On spatio-temporal variation of seismic velocity change associated with large earthquakes

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Seismic velocity of the Earth’s subsurface varies not only with nonstationary phenomena such as earthquakes and volcanic activities, but also with stationary phenomena such as groundwater movement and plate motion. Seismic interferometry is an effective technique that can detect subtle velocity changes caused by these geophysical phenomena, and has been widely applied to dense continuous seismograph networks like Hi-net and F-net that have been prepared in recent decades. The studies so far have revealed that the velocity reduction up to a few percent is commonly observed after large earthquakes, and the velocity recovery continuing over a few months follows after that. The main causes of the velocity reduction due to large earthquakes are considered to be the fracturing of fault zone, the static strain change due to coseismic deformation, and the damage in the shallow ground due to strong ground motion. In the early studies, the observed velocity change had often been interpreted as change of the frictional strength on the fault plane. Recently, however, studies which relate the change to strong ground motion and the damage in the shallow ground are increasing in combination with similar phenomena such as nonlinear ground response and liquefaction. On the other hand, some studies reported velocity reduction associated with slow-slip, postseismic deformation, and earthquake swarm, which are not accompany with strong ground motion. Thus discussions on the main cause of the velocity change are still continuing. In this presentation, I introduce recent studies on the spatio-temporal distribution of seismic velocity change, and discuss on causes of the velocity change due to large earthquakes. On the spatial distribution, I introduce an example that effectively used sensitivity of seismic wavefield to detect velocity changes at different depths, and interpreted the observed depth-dependence by the weighted sum of the contributions of crustal deformation and strong ground motion. On the temporal scale of the velocity recovery, I discuss on the observed recovery process in relation to “slow dynamics”, the log-linear recovery behavior recognized in rock experiments, and to the time-constant of postseismic deformation and groundwater diffusion processes. Because the temporal change is usually observed as combination of background changes and nonstationary changes, I also examine such cases that include multiple time-varying factors.

Keywords: seismic velocity change, seismic interferometry

Formulating sensitivity kernels of coda waves to seismic velocity changes: Extension to vector waves (1)

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Coda-wave interferometry has been used to detect velocity changes in association with large earthquakes and volcanic eruptions. It is important to determine the region of velocity changes correctly for understanding physical mechanisms to cause the velocity changes. It is the sensitivity kernels of travel times of coda waves to velocity changes that concern with this problem. The sensitivity kernels have been formulated so far based on different assumptions for scalar waves using two-dimensional single scattering and multiple scattering, three-dimensional multiple scattering, and diffusion. However, no formulation has been made for vector waves as far as we know. Hence, we tackle this formulation and derive analytical expressions for two-dimensional cases. The key point in our simple extension to vector waves is the projection of seismic phonon energy into horizontal and vertical components by using the square of the direction cosine of the polarization direction. Thanks to this simple idea, we can derive analytical expressions of the sensitivity kernels by using the two-dimensional single isotropic scattering model for scalar waves, though we can treat either P waves or S waves at a time. Our results show that the sensitivity kernels are different for different components, and accordingly two components show different travel time changes with respect to lapse time. These are theoretically shown by this study for the first time. However, the sensitivity kernels for vector waves have also two clear peaks at a source and a receiver like those for scalar waves. We plan to validate the sensitivity kernels by comparing with finite difference simulations of vector wave propagation. The sensitivity kernels for vector waves are more practical and necessary for us to know how to use different components simultaneously.

Keywords: Sensitivity kernel, coda waves, vector waves

Passive monitoring of groundwater using elastic waves

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It is important to monitor the state of groundwater for early prediction of the slope failures. Elastic waves can be a powerful tool to detect a small change in elastic wave speed or attenuation, because they reflect integral values along the propagating paths (Yoshimitsu et al., 2009). Some studies so far applied seismic interferometry in the landslide areas, detecting a decrease in elastic wave speed for coda parts prior to the catastrophic landslide (Mainsant et al., 2012). However, because they assume that change in elastic wave speed is uniform, where such changes took place remains unknown.

In order to estimate the detailed structures in the shallow (~ a few tens of metes) part and their temporal changes, we placed a seismometer at the toe side of a landslide area. We selected the landslide located in Shiga Prefecture, which is shown in the landslide distribution map by NIED. Springs are observed inside the landslide area, suggesting the ground water level is very shallow.

Seismic waveforms are recorded at the sampling frequency of 200 Hz. Travel times of the phases related to the shallow structure are considered to be short, which implies that we need larger sampling frequency. Therefore, we interpolated the raw data using cubic spline functions to obtain the waveform data every 1 ms. Then, we calculated the auto-correlation functions using 1 day records, followed by whitening process. As a result, we detected coherent phases with the travel time less than 1 s. In the next step, we discuss the cause and the temporal changes of these phases together with the changes of noise sources.

