Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SSS27-01 Room:411 Time:April 29 09:00-09:15

Possibility of timelapse survey by seismic interferometry in image domain

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(1) Seismic interferometry in image domain

Seismic interferometry (SI) is generally applied in a data domain by crosscorrelating the different seismic traces without information of media for a redatuming or a signal extraction. Then the synthesized virtual source records are processed for a subsurface imaging. The direct subsurface imaging of passive seismic data by interference of extrapolated wavefields based on an imaging condition can be recognized as a SI in the image domain. Although the image domain SI is based on the velocity model for wavefield extrapolation, the fact that both the passive observation data and the velocity model are required for the depth imaging is common in the data domain SI and the image domain SI.

In the SI in the image domain by combining with the principle of a reverse time migration (RTM), arbitrary time-windowed seismic record is propagated forwards from a receiver point which become a virtual source and the same time-windowed records are propagated backwards from other receiver points. If any multiple reflection waves between the surface and the reflection boundaries satisfy the imaging condition, the reflected energy will be focused on those points. Because the seismic records of all receivers in one passive observation are not independent each other, the wavefield extrapolations can be only once in forward and backward respectively. In the data domain SI, however, the forward and backward extrapolations are repeated over all receiver points in a final RTM, because the virtual source records synthesized by the crosscorrelation should be treated independently. Therefore, total computational cost of the image domain SI could be lower than the data domain SI.

(2) Applicability to a time-lapse study of passive

Passive seismic monitoring or time-lapse survey using permanent observation systems are one of recent research topics. Although high repeatability can be kept in the active seismic survey both on sources and receivers, any repeatability on sources is not guaranteed in the passive seismic survey. In this study, numerical simulation is demonstrated to evaluate the repeatability of the subsurface image and the possibility of extracting a small temporal velocity change by image domain SI with passive seismic data. In this simulation study, simple assumptions with an acoustic wavefield and a same mechanism for all sources are introduced. The passive seismic data for different condition of source distribution or/and velocity perturbation are synthesized, and then the image domain SI is applied for each data set. The repeatability of imaging and the possibility of extraction are measured by some repeatability indexes.

The passive observation records are synthesized using modified overthrust model of SEG/EAGE (15 km x 5 km) with 151 receivers on the surface due to independent 128 sources in the ground (Ricker wavelet with 10 Hz). The sources in the ground are randomly distributed for each model respectively. A velocity change with 10 percent decrease is added in an anticline structure around the center of the model with an elliptical shape (1 km x 0.1 km). A smoothed model from the true velocity model is commonly used for each RTM.

From the simulation study, the global images of the overthrust model are well reproduced in appearance for the different source distributions. However, the repeatability indexes show that the amplitude change due to the source distribution difference is too large to ignore even though the small velocity change can be extracted. Some additional techniques are required to extract only the velocity change without the influence due to the source distribution difference. In addition, there are other difficulties in a real data such as different source mechanism, elastic effects, and some kinds of noises.

Keywords: seismic interferometry, timelapse, reverse time migration

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Temporal changes of P and S wave velocities in NE Japan associated to the M9Tohoku-Oki earthquake from doublets analyses

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Application of seismic interferometry using ambient noise and coda waves of regional earthquakes have shown notable seismic wave velocity decreases associated with the occurrence of the M9.0 Tohoku-Oki earthquake. These analyses can be generally attributed to S-wave velocity changes at shallow structures because these waves are dominant in surface waves. On the other hand, analyses of doublets have also succeeded in detecting temporal changes of direct arrival times of P waves as well as those of S waves. Also, the seismic rays pass deeper portions. However as the medium changes by the M9 earthquake are widely observed in East Japan, it is difficult to separate the observed travel time differences into the effects of hypocenter parameters and the travel time differences caused by the change in the medium beneath the stations. In this study, therefore, we develop a new method to determine temporal changes of P and S wave velocities beneath stations by simultaneously determining hypocenter parameters of doublets. We relate travel time differences of doublets to site factors at each station and the differences of hypocenter parameters. We further give a constraint in which the sum of the differences in origin times of the doublets analyzed is set to be zero, since the doublets are considered to randomly occur. As a result, our inverse problem estimates the model parameters, namely the site factors for P and S waves at each station and the relative locations of hypocenters and origin times of the doublets. Seismic data at 454 stations of the Hi-net seismic network in East Japan are used. We analyze 35 doublets with magnitudes ranging from 3.7 to 4.7 and depths from 30 to 60 km located offshore in East Japan for the period from 2005 to 2013. The seismic data are band-pass filtered between 1-2 Hz and travel time differences of arrival times of P and S waves are measured by applying a cross-spectrum method. The inversion results show that hypocenters of doublets differ by about 0.05 km and 0.12 km at a maximum each other in the horizontal and vertical directions, respectively. Even when we change the data set of doublets, the relative hypocenter locations do not significantly change, which indicates our inversion method is stably determining the hypocenter parameters. For the site factors, we find significant delays of arrival times as large as 0.04 s for the S-waves and about 0.01 s for the P-waves. Time delays are observed mainly at stations located widely in Tohoku region between 37 and 40 degrees in latitude, which are west from the M9 fault zone. The observed spatial distributions of time delays seem not to be well matched with the regions strongly shaken, which are located mostly in the eastern area of Tohoku region, or the regions where seismic velocity reductions at shallow medium are detected from analyses of bore-hole and ground surface records. These discrepancies suggest that the time delays detected from doublets originate from different regions, maybe deeper portions beneath Tohoku region.

