Modeling of high-frequency seismic wave propagation via observed waveform and numerical simulations using 3D heterogeneous model

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To achieve precise modeling of high-frequency (>1 Hz) seismic wave propagation, small-scale heterogeneities, which have characteristics scales less than several kilometers, should be required (e.g., Sato, 1984, 1989; Kumagai et al., 2011; Takemura et al., 2015). In this study, to investigate the effects of small-scale velocity heterogeneity and surface topography on seismic wave propagation, we conducted finite-difference method simulation of seismic wave propagation for shallow moderate earthquake.
We conducted FDM simulations of shallow moderate (Mw 4.4) earthquake occurred in the Shimane-Hiroshima boarder on 25 November, 2011. The model covers a volume of 384×384×128 km^3, which is discretized by an uniform grid size of 0.1 km. Technical details are same as in Takemura et al. (2015). The background velocity structure is referred from the Japan Integrated Velocity Structure Model (JIVSM; Koketsu et al., 2012). Small-scale velocity heterogeneity model of Kobayashi et al. (2015) is embedded over the crust of the JIVSM. Intrinsic attenuations of the crust for *P* and *S* waves is represented by a single-relaxation Zener body with $Q_S^{-1} = Q_P^{-1} = 4.0\times10^{-3}$ and reference frequency f_0 = 1 Hz (Takemura et al., 2017). We assume a double-couple point source referred from the F-net MT catalog.
We also conducted FDM simulation using the JIVSM without small-scale velocity heterogeneity (original JIVSM), as a reference. Our simulations well reproduced observed PGV and characteristics of seismic wave propagation for frequencies of 0.1-4 Hz. However, in the original JIVSM, coda waves are excited due to topographic scattering but its envelope shapes doesn’t show smooth-time decay. By introducing small-scale velocity heterogeneity, simulated coda envelopes well agree with observed smooth coda envelopes.
The effects of small-scale velocity heterogeneity dominate in higher frequencies. Simulated PGVs of JIVSM are widely fluctuated due to the source radiation pattern but this fluctuation is suppressed by homogenizing azimuthal variation of PGVs due to small-scale velocity heterogeneity.

Acknowledgement
We used the Hi-net/F-net data and F-net MT solution. The computations were conducted on the Earth Simulator at the Japan Marine Science and Technology (JAMSTEC).

Keywords: Seismic wave propagation, Small-scale velocity heterogeneity, Irregular topography, High-frequency seismic waves, Numerical modeling

Significant anomalies in high-frequency seismograms for intra-slab earthquakes observed in Kanto area, Japan

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In Kanto-Tokai area in Japan, very complicated high frequency seismograms are frequently observed as it is located above a complicated plate boundary zone between the Pacific plate and the Philippine Sea plate. In this study, we found characteristic high-frequency seismogram anomalies potentially being related to characteristic inhomogeneity in this area.

We analyzed 20 intra-slab earthquakes (M4.4–6.9) occurred within the Pacific slab from October 2004 to April 2016, 227–453 km in focal depth. The datasets are velocity seismograms recorded by 258 NIED Hi-net stations in Kanto-Tokai area. After applying bandpass filters of octave bandwidth ranging from 1 to 16 Hz, characteristic wave packets and their frequency dependence are identified from root mean squared (RMS) envelope seismograms. At a frequency range of 8–16 Hz in Kanto area, we found wave packets preceding the arrival of S waves by about 10–20 s. The wave packets lasted about 10 s and their amplitude was obviously larger than that of the P-coda waves. At lower frequency of 1–2 Hz, we did not find similar packets. These wave packets were not observed for intra-slab shallow earthquakes, less than 200 km in focal depth. The amplitude of the packet at high frequency was always predominant in the vertical component. No strong polarization in the horizontal component RMS envelopes is observed.

Complicated-shape wave packets lasting about ten seconds, without significant pulse of boundary conversion, suggest that a sort of scattered wave packets are generated by the small-scale inhomogeneities. In addition, this cannot be explained by a simple S-to-S scattering because the arrival time of the packet precedes that of the direct S wave. Based on the systematic detection, we found that the wave packet propagated almost along the radial direction from the epicenter with almost the same apparent velocity as that of the S waves. Considering the wave packets arrived earlier than S waves, they are expected to involve mode-conversion such as P-to-S or S-to-P scattering, by characteristic inhomogeneity between the epicenter and seismic stations.

We conducted preliminary numerical simulations of seismic wave propagation with a community velocity model in this area superimposed onto a small-scale stochastic velocity fluctuation. The resultant synthetic waveforms did not explain these peculiar wave packets. Considerable updates especially for small-scale inhomogeneities in the velocity model are expected to contribute to further understandings of seismic wave propagation in the subduction zone.

