported by HPCI System Research Project (hp130118), JHPCN (15-NA12) and KAKENHI (26282105).

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Keywords: adjoint kernel, subduction zone earthquake, modeling short period seismic waves, GPU computing, finite-difference method

Ground-motion prediction based on the scattering theory by incorporating the effects of random velocity inhomogeneities in the crust

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Introduction

It has been reported for the ground motions of local crustal earthquakes that, for frequencies higher than approximately 1 Hz, the azimuthal distributions of maximum amplitudes (hereafter “apparent radiation pattern”) and amplitude fluctuations are characterized by the seismic scattering due to random velocity inhomogeneities in the crust (e.g., Kobayshi et al., 2015; Yoshimoto et al., 2015). In recent years, to investigate the properties of these seismic phenomena, a number of pioneering studies on seismic scattering have been conducted (e.g., Sawazaki et al., 2011). In this study, on the basis of the scattering theory, we propose a new method for predicting the ground motions of local earthquakes by incorporating the frequency and distance changes in the apparent radiation pattern and amplitude fluctuations.

Ground-motion prediction method

In our ground-motion prediction for small to moderately sized local crustal earthquakes, for simplicity, only the effects of scattering due to random velocity inhomogeneities in the crust are considered, whereas the effects of anelastic attenuation (intrinsic attenuation) and local site amplification are not considered. We assume a spatial uniformity for the crustal inhomogeneity and its spatial autocorrelation can be stochastically characterized by using an exponential function. We adopt a double-couple point source as a source model and assume that the maximum amplitude is generated by a certain frequency component of S waves.

We suppose that the spatial distribution of maximum amplitudes can be evaluated by the following two calculation steps: (1) Evaluation of apparent radiation pattern from mean square (MS) seismogram envelopes, and (2) Estimation of amplitude fluctuation and superposition of its value on the MS envelope amplitude. For the calculation in Step 1, we utilize a numerical method developed by Sawazaki et al. (2011) to synthesize seismogram envelopes for a double-couple point source by way of the stochastic raypath technique using the Markov approximation for the parabolic wave equation. For the estimation procedure in Step 2, we adopt a scattering theory (Yoshimoto et al., 2015) for the evaluation of amplitude fluctuations of acoustic waves radiated isotropically from a point source in random inhomogeneous media.

Discussion

The above-stated method, which is based on the scattering theory, has a potential to evaluate the frequency and distance changes in the apparent radiation pattern and amplitude fluctuations for crustal earthquakes. For example, as for the increase in hypocentral distance, our method predicts both the dissipation of the non-uniform azimuthal distribution in apparent radiation pattern and the increase in amplitude fluctuations. The simultaneous appearance of these phenomena results in that, even at large hypocentral distances, the maximum amplitudes at different receivers are not equalized, but differ from receiver to receiver, with up to ten-times difference between the largest and smallest as found in seismic observations.

In our presentation, we will show numerical evaluation results in the frequency and distance changes in apparent radiation pattern and amplitude fluctuations and will discuss their physical relations between random velocity inhomogeneities in the crust. As for our group study on observed characteristics of P- and S-wave amplitude fluctuations during local crustal earthquakes, please see Kobayashi et al. (2016, JpGU) in the same session.

Keywords: Seismic scattering, Apparent radiation pattern, Amplitude fluctuation, Ground-motion prediction, Random velocity heterogeneity

Seismic amplitude fluctuations in small-scale random velocity heterogeneous crust

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Introduction

The amplitudes of high-frequency (> 1 Hz) seismic waves during local earthquakes show large fluctuations, even at similar hypocentral distances. The cause of this observation could be interpreted by the composite effects of local site amplifications, source radiation pattern, and seismic wave scattering due to small-scale random velocity heterogeneity in the crust (e.g., Hoshiba, 2000). Yoshimoto et al. (2015) quantitatively estimated the contribution of scattering effect on *P*-wave amplitude fluctuations during crustal earthquakes using seismograms recorded from Hi-net and demonstrated that the observed features could be explained by their scattering model. However, the characteristics of *S*-wave amplitude fluctuations, which are crucial to the improvement of ground-motion prediction equations, are still unclear. In this study, to quantify the scattering effects on both *P*- and *S*-wave amplitude fluctuations, we investigated the frequency and distance changes in *S*-wave amplitude fluctuations, as well as *P*-wave amplitude fluctuations.