Waveform-based estimation of velocity heterogeneity for prestack imaging from broadband seismic reflection data

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Deep seismic reflection profiling with rugged acquisition topography, crookedness of seismic lines has been imposed serious restrictions and compromises on both data processing and acquisition. In addition to complex subsurface structure, irregular distribution of shots, and large noise level of surface wave and back-scattered wave often result in deterioration of the data quality and poor reflection image in seismic profile. In recent years, the quest for increased precision and channel capacity of receiver system led to the combination of telemetry and autonomous recorders with the deployment of dense seismic array for deep seismic profiling. For deep seismic profiling with wide aperture, dense spatial sampling and low-frequency, velocity structures estimated through turning-ray tomography (TRT) are restricted in resolution, since TRT depends on direct arrivals of seismic wave with the assumption of asymptotic ray theory. On the other hand, full waveform inversion (FWI) based on full wavefield modeling and inversion has an advantage to estimate high-resolution velocity heterogeneity compared to TRT. However, pre-conditioning including coherent noise suppression and relative-amplitude preservation is indispensable for the application of FWI. In our study, multilateral approach beyond the conventional CMP stack is applied to the multi-scale, multi-mode seismic data for extraction of deep crustal reflectors through the reconstruction of velocity heterogeneity. The high-resolution velocity structure can be estimated by the hybrid profiling of reflection velocity analysis, TRT and FWI. The uncertainty of the tomography solutions is evaluated using a nonlinear Monte Carlo approach with randomized initial models, and the velocity structure of upper crust is constrained by subsequent forward reflection and refraction modeling. The combination of CRS-driven velocity attribute and FWI with the short-wavelength structural heterogeneity was confirmed to have the potential imaging capabilities including velocity model for improved prestack depth imaging.

Keywords: Fullwave inversion, Velocity estimation, Reflection seismic exploration

Adjoint tomography and its application to the seismic wave-speed structure beneath Japanese Islands

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Powerful supercomputers enable us to simulate a seismic wavefield using three-dimensional (3D) structure and seismic waveform inversion based on wave theory has become feasible recently to clarify the realistic Earth structure. Adjoint tomography is a method of waveform inversion using the gradient of the misfit function obtained by interaction between a forward and an adjoint wavefield. Wave-speed model is updated by a gradient method, such as the steepest descent method, until the misfits between observed and theoretical waveforms become small. Adjoint tomography has applied to the Californian region (Tape et al. 2009), the Australian region (Fichtner et al. 2009), Europe (Zhu et al. 2013), East Asia (Chen et al. 2015), and other regions. In terms of the 3D structure beneath Japanese Islands, we have the results of the seismic tomography based on ray theory, or layered model by the NIED J-SHIS to predict strong motions. We are working on construction of the realistic wave-speed model beneath Japanese Islands by using adjoint tomography to reproduce observed seismograms and to predict strong motions for future earthquakes. We have obtained the model of the 3D structure beneath the Kanto region, Japan. We picked up the waveforms with a high S/N ratios from the broadband seismograms observed by NIED F-net. The earthquakes were selected between 4.5 and 5.5 for moment magnitude from the F-net earthquake catalog. Almost events occurred at the upper boundary of the subducted Pacific and Philippine Sea plates, and some events occurred in the upper crust of the overriding plate. We used the travel-time tomography result (Matsubara and Obara 2011) as an initial model with considering no ocean, no attenuation structure in the forward and adjoint simulations for 130 sec duration. The minimum period was 2.6 sec for the initial model. We used the spectral element method to calculate forward and adjoint wavefields (e.g. Peter et al. 2011). Large computing was conducted on the Riken’s K computer; it takes approximately 4,000 node hours for each iteration. The inversion involved 3 iterations for the period range 5-20 sec after 4 iterations for the period range 10-20 sec. The new wave-speed model shows the low wave-speed area corresponding to the Kanto basin in the shallower part, and the low wave-speed zone associated with the subducting Philippine Sea plate at around the depth of 35 km. The new wave-speed for the shear wave includes local changes of 10 % with respect to the initial model. These results may be affected by initial structure and source model, number of stations, and the difference between ray theory and wave theory. We are planning to use not only land observations but also ocean-bottom observations to construct the reference structure beneath Japanese Islands.
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Keywords: adjoint tomography, wave theory, large computing, seismic wave-speed structure

An easy-to-use parallel finite difference method numerical simulation code for seismic wave propagation

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Numerical simulation of the seismic wave propagation is a fundamental tool for various aspects of the earthquake seismology, such as the estimation of the inhomogeneous structure, seismic source process, physics of wave propagation in earth media. The significant improvements on the simulation method, unified inhomogeneous velocity structure, and the computer itself eventually enabled us to use the 3D numerical simulation for regular data processing studies with present parallel computers. In this study, we developed the 3D numerical simulation code based on the finite difference method for parallel computers, which is easy to use for non-specialists of the numerical simulations for wider utilization of the earthquake seismology.
Our numerical simulation code is originally developed for cutting-edge supercomputers. It has adopted the generalized Zener viscoelastic body to simulate the wide-band realistic anelastic attenuation, and finely tuned for the machine architectures to achieve the high-efficiency in terms of the computational speed. On the other hand, the code was specialized too much for specific supercomputer environments, and therefore it was not easy to handle by non-specialists.
In this study, we fully restructured the code for improving usability. The new codes allocates the memory dynamically, generate 3D inhomogeneous velocity model automatically, and export the computation result with seismologist-familiar formats. The behavior of the code is perfectly controllable by a simple input file, and it is not necessary to write and/or modify the code for users. In particular, unification of pre-process such as the velocity model preparation and post-process such as the output data handling and conversion are unified to the computation code, resulting a considerable lighten of the user's burden on manipulation.
Although the code uses the Cartesian coordinate, however, the users can use longitude and latitude coordinate for source and receiver location because it implements the Gauss-Krüger's geographical transformation. As for the velocity structure, the code automatically generates the uniform 3D grid model from input set of layers of velocity discontinuity described in longitude-latitude coordinate system. For the seismic source, one can use not only for the moment tensor source but also the body-force source, plane wave incidence from the bottom. One also can efficiently calculate the impulse response of the velocity model by using the reciprocal theorem. These various behavior also can be controlled by the parameter file.
For an example, we simulated broad band seismograms for earthquake occurred nearby Japan with moment magnitude ranging 6.0-6.5. We used 1D velocity profile of the NIED F-net and the Japan Integrated Velocity Structure Model with moment tensor solution based on the F-net catalog, and measured the goodness-of-fit by measuring the cross correlation between simulated and/or observed seismograms.
The numerically simulated seismograms show quite high cross-correlation value at longest period band of 50-100 s, however the correlation rapidly drops as decreasing periods. We note that the source locations and mechanisms used in this study were originally estimated assuming a simple 1D velocity structure, therefore observed waveforms are not necessarily fit the simulation result under 3D velocity model. However the simulated waveforms based on 1D and 3D velocity models sometimes differs at even long period range around 50 s with regionality. This result suggests the 3D effect is still strong, and expects significant improvement on determining source and mechanism

by introducing 3D numerical simulation as Green's functions.