Keywords: Tohoku-Oki earthquake, Velocity change, Similar earthquakes, Direct P and S waves

SSS27-03 Room:411 Time:April 29 09:30-09:45

Estimation for seismic wave propagation property of soil structure based on seismic interferometry

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Recently seismic interferometry was applied to estimation for seismic response of natural ground but also those of artificial structure like a building. We applied seismic interferometry concept for retrieval of seismic response of a model dike of soil structure like a fill dam. We employed deconvolution interferometry to estimate seismic response in time domain. From the waveforms obtained from deconvolution with the motion in the basement of a model dam, we estimate traveltimes of shear wave propagating through it and its mean velocity. Estimated velocity explain the normal mode of a model dike well. This approach can be applicable to monitor change in seismic response a dike caused by strong earthquakes or its internal water content change.

Keywords: Seismic interferomtetry, Soil Structure, Dam body, Dike, Shear velocity, Centrifuge test, Fill dam

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SSS27-04 Room:411 Time:April 29 09:45-10:00

Temporal changes of auto-correlation functions associated with the volcanic activity in Hakone volcano, central Japan

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Auto-correlation functions (ACFs) of ambient noise are thought to be a powerful tool for searching temporal change of crustal structure associated with strong ground motion, or volcanic activity. In this study, we investigated the velocity changes at Hakone volcano associated with an intense swarm activity.

Hakone volcano is located at the northern boundary zone of the Izu?Mariana volcanic arc in central Japan, Many intense periods of swarm activity have occurred in the caldera. It was noted, in last two decades, that seismic swarms were remarkably prevalent in 2001, 2006, 2008-2009, 2011 and 2013. During the swarm activities, except for that in 2011, crustal deformations related to volcanic activities were detected by the GNSS stations network in and around the caldera of Hakone volcano. In particular, remarkable tilt changes were also detected by the tiltmeters within the caldera in 2001 and 2013 activities. It is interpreted that the crustal deformation was caused by pressure from a Mogi point source or dike at a depth of 7 km and two shallow open cracks in the caldera (e.g. Daita et al., 2009; Harada et al., 2009).

To estimate the velocity changes associated with the 2013 activity, we used the continuous velocity waveforms recorded at the stations of Hot Springs Research Institute, National Research Institute for Earth Science and Disaster Prevention Hi-net, Japan Meteorological Agency in and around the caldera, in the period between January 2012 and December 2013. Filtered trace at the frequency band of 1-3 Hz was used to calculate autocorrelation by one-bit correlation technique. To obtain stable record of the one-day ACF, we stacked the ACFs for time intervals of one week. We obtained fluctuations of the velocity structure by using the stretching method (e.g. Wegler et al., 2009).

The velocity fluctuations at the stations in the caldera show a gradual decrease prior to the swarm activity. The velocity decreases at these stations are consistent with increases in base length detected by the GNSS stations around Hakone volcano. We also found that there was sudden velocity decrease at Owakudani station near fumarolic area just after the beginning of swarm activity and tilt changes. We interpreted the velocity decrease at these stations as a material change or a crustal deformation associated with the volcanic activity.

Keywords: auto-correlation functions, volcanic activity, Hakone volcano

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SSS27-05 Room:411 Time:April 29 10:00-10:15

The roles of dispersion and nonlinear effects in the 2001 Tohoku-Oki earthquake tsunami

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The present study aims to reveal the roles of the dispersion and the nonlinear effects in the 2011 Tohoku-Oki earthquake tsunami. Tsunami simulations were conducted based on the nonlinear dispersive equations with a high-resolution source model. The result successfully reproduced the waveforms recorded in both near shore and deep sea. The calculated inundation area showed a good coincidence with the actual inundation at the Sendai Plain, the widest inundation area during this event. Conducting sets of simulations using different equations, we obtained the followings insights. Although the dispersion was neglected in most studies, the maximum-amplitude distribution was significantly overestimated in the deep sea if the dispersion was not included. The waveform observed at the station in which the largest tsunami height ($>$2 m) recorded among deep-ocean stations also verified the necessity of the dispersion. It is well known that the nonlinear effects play an important role for the tsunami inside bays and harbors. Additionally, the nonlinear effects needed be considered for the accurate modeling of the later waves even at the offshore stations. In particular, including nonlinear terms rather than including the inundation was more important for the precise modeling of the waves reflected from the coast.