Data and Methods

We analyzed velocity seismograms recorded at Hi-net stations during 23 shallow strike-slip crustal earthquakes that occurred in Chugoku region, southwestern Japan. The frequency bands used in our analysis were 1-2, 2-4 and 4-8 Hz. Based on the coda-normalization method of Kobayashi et al. (2015), we analyzed the seismograms recorded at hypocentral distances less than 75 km and evaluated the maximum *P*- and *S*-wave amplitudes normalized by the averaged *S*-wave coda amplitude at lapse time of 60-70 s. Hereafter, we simply refer to the measured maximum *P*- and *S*-wave amplitudes as “*P*-wave amplitude” and “*S*-wave amplitude”, respectively. To minimize the effects of source radiation pattern, we only adopted the data with large radiation pattern coefficient (>0.7) expected form CMT solutions in the homogeneous medium (Aki and Richards, 2002, Ch. 4).

Observed seismic amplitude fluctuations

S-wave amplitude fluctuations at frequencies lower than 2-4 Hz gradually increased with increasing hypocentral distance, showing about 10 times difference between the smallest and the largest *S*-wave amplitudes at hypocentral distance of about 70 km. On the other hand, high-frequency (4-8 Hz) ones rapidly increased with increasing hypocentral distance, showing 10 times difference even at hypocentral distance of about 30 km and the saturation of this trend at large distances (>30 km). We also observed very similar characteristics of *P*-wave amplitude fluctuations compared to those reported by Yoshimoto et al. (2015).

Comparing between *P*- and *S*-wave amplitude fluctuations, we found that the characteristics of the frequency and distance changes in amplitude fluctuations for *P* and *S* waves are similar. This result suggests that, as well as *P*-wave amplitude fluctuations, observed *S*-wave amplitude fluctuations were caused by the effects of scattering due to small-scale random velocity heterogeneity in the crust.

Acknowledgement

We used the Hi-net/F-net waveform data and the CMT solutions from F-net, provided by the National Research Institute for Earth Science and Disaster Prevention, Japan. We also used the unified hypocentral catalog provide by the Japan Meteorological agency.

Keywords: Amplitude fluctuation, Ground-motion prediction, Small-scale random velocity heterogeneity, Seismic wave propagation, Seismic scattering

detectability of temporal variation in seismic velocity around an earthquake source fault, using a seismic interferometry

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On the basis of experimental studies (e.g. Yoshimitsu et al., 2009 and Lockner et al., 1977), it has been expected that seismic velocity decreases prior to earthquakes. To detect temporal variation in the velocity, stable monitoring of the velocity for a long time is required. Seismic interferometry using micro-tremors is one of the potential techniques which enable us to detect such variation if seismic stations are densely located. With a seismic interferometry technique, some researchers have tried to detect the velocity variation before and after an earthquake using seismograms of a station pair whose interval was longer than ~20 km, but remarkable variation preceding target earthquakes have never been reported. If we can use seismograms of a station pair with a shorter interval, we might be able to detect the variation. In this study, we chose the 2014 Nagano Kamishiro Fault Earthquake (Mj 6.7) as a target, whose source fault (Kamishiro fault) is located between two NIED Hi-net seismic stations (N.HBAH and N.HKKH). The interval of these stations is about 7.3km.

At first, we investigated how frequency contents of micro-tremors depend on time, such as day or night, weekday or weekend. After checking, we confirmed that seismograms on Saturday night are the best for our analysis. After applying one-bit normalization, we divided continuous seismograms into one-minute seismograms. Then, we calculated the cross-correlation function of each one-minute seismograms pair of two stations, and stacked all cross-correlation functions for a period of six hours, on Saturday night. Finally, we obtained stacked cross-correlation from 2011 to 2015.