Keywords: Seismic wave propagation, Finite difference method, Parallel computing, Numerical simulation

Evaluation of the generation and propagation mechanism of T-phase based on wave propagation simulation

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1. Introduction

The T-phase is the tertiary wave observed after P and S waves, which is acoustic wave propagating in the oceanic layer at speed of 1.5 km/s. T-phases are generated by P and S waves radiated from the earthquake below the ocean floor and transmitted into seawater directly and by S-to-P conversion at the solid-liquid interfaces of sea bottom, and then captured within the seawater by wide-angle reflections of P waves. In the presence of a sloping ocean floor above hypocenter, it is getting easier to make large-angle P reflections, and it is expected to enhance the excitation of T-phase. On the other hand, there is still question why T-phase is also generated on almost flat ocean floor (Okal 2008). For efficient propagation of T-phases, it is also explained that T-phases are trapped in the so-called SOFAR channel (SOund Fixing And Ranging) of minimum sound velocity. Also the T-phase reflected at large variation of topography such as seamounts (Obara and Maeda, 2009). In order to answer these questions and to understand the generation and propagation process of T-phases, we analyzed T-phase observed in ocean-bottom seismometer (OBS) and the conduct in 2D finite-difference method (FDM) simulation of seismic wave propagation.

2. T-phase data observed by OBS

We inspected the seismograms for T-phases in the broadband OBS station (WPAC) placed on North Pacific for 18 events occurred around Kuril and Aleutians in depth range 14-62 km and in distances range 788-1899 km. A band-pass filter of 2-8 Hz was applied to remove surface wave. To compensate the magnitude we examined relative amplitudes of T-phases normalized by P or S waves. We confirmed that T-phases propagated to far-field had a spindle shape of long duration properties. It is also confirmed that T-phase amplitudes were greater when slopes of seabottom above hypocenter is larger and longer. In addition, T-phase amplitudes were usually larger for shallow events. Also T-phase amplitudes attenuated drastically when propagation paths crossed seamounts.

3. Wave propagation simulation

For reappearance of such strong T-phases observed by OBS, we investigated the influence of submarine topography and underground structure by 2D FDM simulation of seismic wave propagation. For analyzing the relation between the generation of T-phases and seabottom topography, we computed the wave propagation using a flat topography model and a linearly sloping topography model. The crust and the mantle structural model was followed by Sereno and Orcutt (1985), and P waves velocity in oceanic layer were set to 1.5 km/s. In a reverse fault earthquake in 33 km depth, ground motion in maximum frequency of 8 Hz was calculated. As a result, in the sloping topography model, T-phases appeared after S waves, but T-phases did not generated in the flat topography model. When heterogeneous topography was added in the sloping model, T-phase amplitudes became somewhat weaker, and waveforms of T-phases became the spindle sphapes. Moreover, in the crust and the mantle model containing horizontally-elongated small-scale heterogeneous structure (Kennett and Furumura, 2014), waveforms had much longer duration of P and S waves (Po and So waves), but waveforms of T-phases were almost the same. Therefore, the generation of T-phase with the spindle shape relates strongly to sloping and roughly subsurface topography. Additionally, we could show that T-phase amplitudes became larger in the case of the shallow focal depth. Also, we could confirm that the attenuation of T-phase energy was weaker by being trapped in the SOFAR channel, and T-phases could propagate to longer distance easily.

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Keywords: T-phase, Submarine topography, Underground structure, Wave propagation simulation

Scattering and attenuation characteristics at active volcanoes inferred from envelope widths of volcano-seismic events

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We propose a method to estimate scattering and attenuation characteristics beneath active volcanoes using envelope widths of volcano-seismic events. In this method, we estimate the peak amplitude (A) and cumulative amplitude (I) using an observed envelope waveform of a volcano-seismic event at each station. We define the ratio of the cumulative amplitude to the peak amplitude (I/A) as the envelope width (T). We used the approximate analytical equation of Paasschens (Phys. Rev. E, 1997) for the radiative transfer theory in 3D isotropic scattering medium to derive the relationship of p with the total scattering coefficient g0 and intrinsic attenuation Q. The estimated relationship indicated that p increases with increasing g0 and Q at a constant source-station distance, and p also increases with the source-station distance. We estimated p values for volcano-tectonic (VT) events at Taal volcano, Philippines, and long-period (LP) events at Nevado del Ruiz volcano, Colombia. Our estimated p values increased with increasing source-station distances in the ranges between 1 and 5 s. We found no correlations between p and event size, indicating that p is determined by the medium characteristics. The observed p values were explained by the mean free path l0 (1/g0) of 500-1500 m assuming Q = 50 based on the relationship. These values are consistent with those estimated at other volcanoes. We compared p values for VT events at Taal, of which source locations were very similar, and found the p values at individual stations showed similar values among the different events. However, these p values were not explained by assuming constant g0 and Q in space. Furthermore, we found that p values at a particular station where rays passed through the attenuation region estimated by Kumagai et al. (GRL, 2014) showed different values in time. These results indicate that the envelope width may be used to as a parameter to estimate the scattering and attenuation characteristics beneath volcanoes.