Keywords: seismic wave propagation, scattering, seismogram envelope, subduction zone, numerical simulation

Comparison of the 3D FD simulation and statistical methods for the scalar wavelet propagation through random media

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Considering seismic wave scattering due to small-scale heterogeneities is important for the analysis of short-period (<1s) seismograms. The scattering causes the broadening of seismogram envelopes and the attenuation of peak amplitudes with travel distance increasing. There are statistical methods to model these phenomena by considering an ensemble of random media and investigating statistical characteristics of the propagation of a wavelet through random media. In order to synthesize the theoretical envelope of a short-period wavelet, the radiative transfer equation with the Born approximation (RTE+Born) and the Markov approximation based on the parabolic approximation have been developed and applied to the observed data to estimate the statistical properties of the earth medium. Comparison of these methods with the finite difference (FD) simulation of the wave propagation is important to check the validity of each method; however, there have been few studies since the computation cost of the FD simulation in 3D is expensive.
In this study, we conduct 3D FD simulations of the scalar wavelet propagation by using the Earth Simulator, which is a vector supercomputer managed by JAMSTEC. The target frequency is 1.5Hz and the grid spacing is 0.08 km. The average propagation velocity is 4 km/s, so there are 33 grids per a wavelength, which ensure to prevent grid dispersion. Precisions of the differentiation are 4^{th} and 2^{nd} order in space and time, respectively. A model medium is a cube of 307 km each side and the number of grids for each axis is 3840. In order to realize such a large random medium, we smoothly merge small-size random media generated by using different random seeds. We use 6 merged random media in total. We set an isotropic source of a Ricker wavelet at the center of the medium and receivers at propagation distances of 25, 50, 75 and 100km. The velocity fluctuation is characterized by an exponential autocorrelation function where the fractional fluctuation is 0.05 and the correlation distances (*a*) are 1 or 5 km. First, we compare the stacked mean square (MS) envelopes of FD simulations with those obtained by RTE+Born and those by the improved Markov approximation (Sato, 2016). For the correlation distance of 1km (ak_c=2.3, where kc is the centered wavenumber), RTE+Born envelopes adequately fit with FD envelopes in entire lapse time. On the other hand, Markov envelopes well model FD envelopes around the peak for the case of the correlation distance of 5 km (ak_c=12). In this case, late coda of FD envelopes are well reproduced by RTE+Born. Next we investigate the distribution of squared amplitudes of each trace. We find that the distribution changes from the log normal distribution at the onset to the exponential distribution at coda. For the case of the correlation distance of 1 km, squared amplitudes show the exponential distribution soon after the onset. This means that the random scattered waves are dominant. According to the FK analysis of the FD traces, we found that the squared amplitudes obey the exponential distribution even when the energy flux of scattered waves is not isotropic.

Keywords: Scattering, Finite Difference Simulation, Markov Approximation, Born Approximation

Synthesis of Scalar Wavelet Intensity Propagating through Random Media Having Power-Law Spectrum

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Observed short-period seismograms of small earthquakes show envelope broadening of an S-wavelet and excitation of long lasting coda waves although the source duration is very short. Those phenomena are interpreted as result of scattering by earth medium heterogeneities. As a mathematical model, we study the propagation of a scalar wavelet through von Karman-type random media. When the center wavenumber of the wavelet is lower than the corner wavenumber, we are able to synthesize wave intensity by using the radiative transfer equation with the Born approximation. When the center wavenumber is in the power-law spectral range higher than the corner wavenumber, we can synthesize intensity time traces by using the Markov approximation method based on the parabolic/paraxial approximation. This method is effective for the intensity synthesis especially near around the peak arrival; however, it fails to synthesize coda excitation due to wide-angle scattering. Here, developing the scheme given by (Sato, 2016), we newly propose the following method for the synthesis of intensity time trace from the onset through the peak until coda: (1) We divide the random medium spectrum into the high–wavenumber (short-scale) and the low-wavenumber (long-scale) spectrum components by using the center wavenumber of the wavelet as a reference. (2) Applying the Born approximation to the short-scale component of random media, we calculate the scattering coefficient. Substituting the scattering coefficient into the radiative transfer equation with a constant velocity, we calculate the intensity by using the Monte Carlo simulation. (3) Applying the Markov approximation to the long-scale component of random media, we analytically calculate the envelope broadening and wandering factors. (4) We convolve these factors with the intensity calculated in step (2) in the time domain, which leads to the Green function in the random media. As a test, we have compared intensity time traces derived from the above method and the FD simulation method for a Ricker source wavelet radiated from a point source in random media. We have confirmed good coincidence between them from the onset through the peak until early coda. The proposed method will be a theoretical basis for the study of random inhomogeneous velocity structure in the earth medium from mean square envelopes of short-period seismic waves of small earthquakes.

Keywords: scattering of seismic waves, Heterogeneous structure of the earth, wave theory

Seismic wave attenuation in carbonate rocks: challenging but promising parameter for petroleum exploration.