Keywords: tsunami, dispersion, nonlinear wave, the 2011 Tohoku-Oki earthquake

SSS27-06 Room:411 Time:April 29 10:15-10:30

Numerical simulation of tsunamis due to a landslide

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Numerical simulation of tsunamis due to a landslide has been performed using a MPS method, where the water surface is indicated based on the spatial gradient of number density of particles. In comparison with the water surface displacements through hydraulic experiments, the calculation results are accurate when the inflow can be assumed as a fluid. The larger the initial potential energy of the inflow is, the larger the tsunami height becomes, although the tsunami height is not large when the initial position of inflow is below the water surface since the initial relative potential energy of the inflow is lower, as well as without impact of plunging. Due to the inflows of the assumed initial values for mass, shape, and velocity caused by a sector collapse of Sakurajima Island, the tsunami height shows more than ten meters in Kagoshima Bay.

Keywords: tsunami, landslide, sector collapse, MPS method

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SSS27-07 Room:411 Time:April 29 11:00-11:15

Point spread functions for earthquake source imaging

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Recently, various methods such as back-projection method (e.g. Ishii et al., 2005), time-reversal (TR) method (e.g. Larmat et al. 2006), and hybrid back-projection (HBP) method (Yagi et al., 2012) have been proposed and applied for earthquake source studies in addition to kinematic waveform inversions (e.g. Hartzell and Heaton, 1983) . In addition, theoretical relationships among the methods have also been clarified (e.g. Kawakatsu and Montagner, 2008, Fukahata et al., 2013). In this study, we introduce the notion of the point spread function (PSF) into earthquake source imaging, and show that the PSF clarifies the meaning of the earthquake source inversions. Under ideal circumstances in which receivers continuously surround the source, the PSF can be interpreted with seismic interferometry.

Kinematic waveform inversion methods are now standard for earthquake source studies. The observation equations (or forward modeling equations) are based on the representation theorem. According to Claerbout (2001), imaging is defined to be the mathematical process of multiplying adjoint Green's functions with both sides of the observation equation. Fukahata et al. (2013) pointed out that the process is very close to the one used in the HBP method. The source image may be blurred and degraded due to uneven distributions and insufficient number of stations. The degree of blurring and degradation can be expressed by the PSF which is often used in optics. The PSF for the source imaging can be expressed by stacked cross correlations of Green's functions between two source points with respect to receivers on a surrounding surface. If distributions of sources and receivers are discretized, the observation equation can be formulated in matrix form. Source inversion is found to remove the effect of the PSF, but other source imaging methods suffer from the PSF.

Ideal circumstances are considered here to better clarify the meaning of the PSF. It is assumed that stations are continuously distributed so as to surround the source points. For this case, we use source-receiver reciprocity of Green's functions. Then, we can consider the following reciprocal configuration in which sources are surrounding two stations. The point spread function is expressed as the stacked cross correlations of waveforms between the two receivers with respect to the surrounding sources. This configuration is exactly the same as ones in seismic interferometry and therefore we can interpret the PSF based on seismic interferometry. For single-force sources, the PSF is found to be the imaginary part of the Green's function. This fact was already pointed out in terms of TR method (e.g. Fink, 2006). For moment-tensor sources, the PSF is shown to be the imaginary part of the spatial derivative of Green's function with respect to each coordinate of the two receivers. This is a novel finding of this study. It is also suggested that the source image is the integrated version of the true source process when the interpretation based on seismic interferometry strictly holds.

In summary, kinematic source inversion methods can remove the effect of the PSF, but other source imaging methods suffer from blurring and degradation by the PSF. As a result, careful weighting of data is necessary for the source imaging methods. For ideal cases in which receivers surround the sources, the PSF can be interpreted with seismic interferometry with the help of the source-receiver reciprocity of Green's functions. This study will contribute to better understanding of the meaning of source inversion methods.

Keywords: Earthquake source imaging, Point spread functions, Seismic interferometry

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SSS27-08 Room:411 Time:April 29 11:15-11:30

Analysis and application of wave propagation process of sweep signals in attenuative media

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The sweep signal is the most extensively used land seismic exploration technique. In conventional data processing using sweep signals, a received trace is cross-correlated with source sweep to convert the extended sweep signal into a pulse signal. For attenuation estimation, a time window is often used to compute the frequencies of the direct-arrival waveforms. Uncorrelated sweep signals are useful in the discussion of harmonics simply because the uncorrelated data are one of the few situations in which we commonly input a nearly pure frequency into the earth. Our previous study proposed a method that enables accurate measurement of ultrasonic attenuation using sweep signals under the assumptions that velocity dispersion can be ignored and the quality factor (Q) is not dependent on frequency. This method is independent of the effect of windowing while the windowing effect underestimates the attenuation results due to a spectral leakage effect. In most cases, however, the presence of attenuation is accompanied by velocity dispersion because of causality. The presence of velocity dispersion causes attenuation to be disturbed, although the proposed method is not so sensitive to the presence of velocity dispersion. The present paper elucidates the wave propagation process of sweep signals in attenuative media with velocity dispersion to develop the method which can take the effect of dispersion into account. We obtain a time-scale representation of sweep signals by using the continuous wavelet transform method to perform a time-series analysis of a seismic trace that decomposes the trace into its respective amplitude and phase components in both the frequency and time domains.