Isotropic radiation of *S* waves at volcanoes revealed by numerical simulations of high-frequency scattered wavefields

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Volcanoes have highly heterogeneous structures, which produce scattered seismic wavefields in seismic wave propagation. At many volcanoes, the amplitude source location (ASL) method has been used to locate volcano-seismic events and tremor. The ASL method uses high-frequency seismic amplitudes under the assumption of isotropic radiation of *S* waves. This assumption has been interpreted to be valid in a high-frequency band because of the path effect caused by the scattering of seismic waves. *Kumagai et al*. [JGR, 2011] simulated seismic waveforms in heterogeneous medium with topography to investigate the validity of this assumption. However, they could not reproduce isotropic radiation and suggested that strong short-scale structural heterogeneity is required to achieve isotropic radiation. To validate the isotropic radiation assumption and to investigate the characteristics of scattered seismic wavefields at volcanoes, we performed numerical simulations of high-frequency seismic waveforms with stronger heterogeneous media. We synthesized seismic waveforms with a 3-D finite-difference method at Taal volcano, Philippines. We used topography of this volcano and heterogeneous structural models characterized by von Karman-type power spectral density function (PSDF). We used the correlation distance (a) in a range between 50 and 1000 m and the root-mean-square amplitude of velocity fluctuation (ε) between 0.05 and 0.2, in which a constant value of 0.5 for $\kappa$was used. To test isotropic *S* wave radiation, we used synthetic seismograms at actual station locations to determine the source location using the ASL method in various frequency bands (0.2-2, 1-6, 3-8 and 5-10 Hz). We found that the source location was determined near the input location when using a = 50 m and ε= 0.2 in a frequency band of 5-10 Hz. In this condition, ka is around 1 and the mean free path is about 1500 m, where k is wavenumber. This mean free path is similar to those estimated at volcanoes, which are around 1000 m [e.g., Yamamoto and Sato, JGR, 2010]. Our study strongly supports that isotropic *S* wave radiation is achieved by the path effect caused by seismic scattering in heterogeneous media similar to actual volcanoes.

Keywords: Scattering, Volcano, Isotropic radiation of S waves, Amplitude source location method, Finite-difference method

Volcanic tremor accompanied by the phreatic eruption at Hakone volcano, 2015

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At Hakone volcano, central Japan, a small phreatic eruption was observed at Owakidani geothermal region on 29 June 2015. A few hours before the phreatic eruption, sudden tilt changes of several micro radians were detected by tilt meters and broad band seismometers installed around the Owakidani geothermal region. The tilt changes can be explained by an opening of shallow crack near Owakidani. The result implies that large amount of hydrothermal fluid (hundred thousand m^3) was intruded into a shallow part beneath the Owakidani geothermal region during the tilt changes (Honda et al., 2015). After this event, we also observed volcanic tremors by seismometers near the Owakidani geothermal region. The predominant frequency of the volcanic tremors ranged from 2 to 8 Hz. The volcanic tremors intermittently occurred for two days from 13:03 on 29 June. To determine the source location of volcanic tremor, we used the cross correlation technique of waveform envelope (Obara, 2002). We found that the volcanic tremors occurred at a shallow part near the crater in the Owakidani geothermal region that was formed during the phreatic eruption. We also found that the volcanic tremors were correlated with the occurrence of infrasonic wave. The infrasonic waves were observed after the occurrence of volcanic tremor. From these results, we can suggest that the volcanic tremors were triggered by migration of the hydrothermal fluid that was intruded during the tilt changes, and the infrasonic waves were probably exited by blowout of the hydrothermal fluid.

Keywords: Volcanic tremor, Phreatic eruption, Hakone Volcano

Monochromatic oscillation and its frequency variation from 7 to 11 mHz observed at F-net IGK station, Ishigakijima, Japan

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Some distinctive oscillations with a frequency of around 10 mHz were frequently found in the F-net IGK broadband seismometer data acquired and distributed by NIED on the feasibility study using initial data of the newly installed seismometers (Nawa et al., 2015) in Ishigakijima, Okinawa, Japan. By analyzing the continuous data (20Hz-sampling BH*, 1Hz-sampling LH* channels) of the F-net IGK station, we found spectral peak of approximately 11mHz at the period of January 2012 to June 2014, and its gradual frequency decrease from 11 mHz to 7 mHz at the period of July 2014 to April 2015, mainly in the NS component. From the comparison between teleseismic waves observed at IGK and those at surrounding stations (Kimura et al., 2015), and noise analysis (Kimura, 2015), it has been confirmed that the F-net IGK seismometer is operating normally at those period. In comparison with observed water level of the Nagura dam for irrigation near the F-net IGK station, it was found that the observation period of frequency of 11mHz corresponds to the period of the full water level of the dam. And we found a good correlation between frequency variation of the peak and the reservoir water level temporal variation. By using numerical simulations via the COMSOL Multiphysics®, we demonstrated that a frequency of fundamental mode of the dam reservoir seiche coincided with the observed frequency of oscillation at full water level. Also, the simulation revealed a relation the frequency decrease with the water level/amount decrease. From these conditions, observed oscillation on F-net IGK broadband seismometer records is concluded as the seiche of Nagura dam reservoir.