We found obvious and pulse-like phases around -2s, from which we estimate apparent seismic velocity ~3.5km/s. Further, we found the increase and decrease in velocity during two years before the earthquake. However, the variation of average velocity is as large as 10%, and we cannot find any corresponding phase in positive time. Moreover, we could not find any coseismic variation. It is suggested that distribution of the micro-tremor sources is anisotropic and asymmetric in space and unstable in time even though we focused only on November and December for every year. Consequently, if we try to detect the structure variation around a seismic source fault, we should confirm that the spatio-temporal distribution of the micro-tremors source does not change.

Acknowledgments: We used continuous waveform records of NIED high-sensitivity seismograph network in Japan (Hi-net).

Keywords: seismic interferometry, micro-tremor

Effect of successive aftershocks for one-bit normalization on the seismic interferometry

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1. Introduction

One-bit normalization is a method of waveform processing and converts amplitudes of a waveform to ±1 depending on their signatures. As the method is possible to retrieve phase information independently of amplitude, it is used to minimize non-noise records such as earthquakes on the seismic interferometry, which uses correlation functions.

Fig. 1 (a) shows the temporal change of auto-correlation functions (ACFs) that we calculated from seismic noise observed at Daigo, Ibaraki prefecture, Japan. The result on each day was averaged by 60 ACFs which were calculated from 1-min waveforms filtered from 1 to 3 Hz and red phases indicate positive correlations. After the 2011 off the Pacific coast of Tohoku Earthquake (hereafter, the 2011 Tohoku Earthquake), we found the change of dominant frequency on ACFs and the broken coherence around the lag time of 5 s.

One possibility is that they were associated with successive aftershocks that occur randomly. We investigated the effect of aftershocks for the one-bit normalization on the seismic interferometry.

2. Analysis

We calculated ACFs from normalized waveforms and investigated effects on the stacking procedure. Stacking is a process of making signals amplified by averaging ACFs.

We used waveforms of Hi-net stations at Daigo and Juoh in Ibaraki prefecture, Japan. First, waveforms were filtered between 1 and 3 Hz and applied by one-bit normalization. We then calculated ACFs for 1-min waveforms at the two stations. We carried out the procedure for waveforms on the 1st and 15th days from February to May, 2011 at both stations and averaged over 1 hour, 3 hours, 5 hours, 10 hours, 24 hours, respectively.

3. Results and Discussions

Fig. 1(b) and (c) show examples of ACFs in Daigo averaged over 10 and 24 hours, respectively. The effect of aftershocks clearly seen around the lag time of 5 s in Fig.1(c) was less dominant in Fig. 1(b). In addition, coherent phases could be traced in Fig. 1(c), whereas it was hard in Fig. 1(b). This would be associated with the number of stacked ACFs.

Our results suggest that the stacking of ACFs calculated from waveforms with the one-bit normalization can dramatically reduce the effect of successive aftershocks.

Acknowledgments

We used Hi-net waveform data.