Keywords: Seismic attenuation, velocity dispersion, sweep waveform

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3D numerical simulation of seismic wavefield in inhomogeneous rock samples

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We focus on expanding the applicability of the transmitted waveforms obtained at laboratory experiments to examine detailed medium structure with the aid of novel numerical simulations. For this purpose, we investigate the feature of elastic waveforms in a centimeter class rock sample based on a 3D finite difference method (FDM) simulation. Previously, there were a few ways to approach the later phase of transmitted waveform in a rock sample because the propagation process of the reflected and converted waves generated in a finite-sized rock sample were not figured out. If analyses with entire waveform including the later phases will be possible, it should bring more detailed information on internal medium structure of rock samples.

First, we obtain transmitted waveforms in laboratory with cylindrical Westerly granite sample which horizontal to vertical ratio is 1 : 2. A source transducer is put on the center of the side surface and step voltage is applied to it. Vibration on sample surface is recorded as velocity waveform by laser Doppler vibrometer.

Next, we prepare the simulation model that covers the size of the rock sample. The volume is discretized into 512 x 512 x 1024 grids with an interval of 100 μm. Assuming proportional relationship with X-ray absorption coefficient obtained from micro focus X-ray CT images of the rock sample, we set the density (2.5 - 3.1 g/cm^3), P wave velocity (5.0 - 6.0 km/s), and S wave velocity (2.8 - 3.5 km/s) on each grid. Then, 3D FDM numerical simulation is performed with a single point force which is the same movement with the source transducer of the experiment. Band pass filter with a cut-off frequency of 50 kHz to 2 MHz is applied to the obtained waveforms.

The wavefield obtained from the simulation show that the reflected (PP, SS, PPP, and SSS) and converted (PS, SP, and PPS) waves are generated at the boundary of the sample. As time progresses, waves reflected at the side boundary return to the source area, and waves reflected at the top of the sample propagate through the sample at same time. Thus, we confirmed that waves trapped in the closed medium generate a very complicated shape of the later part of waveforms. Scattering and conversion at mineral grains are also observed due to the heterogeneity of medium, while they have only a limited effect on the simulated waveform in this case.

Radial component of measured and simulated waveforms recorded in the same horizontal plane at the source position are compared. Each phase shape in entire simulated waveform is matched with measured waveform. Two large amplitude phases observed in the measured waveforms are revealed as direct P wave and reflected SS wave from the simulated waveforms. Complex waveform shapes after the arrival of SS wave are indicated to as multiple reflected and converted S waves at the round boundary of the sample.

Keywords: transmitted wave, reflected wave, rock sample, numerical simulation

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SSS27-10 Room:411 Time:April 29 11:45-12:00

Curvilinear grid finite difference method simulation of seismic wave propagation for depth-dependent velocity structure

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I propose curvilinear grid method on large-scale finite difference method (FDM) simulation of seismic wave propagation in depth-dependent structure. The FDM usually uses uniform-sized grid having spatial scale smaller than 6-10 of wavelength. Although it is quite straightforward method and is therefore suitable to large-scale parallel simulation, it is not economical to use homogeneous grid size under depth-dependent structure in regional scale because of wide dynamic range of wavelength. Low-velocity sediment requires fine scale grid, but such smaller grid size also requires very small time-stepping in deeper part to satisfy the stability condition of FDM. To deal with this problem, discontinuous-grid method (Aoi and Fujiwara, 1999; Lee et al., 2008) has been proposed. However, possible numerical instability at a discontinuous surface in the former method (Kristec and Moczo, 2010).

The curvilinear coordinate method can use any non-linear, non-orthogonal coordinate. The uniform-size numerical grid is used along the curved coordinate in the computation domain. On the other hand, we still uses the Cartesian coordinate for expressing physical quantities such as velocity vector and stress tensor. This method has been used to incorporate rough ground surface (e.g., Hestholm, 1999). However the recent study on staggered-grid FDM (e.g., Nakamura et al., 2012) suggest that the rough surface can be expressed by the fine-scale homogeneous grid. So, I use a coordinate whose grid-width gradually and smoothly increases with depth to make ratio between grid-size and wavelength nearly constant. My coordinate transform equation depends on vertical depth only, so that to make the computational loads in coordinate transformation and additional memory requirements relatively small. The rotated-grid staggered grid (RSG) scheme (Saenger et al., 2000) has been adopted to make central finite differentiation possible in all directions under the curvilinear coordinate.

As a test, we implemented this curvilinear coordinate FDM in 2D SH and P-SV systems, with using the Butterworth-shape grid-size increase function. This coordinate has a characteristic depth. Grid size linearly increases with depth at deeper than the characteristic depth. On the contrary, this curvilinear coordinate converges to the Cartesian at the shallow limit. This feature is preferable since one can connect the homogeneous Cartesian grid in the shallower portion to the curvilinear grid system without any boundary conditions. In the numerical experiments, I found that the method is effective and stable even for the coordinate system having large grid-size ratio of up to 10. Extension to the 3D model is quite straightforward, and it makes possible to perform broadband large-scale wave propagation simulations including slow sediment in medium-sized computers.