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Seismic wave attenuation is an important parameter in geophysical studies, thanks to its sensitivity to physical parameters of the subsurface such as, fluid content, lithology and fractures. So, an accurate estimation of this parameter can help to enhance the geophysical interpretation and also to increase signal to noise ratio of seismic data. However, getting an accurate seismic attenuation profiles is challenging due to its high senstivity to noise and immaturity of the methodology. The challenge is bigger in the case of carbonate rocks media, due to their high heterogeinity and complex lithology.

In this study we estimate seismic wave attennuation from different oilfields having different locations in Abu Dhabi. The subsurface of this region is mainly composed of carbonate rocks. We implemented a robust processing workflow and we developed a new methods, this in order to get an accurate and high depth-resolution attenuation profiles from Vertical Seismic Profiling (VSP) and sonic data. The results show a significant contribution of scattering on total attenuation, this can be interpreted by high the heterogeinity and the complex lithology of carbonate rocks. The scattering and intrinsic attenuation show a sensitivity to fractures, fluid and clay content. This is a good indication about the attenuation potential for reservoir characterization and to enhance geophysical interpretation. The cross plots showed a link between sonic attenuation and petrophysical logs , which means that these latter can be predictible from the attenuation.

The results obtained herein can be improved if we overcome the limitation of the conventional approach, which uses well-log velocities and densities to calculate scattering attenuation based on the assumption that the total attenuation is a linear summation of intrinsic and scattering attenuation. It is important to confirm the validity of the assumption of strong scattering in order to adequately estimate the scattering attenuation from velocity or acoustic impedance data. We proposed a new approach to separate between scattering and intrinsic attenuation based on reforming the modified median frequency shift (MMFS) (Suzuki and Matsushima 2013) method with seismic interferometry (SI) (Matsushima et al 2016) under the assumption that intrinsic and scattering attenuation are frequency independent and frequency dependent, respectively. The numerical results demonstrate the superiority of the proposed method as compared to the conventional approach and the importance of optimizing parameters in the application of preprocessing filters to balance the resolution power and noise reduction effect.

Keywords: seismic wave attenuation, carbonate rocks, fluid and fractures, mechanism

Strong Land-Atmosphere Coupling in Low Frequency Band below 0.05 Hz

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There are now many arrays that have co-located seismometers and barometers. They provide new opportunities to examine the nature of coupling between the atmosphere and the solid Earth. We will discuss some basic characteristics of the coupling that we learned from the Earthscope Array when we analyzed hurricane data.

In our recent paper (GRL, 43, Geophys. Res. Lett., 43, 2016, doi:10.1002/2016GL070858), we showed that there is a threshold pressure for the coupling between atmospheric pressure and vertical seismic motions; below this threshold pressure vertical amplitudes are flat and are irrespective of local atmospheric pressure. Above this pressure the local atmosphere pressure directly controls vertical amplitudes. This applies only to a low frequency range, below about 0.05 Hz, but for such a low frequency band, correlation between vertical displacement and pressure becomes very high. The correlation coefficients (with zero time shifts) are about 0.8-0.9. In a higher frequency range than 0.05 Hz, such a high correlation does not occur; for example, for 0.1-0.4 Hz which is a secondary microseismic frequency band, amplitudes (noise) are generated in the ocean and are irrelevant to the local atmospheric pressure.

As an interesting display of this characteristics, we will show an example from a hurricane. When Hurricane Isaac (2012) moved over some stations in the Earthscope Transportable Array, pressure and seismic data showed clear effects of vanishing amplitudes near the center of this hurricane for a frequency band below 0.05 Hz. Both pressure and seismic time series showed vanishing amplitudes, appearing like data gaps, if the hurricane center moved over a station almost exactly (within less than 10km). But for stations away from the hurricane track by more than 50 km, such gap-like features were not seen. This may not be surprising for barometer data as pressure is known to be small near the hurricane center but vertical seismic amplitudes also showed similar small amplitudes. This is of course related to a high correlation between pressure and vertical displacement in a low frequency band. Such gap-like features were not found for higher frequency bands.

This feature is somewhat counter-intuitive for a seismologist as we tend to think that the generated low-frequency seismic waves should propagate from a high atmospheric pressure region. Such waves should reach the center of a hurricane and cause some seismic signals. There may be some such signals but the data show that they are quite small; what we observe are highly correlated vertical seismic motion with the local pressure, an almost perfect phase-to-phase match.