Keywords: Seismic interferometry, One-bit normalization, Successive aftershocks

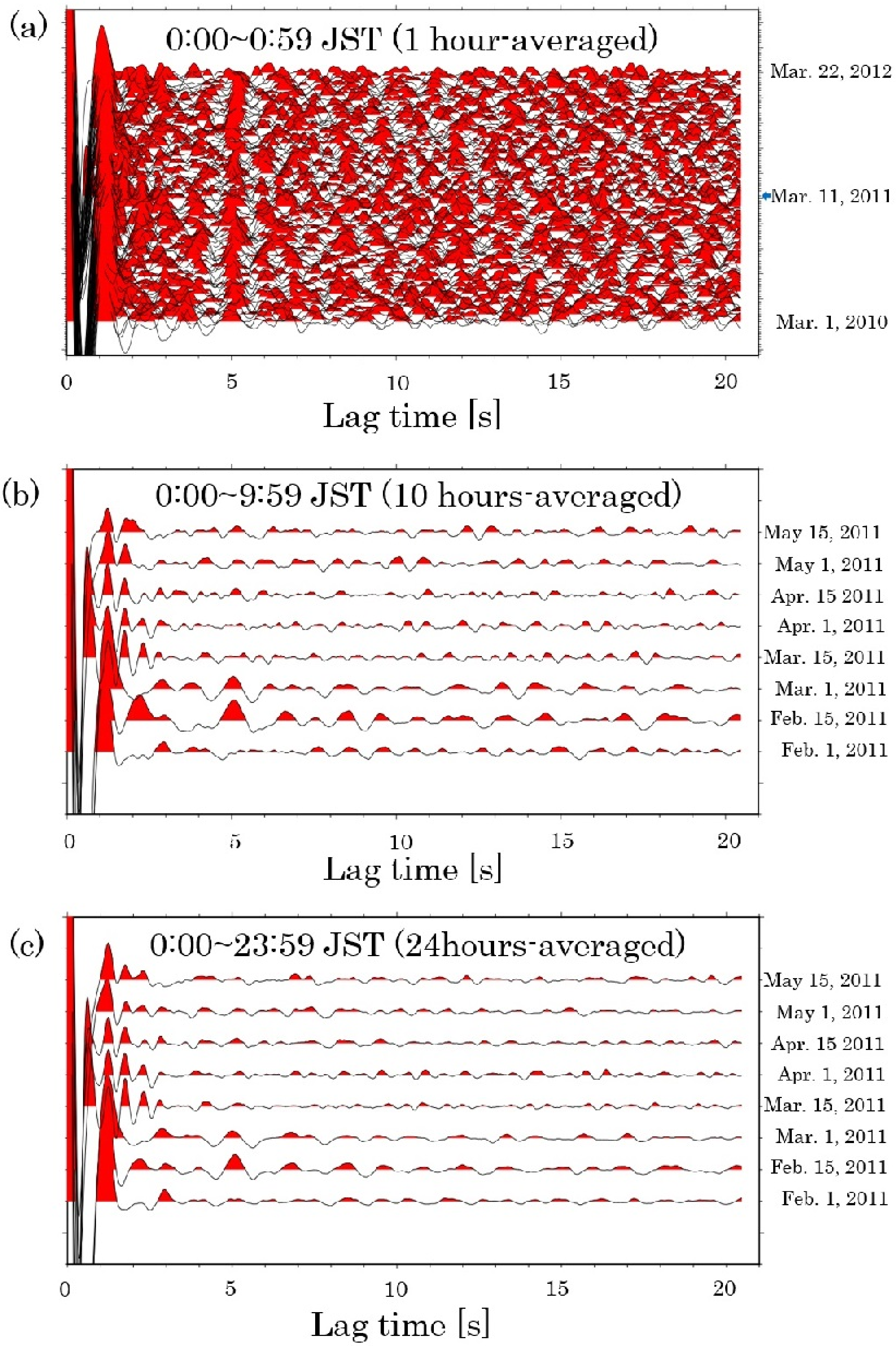

Fig. 1 (a) An example of averaged ACF at Daigo, Ibaraki prefecture, Japan. Individual ACFs were averaged by 60 one-min results. (b) ACFs averaged by 600 results. (c) ACFs averaged by 1440 results.

Subsurface velocity change in Miyagi prefecture associated with the 2011 off the Pacific coast of Tohoku earthquake

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The 2011 off the Pacific coast of Tohoku earthquake (the 2011 Tohoku earthquake) caused a strong shaking in the eastern part of Honshu Island, Japan. We calculated the autocorrelation functions (ACFs) of ambient-noise waveforms in Miyagi prefecture and investigated the velocity change associated with the 2011 Tohoku earthquake.

Seismic Interferometry enables us to extract Green’s functions of between two stations using correlation functions of ambient noise or coda waves (e.g., Campillo and Paul, 2003; Shapiro *et al*., 2005). In other words, an ACF of a waveform gives us the Green’s function in the case that the source and receiver are collocated and let us detect reflected waves beneath the receiver. This method allows for the constant monitoring of the location of underground reflectors and the temporal change on subsurface velocity structure without artificial sources.

We investigated the temporal change in ACFs of the ambient noise observed at 10 Hi-net stations in Miyagi prefecture. Analysis period was 3 months, from February 1 to April 30, 2011. We used waveforms from 2:00 to 3:00 am (JST) to avoid effects of human activities. Detailed waveform processing was as follows.