Keywords: seismic wave propagation, numerical simulation, finite difference method, curvilinear coordinate

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SSS27-11 Room:411 Time:April 29 12:00-12:15

Waveform inversion of seismic reflection data and its application to fault structure survey

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Seismic waveform inversion (Tarantola, 1984) is a novel technique of imaging subsurface structures. It reconstructs a model of physical parameters that best explains waveforms of observed seismic data by incorporating a nonlinear least-squares inversion. Waveform inversion provides high-resolution model than that from traveltime tomography. Recent development of computational environment accelerates studies on practical application of the method to 2-D/3-D field data.

In this study, we investigate an application of the method, originally developed for crosswell seismic data, to reflection seismic data. The problems are (1) singular nature of sensitivity near sources and receivers at the surface, (2) attenuation of sensitivity in deeper part of the section, and (3) contamination of surface wave. We introduced a weight increasing with depth on the gradient, and near-offset trace mute to reduce the effects of the problems listed above. Using the synthetic waveform data numerically generated from a given structure model, we proved that a clear structure image was successfully retrieved after iteration.

Then, we applied the method to the field data of wide-angle reflection survey acquired in the Fujikawa-kako fault zone - ISTL seismic reflection survey conducted in 2012 (2012FIST)(Ito et al, 2013) to reveal the detailed structure of Omiya fault. Although the reconstructed velocity structure is consistent with the recent interpretation that the Omiya fault is a reverse fault, it was far from convergence due to the insufficient number of seismic sources used in the survey. Problems and requirements for future survey design will be discussed in the presentation.

Keywords: seismic reflection method, waveform inversion, fault structure, non-linear inversion

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SSS27-12 Room:411 Time:April 29 12:15-12:30

Site amplification factor of the Hi-net stations

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This study estimated site amplification factors of all the Hi-net stations. Employing the coda normalization method and analyzing more than one thousand earthquakes, we obtained the values of all Hi-net sites in the frequency bands of 0.6-1.0 Hz, 1-3 Hz, 2-4 Hz, 2-6 Hz, 4-8 Hz, 6-9Hz, and 8-12 Hz. The cite amplification factors were rather small showing that 90 % of the cite amplification factors ranged within 20 dB. The site amplification varies from station to station more largely with decreasing the frequency. A correlation between the site amplification factor and the S-wave velocity where the sensor is installed was recognized. The cite amplification factor decreases with increasing the S-wave velocity when the S-wave velocity is less than 1.5 km/s. When the S-wave velocity is larger than 1.5 km/s, the correlation disappears. Stations in southwest Japan show smaller site amplification factors, while stations in plains and around the volcanic front in the northeastern Honshu, Japan show larger site amplification factors.

Keywords: Hi-net, Site amplification factor

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SSS27-13 Room:411 Time:April 29 12:30-12:45

Separating body and Rayleigh waves with cross terms of the cross-correlation tensor of ambient noise

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We develop a novel method to separate body and Rayleigh waves with the vertical-radial (ZR) and radial-vertical (RZ) components of the cross-correlation tensor of ambient noise. Furthermore, analyzing ambient noise records observed at a seismic array, we validate the method. For the separation, we utilize the difference in polarizations between the rectilinear P and the elliptic Rayleigh waves. Assuming the two-dimensional surface and three-dimensional body waves are the superposition of random uncorrelated plane waves, we derive two fundamental characteristics of the ZR and RZ correlations. One is that, between the ZR and RZ correlations, Rayleigh wave contributions have the opposite signs and P waves have the same signs. The other is that, for both ZR and RZ correlations, Rayleigh wave contributions are time-symmetric and P waves are time-antisymmetric. Accordingly, we can separate P and Rayleigh waves by just taking the sum and difference between ZR and RZ correlations and by just taking the time-symmetric and time-antisymmetric components. This method can be performed (1) without any knowledge of velocity structure, (2) using only two stations with three-component sensors on a ground surface, (3) even in the case of anisotropic wave incidence, and (4) with the quite simple procedure. We consider that the developed method can make better use of three-component observations of ambient noise for evaluating the cross-correlation tensor accurately, for improving deep velocity structure using both of extracted body and surface waves and, more fundamentally, for understanding the composition of ambient noise.

Keywords: ambient noise, seismic interferometry, cross-correlation function, wavefield separation, polarization, body and Rayleigh waves

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SSS27-14 Room:411 Time:April 29 14:15-14:30

Study of high-frequency seismic wave propagation by active-source experiments

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Seismic wavefields generated by resonant shaking experiments of the Millikan Library, on the campus of California Institute Technology (Pasadena, California, USA), were analyzed. Because the resonant shaking frequencies are 1.12 Hz (the east-west direction) and 1.64 Hz (the north-south direction), this active-source experiment can provide opportunities for studying high-frequency seismic wave propagation in Southern California.

Two such experiments for each frequency were analyzed; for the north-south shaking experiments, the harmonic signals were observed up to distance 323 km in one experiment and up to 396 km in another experiment. For the east-west shaking (1.12 Hz), the maximum distance was 200 km but most observations were confined to less than 100 km.