Keywords: Land-Atmosphere coupling, Seismic and barometer array

Source locations of Rayleigh waves in secondary microseisms inferred from polarization analysis of Hi-net data

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Microseisms are energetic ambient seismic wavefield generated by ocean swells, which are categorized into primary (10-14 s) and secondary microseisms (5-7 s). Although observation and application, such as seismic interferometry, of microseisms have been established well, source locations of secondary microseisms still remain uncertain. In the present study, we locate dominant source locations of Rayleigh wave microseisms observed in the Japan islands using Hi-net records. In order to locate microseism source, we first estimate back azimuths of Rayleigh waves in the period of 4-8 s based on polarization analysis. Since fundamental Rayleigh waves, dominating secondary microseisms, generally show retrograde particle motions, back azimuth of Rayleigh waves can be determined without uncertainty of 180 degrees from three component records at single stations. We then search locations explaining the back azimuth distribution, and select source locations with small location errors. The dominant sources of Rayleigh waves mainly distribute in two specific regions: 100-200 km off the coast of Fukushima in the Pacific and off Tottori in the Sea of Japan. The off Tottori sources show a clear seasonal variation, existing only in the winter season. In contrast, the off Fukushima sources are detected stationary. The seasonality is consistent with ocean wave activity in the sea near Japan predicted by an ocean action model WAVEWATCH III. The observation suggests that Rayleigh waves in secondary microseism are dominated by contribution from adjacent sea. The off Tottori and off Fukushima sources are located at an ocean basin with the depth of 1000-2500 m and at shelf slope with the ocean depth of 2000-6000 m, respectively. The oceanic depths are close to the resonance depth of 1500-3000 m for the period of 4-8 s. Improving source locations and investigating their frequency dependence may deepen our understanding of mechanism of microseisms.

Keywords: Microseisms, Surface waves

Global source locations of P-wave microseisms using Hi-net data from 2005 to 2011

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Observations of microseisms date back to the early 1900s [Wiechert 1904]. Although observations of microseisms were firmly established, the excitation mechanisms are still in debate. According to the typical frequency, they can be categorized as primary microseisms (0.02-0.1 Hz), and secondary microseisms (0.1-1 Hz). The former frequency range corresponds to that of ocean swell itself, whereas the latter corresponds to double the frequency of ocean swell. Excitation of primary microseisms can be attributed to linear forcing by ocean swell through the topography in shallow depth, whereas that of secondary microseisms can be attributed to non-linear forcing by standing ocean swell at the sea surface in both pelagic and coastal regions.

The source distribution of secondary microseisms is crucial for understanding the excitation mechanism of secondary microseisms. A back projection method is feasible for locating secondary microseisms. However, complex wave propagations of surface waves caused by strong shallow, lateral heterogeneities prevent from the precise location of the sources. In contrast, body wave microseisms are less scattered than the surface-wave microseisms. Although the amplitudes of body wave microseisms are smaller than surface wave amplitudes, recent developments in source location based on body-wave microseisms enable us to estimate precise locations of forcing and the amplitudes quantitatively [e.g. Nishida and Takagi, 2016].

In this study, we made a catalogue of P-wave microseisms by array analysis using the high-sensitive seismograph network (Hi-net) operated by NIED from 2005 to 2011. We analyzed vertical-component velocity-meters with a natural frequency of 1 Hz at 202 stations in Chugoku district. The instrumental response was deconvolved by using an inverse filtering technique [Maeda et al. 2011] after reduction of common logger noise [Takagi et al. 2015]. The records were divided into segments of 1024 s. After exclusion of segments which include transients, the frequency-slowness spectra were calculated. The spectra at 0.15 Hz show that clear teleseismic P-wave microseisms on seismically quiet days when local swell activities were calm. The local maxima of the spectra were picked up. The centroids of the sources were located by backprojecting the corresponding slowness. The source locations show clear seasonal variations. In winter months, they were located in the northwestern Pacific, and in the summer months, they were located in the southern Indian ocean. Through the years, centroids stayed in the north Atlantic ocean, although they show a weaker seasonal variation with the maximum in winter. The locations can be explained by an ocean action model (WAVEWATCKIII: Ardhuin et al. 2011). In further studies, we will calculate the equivalent vertical single force for quantitative discussions.

Keywords: microseisms, ocean swell, P wave

Multi-mode phase speed measurements of surface waves with array-based analysis

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Recent deployment of dense broadband seismic networks, such as USArray in the United States, leads to the construction of improved 3-D upper mantle models with unprecedented horizontal resolution using surface waves, although many of such dispersion measurements have been primarily based on the analysis of fundamental mode. Higher-mode information can be of great help in the further improvement of the vertical resolution of 3-D models, but their phase speed analysis is intrinsically difficult, since wave trains of several modes are overlapped each other in an observed seismogram. In case of Love waves, even the fundamental mode tends be overlapped with higher modes, which result in larger uncertainties in the phase speed measurements of the fundamental-mode Love waves than those of Rayleigh waves. Modal separation is not a straightforward issue because several higher-modes share similar group speeds, but it can be done by utilizing a dense seismic array. In this study, we develop an efficient method for measuring the phase speeds of the fundamental- and higher-mode surface waves based on an array-based analysis, and demonstrate its utility through extensive synthetic experiments and its application to USArray.