First, the data were band-pass filtered from 1 to 3 Hz to improve of the signal-to-noise ratio. We then applied the one-bit normalization (Shapiro *et al*., 2005) to remove the effect of natural earthquakes as much as possible and calculated ACFs of ambient noises at stations in Miyagi prefecture. Finally, we obtained ACFs for individual day by averaging 60 one-minute ACFs to ensure the stability of the results which were used to monitor temporal changes.

Figure 1 shows calculated ACFs at Shiroishi station from February 1 to April 30, 2011. Black arrow indicates the date of the 2011 Tohoku earthquake (March 11, 2011). There are coherent wave groups with lag times around 4 and 5 seconds, which are reflected waves. We can see that the arrival times of the coherent waves after the 2011 Tohoku earthquake are later than the times before the earthquake, suggesting that the subsurface velocity became slower due to the 2011 Tohoku earthquake. This is consistent with the result of Nakahara (2014). In addition, we found that amplitudes of ACFs were reduced after the 2011 Tohoku earthquake. This would be due to the successive aftershocks. Isono *et al*., (2016, this meeting) discusses the effect of aftershocks on the one-bit normalization in the ACFs.

Acknowledgement:
We used Hi-net waveform data.

Keywords: Seismic interferometry, Velocity change, 2011 Tohoku earthquake

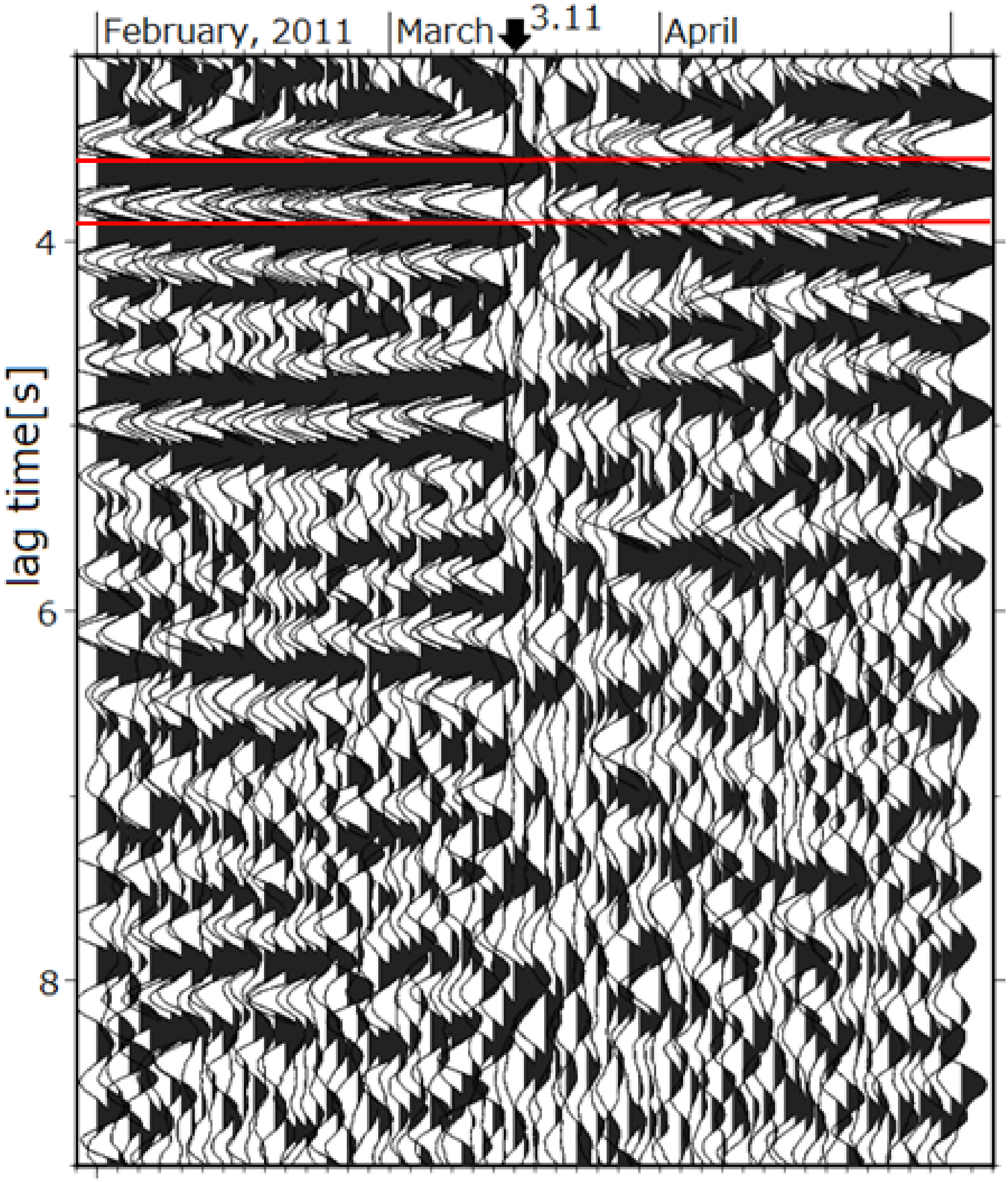

Figure 1. Calculated ACFs at Shiroishi station.
Horizontal axis indicates dates from February 1 to
April 30, 2011. Vertical one shows lag times of ACFs.

Seismic Wave Propagation in a 6-story Building Using Seismic Interferometry of Strong Motion and Broadband Records

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Seismic waves generated by earthquakes propagate from the source in all directions throughout the Earth. At a given site on which a building is situated, incoming seismic waves, which are a convolution of the source, path, and site effects, propagate inside the building causing the structure to vibrate. The response of a building to earthquake ground motions mainly depends on the velocity of shear waves and their attenuation in the building. To investigate the response of a 6-story campus building of the University of Tokyo, we deployed ten 3-component seismometers (5 strong motion and 5 broadband sensors) for 5 months between July and November 2015. The building is 28.8 m high from the basement to the roof top, and has a rectangular shape of 85 m by 16 m, with the long side on the east-west axis. The strong motion and broadband seismometers were placed together at the basement, 2F, 3F, 5F, and roof top, and recorded continuous data with a sampling rate of 100 Hz that was shifted to 200 Hz for the last month of the experiment. We use deconvolution interferometry of ambient vibration and earthquake records to determine the properties of the waves (e.g., wave velocity, frequency content, and attenuation) propagating inside the building. We