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.

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