Our array-based analysis of multi-mode dispersion measurements is modeled on a one-dimensional frequency-wavenumber method originally developed by Nolet (1975, GRL), which can be applied to broadband seismic records observed in a linear array along a great circle path. At first, proper seismic signals are extracted using varying group-speed windows and slant-stacked with a fixed wavenumber to generate a “beam”. Since the spectrum of this beam is a function of frequency f, phase speed c and group speed U, we can construct spectrograms in c-U domain for each f. After the reduction/removal of spurious spectral peaks by applying narrow wavenumber filter to the largest spectral peaks, the spectrograms in c-U domain are projected in a c-f domain, which eventually provides us with multi-mode dispersion curves.

Extensive sets of synthetic experiments suggest that the method works well for a long linear array with lateral extension of several thousand kilometers. Estimated dispersion curves in the period range between 20 and 150 seconds using a heterogeneous array (i.e., an irregularly distributed stations) reflect an average velocity structure beneath the centroid of the array. The dispersion curves are matched well with theoretical estimation from the average structure depending on the station configuration, especially in a period range with sufficiently strong excitation of each mode. In practical applications, the reliability and errors of measured phase speeds can be assessed by using the width of spectral peaks in a c-f plane. This array-based method of multi-mode phase speed measurement can be of help in the reconstruction of 3-D upper mantle structures with enhanced vertical resolution.

Keywords: surface waves, higher mode, seismic array, North America, USArray

How wide is observation range of the developed stress meter ? - Comparison with STS seismometer -

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The Tohoku earthquake (*M*9.0) occurred on 11 March 2011. STS seismometers in Japan almost scaled out and could not record larger amplitudes of wave forms. However, stress meters and strain meters developed by Tono Research Institute of Earthquake Science (TRIES) could beautifully record wave forms caused by the earthquake. It is important to record long period seismograms for especially earthquakes occurred in sea because we have to estimate if the earthquake causes large Tsunami or not. Therefore, we compared observation ranges among STS seismometer, stress meter and strain meter. We also investigated how large variations can be observed by stress meter and strain meter. The main results obtained are as follows:

1. Stress meter and strain meter have as 10 times wider observation range than STS observation range.
2. Vertical component of the borehole stress meter of TOS borehole station (depth: 512m) recorded maximum amplitude of about 300kPa for the 2011 Tohoku earthquake. However, the stress meter of high sensitivity can record amplitude of about 5 MPa.
3. The stress meter can observe not only stress but also strain. And observation range of stress meters were about $2x10^{-4}$, though maximum amplitudes of observed strain were about $5x10^{-5}$.
4. It can be concluded that stress meter developed by us can record whole stress seismogram without scaling out even for gigantic earthquake. Therefore, the stress meter is reliable instrument for estimating Tsunami generation , determining magnitude and reseach of earthquame mechanism.

Keywords: stress meter, STS seismometer, observation range, Tohoku earthquake (M9.0), record of maximum amplitude

A smoothing scheme for numerical solutions of the seismic wave equation

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In seismic wave propagation simulations for the long-period ground motion evaluation, a stable long-term integration is required for the structure model based on the shallow-deep integrated model. However, numerical instability often causes some divergences of calculation in practice. From experience it has been confirmed that some divergences of calculation often occur in the case that the spatial distribution of the structure has locally severe contrast. Therefore, as a method for mitigating numerical instability, it is reasonable to introduce a smoothing scheme in seismic wave propagation simulation. In order not to impair the characteristics of long-period ground motion by the smoothing scheme, it is desirable for the scheme to remove only spatially localized disturbance components of ground motion. In this study we discuss a smoothing scheme for numerical solutions of the seismic wave equation.

The smoothing scheme proposed in this research consists of both of the seismic wave equation and a correction term, which removes short wavelength components of ground motion selectively. The correction term for the smoothing scheme was derived heuristically by formally extending the operation of upwind difference method of advection equation, which is a stabilized method of the advection equation, to the one dimensional wave equation. As a result, we found that the derived correction term is an operator represented by a combination of the Laplacian and the heat equation. In what follows, we refer to the proposed smoothing scheme as a modified equation scheme. The modified equation scheme has the following features:
(a) It preserves the characteristics of the wave equation (wave propagation speed).
(b) It removes short wavelength components of ground motion selectively.
(c) It decreases energy moderately after short wavelength components of ground motion are removed.
In this study, we reveal that the modified equation scheme have the features above by numerical experiments and mathematical consideration of discretization method for the one dimensional wave equation. We also show that it is necessary to properly set a parameter related to the correction term.

Since the correction term added in the modified equation scheme is simple, we can easily apply it to two dimensional or three dimensional wave equation and more general seismic wave equations. By applying the modified equation scheme to two dimensional wave equation and seismic wave equation, it turned out that the modified equation scheme is also available for more realistic problems.