find that the frequency of the fundamental mode is around 2.7 Hz for the EW component and 3.1 Hz for the NS component, due to the rectangular shape of the building. Moreover, extracted waves propagate faster in the NS direction than in the EW direction. We also find that the deconvolved waves computed from strong motion and broadband records are similar for this building. However, broadband sensors would be more appropriate to investigate the characteristics of high-rise buildings that have long natural periods.

Keywords: Ambient seismic field, Seismic interferometry, Building response

1-D SIMULATION OF LONG-PERIOD GROUND MOTIONS IN THE KATHMANDU VALLEY DURING MEDIUM AND LARGE EARTHQUAKES

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Kathmandu valley, housing the capital and most populous city in Nepal, lies in seismically active region of the Himalayan collision zone where large earthquakes occur during certain periods. The valley in central Nepal is a basin formed by drying up of a lake of Plio-Pleistocene origin and has ~ 600 m thick unconsolidated sediments. It has suffered the brunt of past earthquakes due to the wave amplification as a result of basin effect. The impact of an earthquake is directly related to the amplification of seismic waves due to the sediments in a basin. Hence, it is necessary to study the behaviour of seismic waves in the basin to help reduce the damages to infrastructure during earthquake. To meet the aim, seismic records and information of underground structures are necessary. Though previous studies have tried to study the underground structure of the valley, there is still much to be done.

The records of a medium sized (mb4.9) earthquake is used to construct a 1-D velocity model of the basin. The earthquake occurred in 2013 August 30 in Tibet-Nepal border (80 km NE of Kathmandu) was recorded in four accelerometers installed as a collaborative work between Hokkaido University and Tribhuvan University. We used acceleration record from the rock-site station as the input motion to model the velocity structure under three sediment-site stations. Available geological maps and borehole logging data were used as the basis for constructing the velocity models which were tuned with trial-and-error. The SH component of the input motion was band-passed filtered (0.1-0.5 Hz) and passed through the velocity models by using the Propagator Matrix method to simulate the waveform for the sediment sites. The input motion was considered to impinge the basin perpendicularly as the hypocentre of the earthquake was more than 50 km deep. We fixed the shear wave velocity of basement rock as 3.2 km/s based on the 1-D velocity model of the Himalaya region. As the shear-wave profiling carried out in 2011 during the installation of the accelerometers shows the rock-site station to have a shear wave velocity of more than 700 m/s, we considered a ~20 m thick weathered rock layer at the bottom of the basin overlying the fresh bedrock.