Spectral amplitudes showed a systematic decaying trend with distance in all cases. Numerical simulations indicated that the predominant signals were surface waves. Assuming that all signals were surface waves, we obtained estimates for the parameter QU for surface waves where Q is the attenuation parameter and U is the group velocity (in km/s). There was, however, a major break in the amplitude-distance trend at a distance about 50 km; for data with distance less than 50 km, QU = 95 $\pm$16 , where U is in km/s. For data beyond 50 km, we obatined QU= 1454 $\pm$ 226. This change in trend must be related to the regions sampled by waves, as the shorter-distance data were dominated by paths in the Los Angeles basins while the longer-distance data did not contain paths in the basin structures.

Through cross correlations between MIK (station in the Millikan library) and a station in the regional network, phase information was also analyzed. For many stations, phase was stable for frequencies between 1.637 and 1.638 Hz which meant that phase is locked between MIK and a station. While it was not possible to estimate phase velocity, because the number of cycles cannot be resolved for high-frequency waves, a stacking approach for multiple-window data allowed us to estimate frequency derivative of phase and group velocity for 25 paths. Group velocity between MIK and network stations are mostly less than 2 km/s. For stations with distance less than 50 km, most group velocity results were about 0.5 km/s or less. Combined with the estimate for QU from the amplitude-distance data, Q is estimated to be 190 for distances less than 50 km. This estimate, however, contains uncertainty up to a factor of two as variations in group velocity estimates differ from station to station.

Keywords: Seismic wave propagation, Crustal structure, Active source experiment

SSS27-15 Room:411 Time:April 29 14:30-14:45

Estimations of seismological structure in the northwestern Pacific using OBS records: Approaches from >1 Hz component

TONEGAWA, Takashi[1*] ; FUKAO, Yoshio[1] ; FUJIE, Gou[1] ; TAKAHASHI, Tsutomu[1] ; KODAIRA, Shuichi[1] ; SUGIOKA, Hiroko[1] ; ITO, Aki[1]

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Tentative ocean bottom arrays using seismometer, hydrophone and pressure gauge have recently been deployed through many scientific projects all over the world. However, in Japan, a permanent ocean bottom monitoring system, called DONET, is now working, and dense cabled-OBSs (ocean bottom seismometers) have been constructed around the Japan Trench. It seems that, compared to other countries, such environments in Japan potentially give us some advantages for investigating the Earth ' s interior, seismic activity, and wavefields under the ocean. In order to easily kickoff the use of these records, it would be better to know characteristics of wavefields observed at seafloor.

A large amplitude in the frequency range of 0.07-0.5 Hz can be often seen in the spectrum of noise record observed at seafloor, which is known as microseisms that are generated by wind propagating sea surface. This large amplitude also emerges at land observation. At frequencies longer than 0.02 Hz in the spectrum observed at typical broadband OBS, the amplitude of infragravity wave is strong in the vertical component, and that of tilt effect is dominant in the horizontal component.

In this presentation, avoiding the use of such longer period components, we focus on shorter period components than 1 Hz of records observed at OBSs. We introduce what kind of analyses we can do hereafter with permanent OBS records, which is based on the use of records observed at tentative ocean bottom arrays. In particular, we will introduce ambient noise and receiver function analyses, in which short period components are mainly used.

Keywords: OBS records, short period components, receiver function, seismic interferometry

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Nonlinear radiation of hypocenter and prevision of earthquakes

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Hypocenter vibrations have been analyzed using the analysis method based on time reversal. The dynamic model of the hypocenter vibrations based on the results was advocated. In addition, the effectiveness of the dynamic model was confirmed. The activity regions in the hypocenter are presumed using the dynamic model here.

First, the outline of the dynamic model is described. The time-reversal process was executed to the P wave signals received at the observation stations for the earthquake that occurred in the central part of Suruga Bay in August, 2009, and the pulses formed at the position of the hypocenter, that is, time reversal pulse (TRP) was obtained. The TRP corresponds to an equivalent source to which the hypocenter emits. The obtained TRP provided clear orientation dependency. To clarify the origin of the azimuthal dependence, the frequency spectrum of the TRP to azimuth was obtained. The frequency spectrum was greatly changed by the azimuth. Then, the distribution of the maximum amplitude frequency to azimuth was obtained. As a result, the maximum amplitude frequency rises greatly as azimuth moves from west to east and it has descended afterwards. This frequency rise shows the local movement of sources by high speed. The moving direction converged in the direction of Nishiizunishi, Kawazu, and Ito.

The P waves received at these observation stations exhibited a unique behavior. The head part of the wave received in Nishiizunishi was expanded. However, there was no expansion in the head part in the waves received in Ito and Kawazu near Nishiizunishi.

The head's growing in this manner occurs when the progression rate of cracks in an active fault becomes near the velocity of propagation. The pressure that occurs due to the crack is added cumulatively by moving by high speed. That is, the parametric effect occurs in the active fault. Nishiizunishi is a specific point that reflects the feature of this earthquake.