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Keywords: broadband seismometer, noise, seiche, dam reservoir, Ishigaki Island

Envelope broadening and scattering attenuation in random media having a power-law spectrum

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In short-period seismograms of small earthquakes, we see peak delay and envelope broadening of an S-wavelet with travel distance increasing. Those phenomena are results of scattering effect caused by random velocity inhomogeneities of the earth medium. As a simple mathematical model, we study how the envelope of a scalar wavelet varies in von Karman type random media, which have a power-law spectrum at large wavenumbers. Using the center wavenumber of a wavelet as a reference, we propose to divide the random medium spectra into the low-wavenumber spectral (long-scale) component and the high-wavenumber spectral (short-scale) component. For the wave propagation through the long-scale component of random media, we may apply the parabolic approximation to the wave equation. Using the Markov approximation, we statistically synthesize the mean-square (MS) envelope of a wavelet, which shows a delay of the maximum peak arrival from the onset and broadening of envelope duration. The resultant envelope duration increases according to the second power of travel distance. Wide angle scattering caused by the short-scale component of random media attenuates wave amplitude with travel distance increasing. We use the total scattering coefficient of the short-scale component as a measure of scattering attenuation per distance, which is well described by the Born approximation. Multiplying the exponential scattering attenuation factor by the MS envelope derived by the Markov approximation, we can synthesize the MS envelope reflecting all the spectral component of random media. When the spectral role-off is steep at large wavenumbers, the envelope broadening is small and frequency independent, and scattering attenuation is weak. When the spectral role-off is small, however, the envelope broadening is large and increases with frequency, and the scattering attenuation is strong and increases with frequency. The proposed envelope synthesis is fully analytic. It can be a theoretical basis for the evaluation of random inhomogeneities of the earth medium from the analysis of seismogram envelopes.
Sato, H. (2016) *Envelope broadening and scattering attenuation of a scalar wavelet in random media having power-law spectra*, Geophys. J. Int., 204, 386–398.

Keywords: seismic waves, envelope, random media, scattering, attenuation, wave theory

Envelopes in 3-D Random Media: Comparison of the new Markov approximation and the finite difference simulation

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Short-period seismograms show complex waveforms reflecting small scale heterogeneities in the earth. For example, the main part around the peak of the seismograms becomes broader than the source duration and long lasting coda waves are excited. We can interpret these phenomena by considering the wave propagation through the random velocity fluctuated medium based on the scattering theory. There are several stochastic methods such as the radiative transfer theory, diffusion approximation and the Markov approximation. In this study, we focus on the Markov approximation based on the parabolic approximation. The applicable range of the Markov approximation has been validated by comparing with the finite difference (FD) simulation of the wave equation in 2D random media. However, the validation in the 3D random media is limited. Taking the wavenumber of a wavelet as a reference, Sato (2016) proposed an extension of the Markov approximation by dividing the spectrum of the fluctuation into the long-scale which contributes the envelope broadening and small-scale component which affect the attenuation. By applying the Markov approximation to the long-scale component, we can obtain the analytical solution of the mean square (MS) envelope for random media having the power-law type spectrum of the fluctuation. Here, conducting 3D FD simulations, we seek the applicable range of the new Markov approximation by comparing the theoretical envelopes with FD simulation envelopes.
In the FD simulation we use 1.5 Hz and 3.0 Hz Ricker wavelets. We assume that the average velocity is 4 km/s. The grid spacing is 40 m and the time interval is 3 ms. We solve the 3D scalar wave equation with the 4th and 2nd order accuracies for the space and the time, respectively. The medium size for x and y directions are 174 km and that for z direction is 250 km. For the 1.5 Hz case, we double the grid spacing and time interval and half the number of the grid for each direction. We conduct at least 5 FD simulations with different random seeds and set 9 receivers at each propagation distance. Therefore we stack at least 45 envelopes to calculate the MS envelope.
We assume that the correlation distance is 5 km and the root mean square of the fluctuation is 5 %. We change the κwhich controls the roll-off of the power spectrum for 0.1, 0.5 and 1.0. For 3 Hz simulation, we set κ=0.5.
The duration of the MS envelopes derived by the FD simulation becomes broad with the propagation distance. The peak amplitude of the MS envelope decreases as $r^{-2.6}$ to $r^{-3.5}$. This decay rate is large for a small κ. For the case of the 3 Hz, the decay is $r^{-2.7}$. The excitation of the coda is strong for a small κ.
Sato (2016) define the corner wavenumber of the small-scale component as $1/a_s = \zeta k_c$, where k_c is the central wavenumber of the wavelet. Hence $\zeta$is a fine tuning parameter of the reference scale. For the case of the small ζ, the contribution of the small scale component becomes large. The envelope broadening is weak and the scattering attenuation is strong. The envelope duration becomes long and the scattering attenuation becomes small for large ζ. We found that the theoretical envelopes are well fitted to the FD envelopes for ζ=1.0 and 1.5. Even when κ=0.1, the theoretical envelopes can roughly model the FD envelopes. However, the decay rate with the propagation distance of the FD envelopes is larger than that of the theoretical envelopes for all values of ζ.
We will examine the validity of the new theory for different $\kappa$and center frequencies in the future. We will analyze the fluctuation of MS envelopes of the FD simulation, too.

Acknowledgement: We used the Earth Simulator run by JAMSTEC for the 3D FD simulation.