Keywords: seismic wave equation, smoothing scheme, long-period ground motion evaluation

Time-lapse seismic full waveform inversion for monitoring near-surface velocity changes during microbubble injection

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Seismic monitoring provides valuable information regarding the time-varying changes in subsurface physical properties caused by natural or man-made processes. However, the resulting changes in the subsurface properties are often small both in terms of magnitude and spatial extent, leading to minimal time-lapse differences in seismic amplitudes and travel time. In order to better extract information from the time-lapse data, exploiting the full seismic waveform information in the data can be critical. We explore methods of seismic full waveform inversion that estimate an optimal model of time-varying elastic parameters at the wavelength scale. The full waveform inversion methods fit the observed time-lapse seismic waveforms with modelled waveforms based on numerical solutions of the wave equation. Using waveform information beyond first arrivals enables full waveform inversion to achieve much higher resolution (wavelength scale) compared to conventional traveltime tomography (Fresnel zone scale).

We apply acoustic full waveform inversion to time-lapse cross-well monitoring surveys, and estimate the velocity changes that occur during the injection of microbubble water into shallow unconsolidated Quaternary sediments in the Kanto basin of Japan at a depth of 25 m below the surface. Microbubble water is comprised of water infused with air bubbles of a diameter less than 0.1mm, and may be useful to improve resistance to ground liquefaction during major earthquakes. Monitoring the space-time distribution of microbubble injection is therefore important to understand the full potential of the technique.

The time-lapse data set consists of 17 monitoring surveys conducted over 74 hours which exhibit excellent repeatability, allowing us to analyze small time-lapse changes in the subsurface. We observe transient behaviors in the seismic waveforms during microbubble injection manifested as traveltime shifts and changes in amplitude and frequency content. Time-lapse full waveform inversion detects changes in P-wave velocity of less than 1 percent during microbubble injection, initially as velocity increases, and then subsequently as velocity decreases. The velocity changes are mainly imaged within a thin (1 m) layer between the injection well and the receiver well, inferring that microbubble water flow is constrained by the fluvial sediment depositional environment. The resulting velocity models fit the observed waveforms very well, supporting the validity of the estimated velocity changes. In order to further improve the estimation of velocity changes, we investigate the limitations of acoustic waveform inversion, and by applying and comparing elastic waveform inversion to the time-lapse data set.

Keywords: Full waveform inversion, Seismic monitoring, Fluid injection

Nonlinear Attenuation Caused by the Wave Interaction in the Near Surface

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Strong seismic waves produced dynamic stresses that bring the shallow subsurface into nonlinear frictional failure. Therefore, when the dynamic stress of one type of waves is strong enough to reach the frictional failure, the structure cannot hold other types of waves, and hence these waves have to be attenuated. Physically, the anelastic strain rate increases with increasing dynamics stress, and the dynamic stress is proportional to the difference between total strain and anelastic strain. To the first order with frictional rheology, the effective friction bounds the resolved horizontal acceleration. This hypothesis can be tested at single-station seismograms. We select five earthquakes as examples for examining the effect of the nonlinear attenuation: 1992 Mw 7.3 Landers earthquake, 2008 Mw 6.9 Iwate-Miyagi earthquake, 2011 Mw 9.0 Tohoku earthquake, 2015 Mw 8.3 Coquimbo Chilean earthquake, and 2016 Mw 7.0 Kumamoto earthquake. The strong Rayleigh waves generated by the Tohoku earthquake brought rock beneath MYGH05 station into frictional failure, and the high-frequency S waves simultaneously arrived at the station suppressed. We discover the similar wave phenomena occurred at the Coquimbo Chilean earthquake. In the example of the Iwate-Miyagi earthquake, we find that the P and S waves are nonlinearly attenuated. For this example, the boundary of the observed horizontal and vertical acceleration is close to the gravity acceleration since cohesion of near-surface rock is relatively small. During the Kumamoto earthquake sequence, two strong waves hit at a station within 30 hours and modified the condition of the friction.

Interferometric imaging from borehole seismic data with long-term observatory system and vertical seismometer array

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We applied interferometric seismic imaging with multiple reflections to borehole seismic survey data with airgun shooting. In the conventional primary reflection imaging such as a vertical seismic profile (VSP), we obtain the reflection image around boreholes in a deeper section than receiver locations, but do not obtain the reflection image in wide range including shallower part than receivers. In addition, boreholes are sparsely distributed. The multiple reflections are generally noise in the primary reflection imaging, but they contain much information in both the deeper part and the shallower part. One effective method to utilize them to obtain subsurface image is seismic interferometry. It is a technique to redatum the multiple reflections to all airgun shooting points them as pseudo-primary reflections by means of cross-correlation for each borehole seismic survey data. Then continuous subsurface image can be obtained along airgun shooting lines.
In this study, we use the borehole seismic data in Nankai Trough. One dataset is a walkaway VSP data acquired in 2009 at IODP C0009 site. The vertical seismometer array was temporally deployed by D/V Chikyu using a downhole wireline tool at 16 levels in the borehole, and a tuned airgun array of R/V Kairei was fired along 54 km shooting line. Other datasets were acquired in airgun surveys with the long-term borehole observatory systems installed at IODP C0002 site and at C0010 site. The airgun surveys were repeatedly conducted with tuned airgun array on R/V Kairei in 2013, 2015, and 2016, In this study, we used the dataset in 2016 along a 128-km-long shooting line, NS1. This line is almost crossing three holes: C0009, C0002, and C0010, and it is very close to the shooting line of the walkaway VSP survey at C0009. The distances from C0009 to C0002 and from C0002 to C0010 are about 20 km and 11 km, respectively.
In this study, final reflection image was obtained after merging the post-stack migration sections from each borehole dataset. We achieved to obtain the continuous reflection image along the survey line in the shallow part, including the structures in Kumano forearc basin and faults in frontal thrust zone. Integration of the multiple reflection imaging with the primary reflection imaging will be useful to obtain the whole subsurface image from the shallow to the deep. The spatial resolution and artifacts due to the data sparseness should be investigated for further practical applications. Our result shows an important possibility of the reflection imaging from the sparse borehole seismic data for future monitoring surveys, for example, we might be able to image the location of timelapse change on the subsurface section with the long-term observatory system.