As for the waveform of the aftershock that received at the specific observation station, the head part of the P waves expanded more than that of main shock. Similarly, the expansion of the head part was observed for the precursor earthquake that occurred before the main shock. The dynamic model of hypocenter vibrations has advocated from these results. The point where the narrow beam emitted from an active fault reaches the surface of the earth is called a parametric spot. The head of the pulse to which the head expands is called a parametric head. This model was verified about four earthquakes larger than M5 that occurred from 2012 to 2009 near Mt. Fuji. The effectiveness of the dynamic model was confirmed.

The dynamic model is consistently approved for precursors, a main shock, and aftershocks. Therefore, the dynamic model may be used for the prevision of earthquake.

The precursor earthquakes of the earthquake that occurred in the central part of Suruga Bay in August, 2009 are examined. The receiving waves that accompanied the parametric head in that were observed seven times. These represent evidence that the progress of the crack began to become a high speed in the active fault. Therefore, observing the seismic waves of a slight earthquake at the peculiar parametric spot and examining the change, may foresee a big earthquake afterwards.

Keywords: hypocenter vibrations, dynamic model, time reversal, prevision of earthquakes

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Frequency domain calculation of the seismic wavefield propagating along an ocean trench, with a constant Q attenuation

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For shallow interplate earthquakes, large long-period later phases are frequently observed at long distance. Simulations using the finite difference, which we have performed, revealed an important effect of seawater on those later phases (e.g. Furumura et al., 2011).

However, attenuation exp(-πft/Q) in the finite difference calculation is set to exp(-πft/(Q_of/f_o)), meaning Q/f=Q_o/f_o is set as a constant, where f_o is a target frequency of the calculation purpose, and Q_o is its corresponding attenuation factor, so it causes some problems especially for waves propagating for a long distance.

Then we calculated waves propagating in a 2.5D structure in the frequency domain with FEM to realize Q as a constant instead of Q/f, for both cases with and without seawater. We could confirm the important effect of seawater on later phases as well as the finite difference calculations. Calculated later phases have relative large amplitude for frequencies lower than f_o in the Q-constant model compared with the Q/f-constant model. It indicates necessity of estimation of difference between realistic Q and modeled one, when we use the finite difference method. In addition, the results reveal large later phases in the case with seawater, which are rarely seen in the calculated waveforms without seawater. It implies overestimation of magnitude of ocean earthquakes obtained from analysis of waves propagating through a long distance along and across an ocean trench, such as the 1911 off Kikai Island earthquake and the 1933 off Sanriku earthquake observed in Honshu.

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Development and extinction of long-period ground motion in thick sediments

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To obtain better insights of long-period ground motion in thick sediments, which often cause severe damage of large-scale man-made structures, we analyzed horizontal seismograms recorded by dense strong motion networks in the complex large Kanto basin. We found distinct large amplitude long-period ground motion around northern Kanto, which is caused by Love wave excited at the northwestern edge of Kanto basin. Amplitude of Love wave significantly developed during propagation in thick (>3 km) sediments and then suddenly weakened at region where significant change of basin structure exists.

To clarify causes of such observations, we conducted 3D finite difference method (FDM) simulation of seismic wave propagation. In simulation, we assumed plane SH-wave incident into a realistic basin structure model embedded in a homogeneous half-space background structure, to focus characteristics of Love wave excited at the basin edge. Simulation result in a realistic basin model referred from JIVSM (Koketsu et al., 2008) well reproduced observed Love wave development around the northern Kanto. Another simulation in the model, which is limited to maximum bedrock depth of 3 km, shows no significant difference of simulated waveforms compared with the previous model. Thus, development of surface waves in thick sediments is mainly caused by the deepening of shallower low-velocity layers, rather than the depth variation of bedrock.

Acknowledgement

We acknowledge the National Research Institute for Earth Science and Disaster Prevention, Japan (NIED) for providing the K-NET/KiK-net waveform data. We also use strong motion data from SK-net.

Keywords: long-period ground motion, surface wave, kantou basin, basin structure, numerical simulation

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Receiver function travel time tomography

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Hirahara et al. (2006) proposed a method of Receiver Function (RF) Tomography which combines travel time tomography using travel times from local and teleseismic events with receiver function analyses. In the method, a 3-D P and S wave velocity structure is estimated together with the velocity discontinuity interfaces, where we add both data of the amplitudes and differential travel times of Ps converted phases in RFs employing Gaussian beam RF synthetics. We found, however, that it is difficult to match the amplitudes of Ps phases to estimate the velocity contrasts between velocity discontinuity interfaces with 2-D undulations.

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Here, as a step toward RF Tomography, we are developing a method of RF Travel Time Tomography using only travel times of P and S waves from local and teleseismic events and P-Ps times of Ps converted phases obtained with the receiver function analyses. Abe et al. (2011) developed a method to estimate iteratively geometries of dipping seismic velocity discontinuities with high dipping angles of 30 to 70 degrees from common conversion point stacking of receiver functions, in which the multistage fast-marching method (de Kool et al., 2006) is applied to the ray tracing with refraction at dipping interfaces. The large amplitudes of RFs stacked in 3-D cells are interpreted to the Ps phases converted at the velocity discontinuity interfaces and the differential travel times P-Ps of the corresponding phases are additionally used for the travel time tomography of P and S waves from local and teleseismic events.