Keywords: Scattering, finite difference simulation, envelope

Vector energy transfer of seismic waves and lithospheric heterogeneities beneath the US

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Stochastic analysis of seismic waves can provide a different vision of the structures in the lithosphere, complementing the deterministic pictures provided by seismic tomography models. To infer the stochastic properties of the lithosphere beneath US we analyzed the vector transfer of energy using 3 component seismograms recorded at USarray seismic network. The application of theoretical scattering model based on the Markov approximation permits to interpret the vector energy ratio and derive statistical information about the heterogeneity distribution in the analyzed medium. By using high frequency seismic waves a continental vision of the scattering properties of the US lithosphere is obtained by the regionalization of our observations. The derived map of the lithospheric scattering reveals strong correlation of the scattering property with well-known geological features of the US lithosphere. High scattering is observed in tectonically active east US and highly deformed central regions, while low scattering is characteristic of old cratonic regions in the eastern US.

Keywords: Scattering, Stochastic imaging, Wave propagation in complex media

Imaging melting of Philippine-Sea Plate subducting beneath central Japan

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The central Japan is a globally unique seismo-tectonic zone with the complex interaction of the Eurasian, North American, Pacific (PAC), and Philippine-Sea Plate (PHS). Thermal and petrologic models predict that the oceanic crust of the young (<20 Ma) PHS subducting beneath central to south-west Japan is ~300^{o} to 500^{o}C warmer than that of the old (~100 Ma) PAC subducting beneath northeast Japan, and is thus more prone to melting. Deriving a high-resolution image of the slab melting is a key to understand the basics of plate tectonics and magma genesis.
Although several structural models of the PHS, based on travel-time tomography (Hirose et al., 2008) and receiver function analyses (Shiomi et al., 2004), detected the gross features of subduction zone, the melting in PHS, at a scale on the order of seismic wavelength, is yet to resolve from the tomography image of the slab due to the coarser spatial resolution. The high-resolution waveform analysis and numerical simulation of wave propagation are alternatives to obtain such images of complex subduction zone. In this direction, Padhy et al. (2014) recently detected slab thinning/tearing in PAC by analyzing deep-focus earthquakes beneath central Japan. Similarly, Lin et al. (2013) proposed slab melting as one of the probable causes for the observed spindle-shaped, highly scattered waveforms from mantle earthquakes in central Japan. Their study is, however, based on mere observation of only two mantle earthquakes recorded at few stations. To build on this work, we extensively analyzed waveforms of intermediate (50-300 km) to deep (>300 km) intra-slab moderate-sized (M4-6) earthquakes occurring in central Japan and conducted numerical simulation to derive a fine-scale PHS model, incorporating slab melting in the model.
Spindle-shaped seismograms with strong excitation of slowly decaying, long-duration high-frequency coda are observed for a group of PAC events occurring in northern part of central Japan recorded by Hi-net. These waveform anomalies can be explained by the 2-D finite difference method (FDM) simulation of high-frequency (up to 10 Hz) seismic waves in subduction zone containing features such as the melting in PHS crust, serpentinized mantle wedge, and the heterogeneous PAC. Comparison of observations and simulations shows that the data are primarily explained by the presence of an anomalous low-velocity zone in upper mantle, that focuses the high-frequency energy, which is further guided through multiple forward scattering by the overlying heterogeneous PHS. These anomalies inside the PHS exhibit the net strong effect of scattering of high-frequency seismic waves. The data are also moderately explained by melting, mainly in the basaltic crust of PHS; features like melting of the eclogitic crust and serpentinized wedge have a minimum effect on waveforms. By further conducting a suite of simulations by changing the shape and location of the mantle anomaly, as constrained by both findings of very similar study on PAC thinning/tearing (Padhy et al., 2015), as well as the gradual change in waveform anomaly in the region, we find that all the models explain the observations, although the vertically elongated mantle anomaly is more effective for stronger focusing over a longer distance range. We also examined the influence of thickness of melt and its location in relation to the plate bending on waveform changes. The simulation results show that the melt zone, especially in the basaltic crust, has to be thicker than 10 km to produce a detectable waveform effect. The findings of this study have important implications for our understanding of the mechanism of intermediate to deep earthquakes under the dehydration embrittlement hypothesis.

Keywords: Wave propagation, Finite-difference method simulation, Philippine-sea plate, Melting

Seismic imaging of crustal structures by a trans-dimensional coda-wave analysis

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Seismic waves at high frequencies (>1Hz) usually show incoherent and complex wave trains due to medium random inhomogeneity and inelasticity. Multiple lapse time window analysis (MLTWA) is one of the frameworks for a separate estimation of scattering and intrinsic 1/Q values (e.g., Fehler et al. 1992). This approach analyses the spatiotemporal variation of the normalized energies from direct S-wave to coda wave, and gives a relatively stable estimation of 1/Q values. A single station approach of MLTWA (e.g., Hoshiba 1993) has been applied for large scale seismic networks to estimate spatial variations of scattering and intrinsic 1/Q values (e.g., Carcole and Sato, 2010). However, the MLTWA usually assumes horizontally uniform 1/Q in data-fitting. Then, we should take into account of the spatial variations of 1/Q in MLTWA to estimate these structures. To achieve this aim, this study generalized the MLTWA under the Bayesian framework in dimension-variable space for an adequate estimation of scattering and intrinsic 1/Q structures.
This study partitioned the study area by means of the discrete Voronoi tessellation, and assumed that each Voronoi cell is characterized by constant scattering and intrinsic 1/Q values. We evaluate the misfit of the normalized energy of the MLTWA for all Voronoi cells, and define the posterior probability under the Bayesian framework. We applied the reversible jump Markov Chain Monte Carlo (Green, 1995) to conduct a parameter sampling under the posterior probability with changing the number and spatial layout of Voronoi cells. This trans-dimensional sampling in dimension-variable parameter space would generate uniform structure areas under the information of input data, and would estimate seismic structure with an adequate spatial resolution for input data. We applied this method for seismic data at the outer-rise region off Tohoku area. This observation (Obana et al. 2012) covered a large outer-rise earthquake (Mw7.6) and its aftershocks that occurred soon after the 2011 Tohoku-Oki earthquake. The single station analysis of MLTWA gives weak intrinsic attenuation (1/Q ~ 1/1000) at all stations and some high scattering stations with 1/Q ~ 1/300. However, this result could not give clear insights on the origins of strong scattering due to the sparse seismic network. The trans-dimensional analysis of this study found the weak intrinsic attenuation (1/Q ~ 1/1000) as with the single station approach, and imaged two anomalies of strong scattering 1/Q. One of strong scattering is imaged at the northern part of seismic network. This is almost located at the epicenter of the Mw7.6 event. Another one is imaged at high activity area of aftershocks at the south of seismic network. This result suggests coda-wave analysis has sensitivity for fractured structures due to seismic activity, and the trans-dimensional analysis is effective to extract spatial variations of inhomogeneity and inelasticity.