Keywords: borehole seismic survey, long-term borehole observatory system, vertical seismometer array, seismic interfetometry

Application of full waveform inversion and pre-stack imaging to 2D land seismic data in a complex terrain

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Imaging deep structures using land data acquired in complex terrains of Japan often faces problems such as irregularity of topography and variable shallow structures, variation of reflection points caused by crooked-line geometry, irregular shot interval and low signal to noise ratio. Recently, acquisition of long-offset high density data using combination of cable and cable-free systems in complex terrain is standardized in domestic land acquisition. First Arrival Travel-Time Tomography is applied to such data to estimate subsurface velocity structure where conventional velocity analysis is difficult because of the above mentioned problems.

Although Tomography is able to estimate velocity structure accurately, limited resolution is one of the problems in this method. Full Waveform Inversion (FWI) is a method to estimate high resolution velocity structures compared to tomography since the method uses more information in the inversion process where tomography uses only first arrival time. Recently, a lot of applications are reported widely.

We tried FWI on 2D land data acquired in Japan. First, a synthetic study was done using a similar situation of domestic land data including different source wavelets, irregular sampling, etc. Next, the real data case study is done. We finally applied Pre-stack Depth Migration using FWI result as input and verified their capability of imaging deep structures in the complex terrain.

Keywords: Full Waveform Inversion, Velocity estimation, Reflection seismic exploration

Simulation and field studies of the seismic time lapse by ACROSS methodology

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Introduction

The temporal change of seismogenic zone and the volcanic evolution are the typical examples of time progression problems in earth sciences. The seismic time-lapse technology is used to estimate the change of subsurface in such cases. ACROSS (Accurately Controlled and Routinely Operated Signal System) methodology has been developed by Kumazawa and others since 1994. According to this methodology, the ACROSS seismic sources were built and has been tested by the groups of JAEA, Nagoya University and JMA. We tested the application of ACROSS technology by simulations and the field tests in Japan and Saudi Arabia.

The authors have applied this methodology for the monitoring of CCS (Carbon Capture and Storage), and EOR (Enhance Oil Recovery). We tried to image the changing zone by the backpropagation of residual waveforms before and after some temporal change in subsurface (Kasahara and Hasada, 2016). In this presentation, we introduce the recent advances of the ACROSS application.

ACROSS methodology

The typical signal used by the ACROSS seismic source is chirp signal within the desired frequency range. By the deconvolution of observed waveforms by the source signature in frequency domain, the transfer function can be calculated. Enhancement of S/N can be obtained by stacking of data during long duration owing to the steady control and the strict synchronization of the source and recording devices.

Detection and imaging of temporal changes

We carried out the field experiment in Awaji Island in 2011 using an ACROSS seismic source with air injection to the 100 m depth during 5 days (Kasahara et al., 2012). Because of excellent repeatability of source signature of the source, the residual waveforms before and after the injection show almost no temporal change before injection and large waveform changes after the injection. We attempted the imaging of the temporal change by backpropagation or reverse-time migration using the residual waveforms.