In this paper, we do not analyze the actual data but aim at developing the code of RF Travel Time Tomography based on the code of FMTOMO (Fast Marching Tomography) by Rawlinson (2007). First, for a 3-D heterogeneous structure with interfaces of a Moho and a subduction slab, we synthesize travel times of P and S waves from local and teleseismic events, and also Ps times converted at the Moho and the slab top and the oceanic Moho interfaces. Then we investigate the ability of retrieving the 3-D velocities and the undulation of the Moho and the dipping slab interfaces.

Keywords: Receiver function, Tomography, Ps convered wave, Travel time, Seismic velocity discontinuity interface

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Ocean acoustic Rayleigh wave persistently excited by earthquake signals

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In the interferometry, the wavefield propagating between two positions can be retrieved by correlating ambient noise recorded on the two positions. This approach is useful for applying to various kinds of wavefield, such as ultrasonic, acoustic (ocean acoustic), and also seismology. Off the Kii Peninsula, Japan, more than 150 short period (4.5 Hz) seismometers, in which hydrophone is also cosited, had been deployed for 2 months on 2012 by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) as a part of " Research concerning Interaction Between the Tokai, Tonankai and Nankai Earthquakes " funded by Ministry of Education, Culture, Sports, Science and Technology, Japan. In this study, correlating ambient noise recorded on the hydrophones, we attempt to investigate characteristics of wavefield observed at seafloor.

The observation period is from Sep. 2012 to Dec. 2012. Station spacing is around 5 km. For 5 lines off the Kii Peninsula, the 30 - 40 seismometers are distributed at each line. Sampling interval is 200 Hz for both seismometer and hydrophone. The instruments are located at 100 - 4800 m in water depth. In the processing for the both records, we applied a bandpass filter of 1 - 3 Hz, replaced the amplitude to zero if it exceeds a value that was set in this study. We calculated cross correlation function (CCF) by using continuous records with a time length of 600 s, stacked the CCFs over the whole observation period.

We first aligned only CCFs using two stations with a separation distance of 5 km along lines off Kii Peninsula. As a result, we could detect strong signals in the CCFs that clearly show travel time variation as a function of water depth. The group velocity of the signal gradually changes from 1.3 km/s to 0.7 km/s at water depths from 2000 to 4000 m. In addition to the wave, a relatively weak signal with a group velocity of 1.4 - 1.5 km/s can be seen in the region at water depth of 4,000 m.

We investigated the wavefield by using a numerical simulation with finite difference technique. As a result, all of these signals can be explained by acoustic Rayleigh wave, which has the energy within not only the ocean but also sediment. A case in which vertical forces are located at subseafloor generated the acoustic Rayleigh wave well, and the CCFs using synthetic waveforms match well with the observed ones. However, another one in which vertical forces are located at sea surface failed to describe the observation. This means that the observed acoustic Rayleigh wave in background wavefield would be generated by earthquake signal, not signals due to microseisms. Moreover, we will show that the amplitude of the signals possibly correlates with seismicity distribution, which also supports that the signals are excited by earthquake signals.

Keywords: acoustic Rayleigh wave, ambient noise, correlation analysis

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Modeling inclined cracks in a 2-D finite difference grid

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Seismic scattering due to cracks are often numerically simulated using a boundary integral equation method (BIEM), a finite element method, or a finite difference method (FDM). Among others, the FDM has a great advantage in tractability, though having a limitation that it can treat rectangular grids only. Using the rotated staggered grid that they developed, Saenger et al. (2000, Wave Motion) modeled a crack or cavity as a gather of grid points with zero elastic constants. In contrast, Suzuki et al. (2006, 2013, Earth Planets Space) modeled a 2-D empty crack as a linear array of grid points with zero traction on the basis of a standard staggered grid (Virieux, 1984, 1986, Geophysics). Using this method, these authors successfully simulated seismic wave scattering due to cracks. However, they only treated cracks parallel to grid lines.

Here we extended the method of Suzuki et al. (2006) for modeling cracks with zero antiplane shear traction to the case of cracks inclined with respect to grid lines. Using the idea of the staircase approximation to irregular free surface (Ohminato and Chouet, 1997, Bull. Seis. Soc. Am.), we modeled an inclined crack as staircase-like arrayed grid points with zero antiplane shear traction within a staggered grid. We then simulated a plane harmonic SH wave obliquely incident on the crack until the resultant oscillation of the crack became stationary. We then measured the amplitude of displacement discontinuity along the crack. We also calculated the same displacement discontinuity using a frequency-domain BIEM (Murai et al., 1995, Geophys. J. Int.). It was confirmed that the both results were consistent, irrespective of the crack inclination angle, if the grid spacing was much smaller than the crack length and hence the staircase-shaped crack plane was sufficiently smooth. This implies the validity of the present method of modeling inclined cracks.

Acknowledgments: For the BIEM calculations, we used a code of Dr. Yoshio Murai (Hokkaido University), and used the computer systems of the Earthquake and Volcano Information Center of the Earthquake Research Institute, the University of Tokyo.

Keywords: finite difference method, crack, SH wave