We found a good-fit of the simulated waveforms when compared with the observed waveform in the initial S-wave motion of the Tibet Earthquake. We also used the same velocity models to simulate the 2015 Gorkha Earthquake (Mw7.8) and they also showed a good-fit with observed waveforms. Nevertheless, the amplification in the later phases in one of the station couldn’t be simulated properly. The complex basement topography and 3-D basin structure might have played a role in the high amplification in the later phases. We will work further in understanding the 3-D basin structure of the Kathmandu valley in future.

Keywords: Kathmandu Valley, 1-D velocity structure, Propagator Matrix

Numerical simulation of long-period ground motion generated from intraplate earthquakes around Ibaraki and Fukushima prefectures ~ Part II

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After the occurrence of 2011 Tohoku-Oki earthquake, phenomena of long period ground motion have been observed at seismic observation stations around the coastal region of Ibaraki prefecture for the occurrence of shallow depth intra-plate earthquakes (including 2011 Fukushima-ken Hamadori Earthquake) around Ibaraki and Fukushima prefectures. Before the occurrence of Tohoku earthquake, there was little noticeable intraplate large earthquake, and physical characteristics of generation of long-period ground motion mostly remained unclear. Therefore, better understanding nature of generation of long-period ground motion and improving seismic wave propagation around this region are very important for evaluating ground motion around the coastal region of Ibaraki prefecture. They will also lead to more reasonable evaluation of earthquake-proof safety of important infrastructures and subsurface structure around this region.
In this research, for achieving more accurate evaluation of seismic wave ground motion of intra-earthquakes around the coastal region of Ibaraki prefecture (strong motion, long-period ground motion, and etc), the 3-D underground structure model, which fairly explains phenomena of long-period ground motion, is reconstructed by using postseismic events of Hamadori Earthquake. This presentation introduces the updated results which additional data are analyzed (preliminary results were presented in the 2015 JPGU).
First, we constructed an initial underground structure model, on the basis of the underground structure model of the Headquarters for Earthquake Research Promotion of Ministry of Education Culture, Sports, Science and Technology in Japan (http://www.jishin.go.jp/main/chousa/12_choshuki/, Koketsu et al., 2008, Koketsu et al., 2009). Next, based the finite element method using on the structure model, we performed seismic wave propagation simulation of intraplate earthquakes (moderate scale, M<6.0), and try to forward-model the long-period ground motion being generated during propagation thorough the inhomogeneous underground structure. For optimizing the 3D underground structure model, we used seismic observation stations of KIK-net and Japan Atomic Energy Agency around this region. The result showed that optimized 3D structure model could better explain the generation of long-period ground motion around this region, and suggested that they are generally originated from the regional-scale characteristics of basement structure beneath intra region.

Keywords: 3D structure, Seismic wave propagation, FEM simulation, Hamadori

The feature of waveform in Japan of two deep earthquakes which occurred beneath Peru on November 24, 2015

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Two deep earthquakes occurred successively on November 24, 2015 in Brazil. According to USGS, magnitude of these earthquakes are Mw 7.6, and focal mechanism of these earthquakes is the normal fault type. These two deep earthquakes were observed at whole part of Japan, but in trace, the amplitude ratio of the two earthquake are not constant.
From the two earthquakes, the Japanese observation seismic networks locate between 135 and 150 degree. Then half of the stations are in the shadow zone, the others are out of the shadow zone. The borderline of the shadow zone is crossing at the Chubu district, and maximum amplitude is caused PKP or PKIKP. Because two hypocenters are 0.5 degrees distant, amplitude ratio is varied.

Keywords: shadow zone, deep earthquake