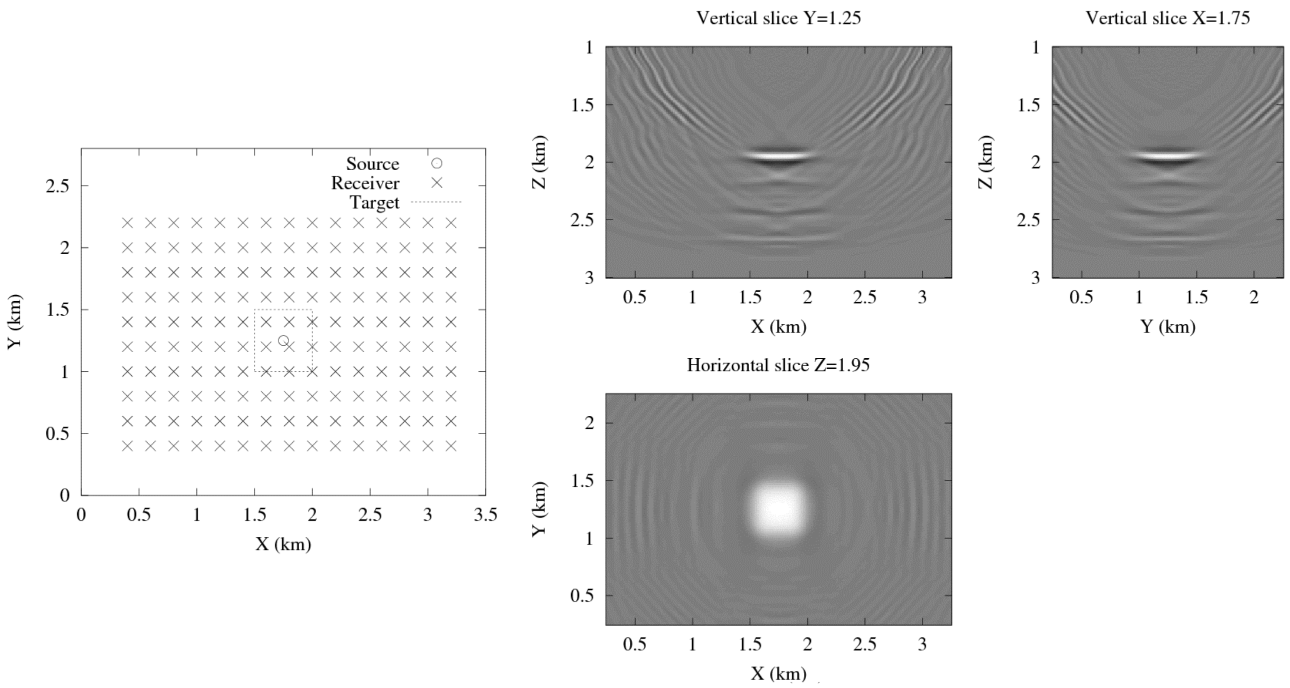
Another field experiment using the ACROSS seismic source was held in Saudi Arabia. We detected temporal changes possibly due to water movement in the aquifers. We discussed the repeatability of observed system and concluded that the repeatability using ACROSS seismic source was the excellent (Kasahara et al., 2016),

We also carried out several simulation in some cases to investigate the effective source and receiver arrangement for subsurface imaging (see figure).

Conclusions

We examined the time-lapse study using the ACROSS seismic source by field tests and simulations assuming a few source and a dense seismic array (Kasahara and Hasada, 2016). Through field studies and simulations, we showed the temporal changing zone by the backpropagation of residual waveforms. Although we studied the time lapse in a few km scales, this technology can be applied to many cases such as seismogenic zones, volcanic region, civil engineering such as road, river levees, bridges, tunnels and buildings.

Keywords: time lapse, ACROSS, residual waveform, backpropagation, imaging, temporal change



The model setting (left) and the result (right) of the simulation assuming a 2 km deep reservoir.

Detection of spatio-temporal changes of seismic scattering properties with seismic interferometry: Dike intrusion event on 15 August 2015 at Sakurajima volcano

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In recent years, seismic interferometry has been used to detect spatio-temporal changes of seismic scattering properties (e.g. Obermann et al. 2013a). At Sakurajima, a dike intrusion took place on 15 August 2015, and large ground deformation was observed (e.g. Hotta et al. 2016). Such a dike may work as a new scatter for seismic waves. Therefore, we applied seismic interferometry to detect spatio-temporal changes of seismic scattering properties associated with this dike intrusion. We used the vertical components of ambient seismic noise data at 1 –2 Hz recorded at 6 JMA stations from 1 January 2012 to 31 August 2015. We calculated coherences between reference CCFs (stacked over 2012 and 2013) and daily CCFs, and found that all station pairs showed significant decreases of coherences before and after the dike intrusion. To locate the region where the seismic scattering properties changed, we used sensitivity kernels calculated from 2D radiative transfer model. Parameters of scattering and intrinsic absorption that are needed to calculate sensitivity kernels were estimated by modeling the space-time distribution of energy density of active shot records in 2013. The best-fit parameters were as follows: Mean free path of Rayleigh waves was 1.2 km at 1 –2 Hz, and the value of intrinsic absorption Q was $62.8f$ (f is the frequency). Then, we calculated the differences between mean values of coherence in 2014 (before the event) and those of from 16 August 2015 to 31 August 2015 (after the event) (hereafter called ΔC). Assuming that one seismic scatterer appeared on the surface projection of the dike, we searched the best location of the scatter to explain observed . As a result, such region was located at the same place as the dike determined by using GNSS, tilt, and strain data (Hotta et al. 2016) with an accuracy of about a few km, and the amount of change of scattering coefficient (Δg) was estimated to 1.4 km^{-1}. These results indicate that seismic interferometry is one of useful methods to detect structural changes of volcano.

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Keywords: seismic interferometry, seismic scattering property change, Sakurajima volcano