Keywords: coda wave, MCMC, wave scattering, wave attenuation, outer rise

Effects of seawater layer on broadband seismic wavefield

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Recently, some studies investigated the effects of seawater on seismic waves propagating through ocean area (e.g., Noguchi et al. 2013; Maeda et al., 2014; Nakamura et al. 2015). Detailed characteristics of seismic waves propagating around ocean area should be required for practical use of seismograms recorded at ocean bottom seismometer networks, such as S-net and DONET. In this study, to reveal the effects of seawater on broadband seismic wavefield, we conducted numerical simulations of seismic wave propagation using the model with seawater layer.
The model covered the zone of 512 x512 x128 km^3, which was discretized by a grid interval of 0.05 km. The propagation of seismic waves was calculated by solving equations of motion based on the staggered grid finite difference method (FDM) with fourth- and second-order accuracies in space and time. The background velocity structure was Japan Integrated Velocity Structure Model version 1 (Koketsu et al., 2012) and the seismic source was referred from CMT solution of F-net. Since minimum S-wave velocity of 0.9 km/s is assumed in this study, our FDM simulation can examine seismic wave propagation for broadband frequencies of 0.01-1 Hz.
We conducted a FDM simulation of seismic wave propagation for Mw 6.8 earthquake occurred at depth of 68 km beneath northwestern Chiba. Simulation result roughly reproduced observed seismograms at both land and ocean stations. We also conducted an additional FDM simulation in model without seawater and compared simulated waveforms at ocean area derived from model with and without seawater to examine the effects of seawater. Differences between simulation results more clearly appeared in vertical component seismograms than horizontal ones. Since S wave components are dominant in horizontal seismograms, the effect of seawater is not so large in the horizontal components. Amplification of the amplitude and increase of the duration were recognized in coda waves of the vertical seismograms due to the seawater layer. This indicates that P and Rayleigh waves in vertical component are strongly affected by seawater layer.

Acknowledgement
The computations were conducted on the Earth Simulator at the Japan Marine Science and Technology (JAMSTEC).

Keywords: Seismic wave propagation, Seawater, Coda wave, Numerical Simulation

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

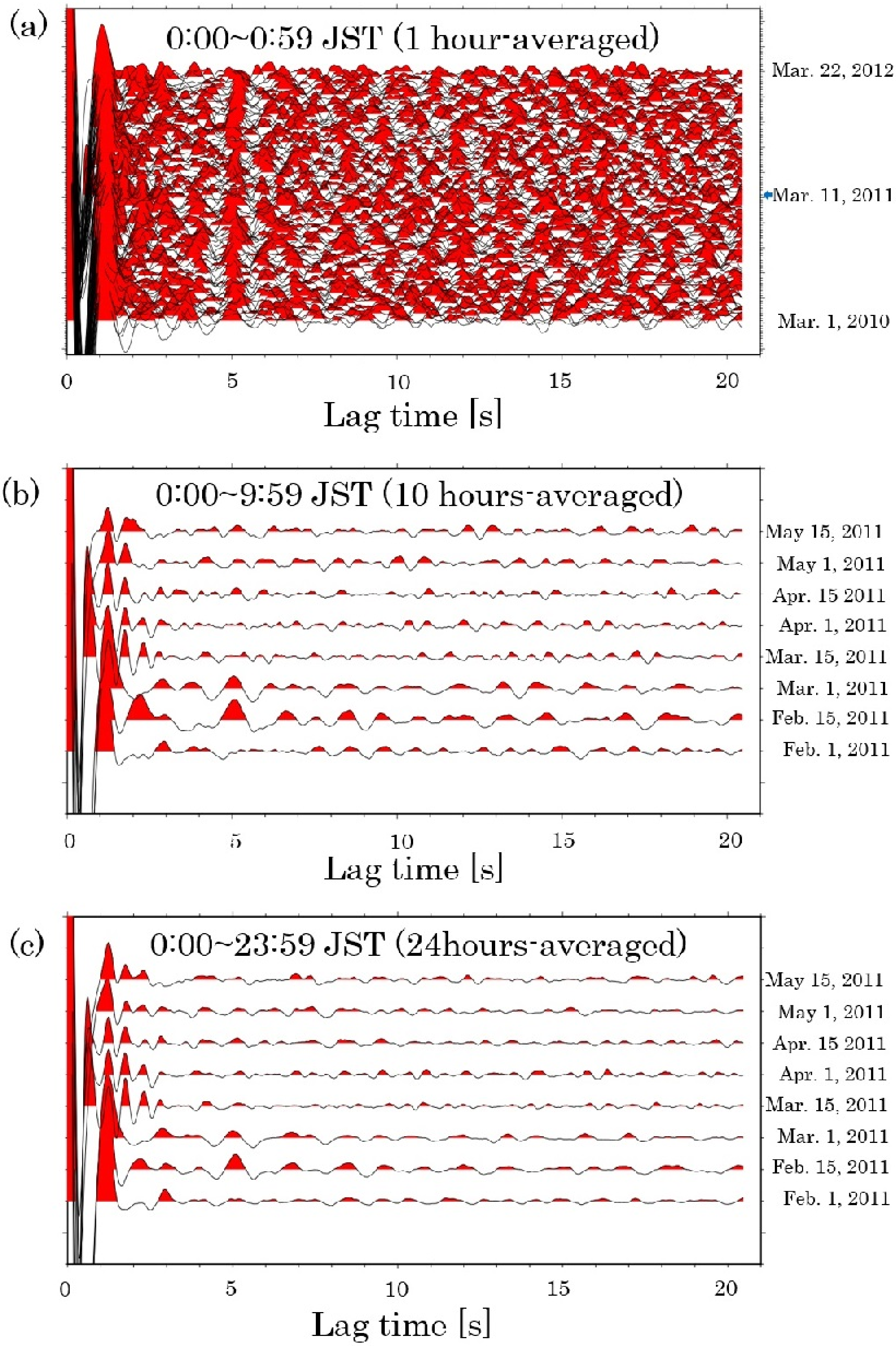

Fig. 1 (a) An example of averaged ACF at Daigo, Ibaraki prefecture, Japan. Individual ACFs were averaged by 60 one-min results. (b) ACFs averaged by 600 results. (c) ACFs averaged by 1440 results.

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

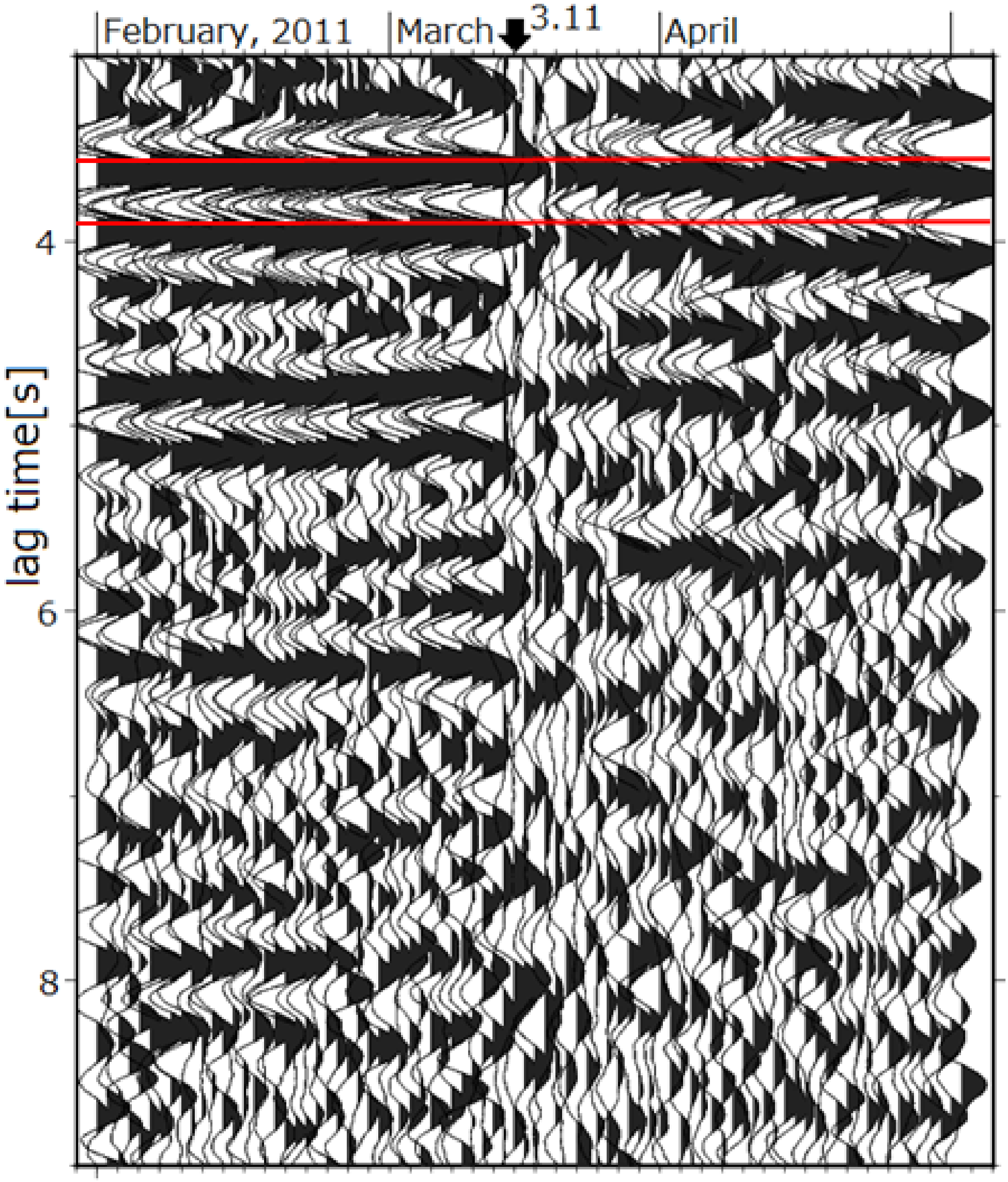

Figure 1. Calculated ACFs at Shiroishi station. Horizontal axis indicates dates from February 1 to April 30, 2011. Vertical one shows lag times of ACFs.

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

