Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

SSS027-01 Room:105 Time:May 22 10:45-11:00

Retrieval of tsunami Green's function from the cross-correlation of continuous ocean waves

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Recently, a technique called seismic interferometry has drawn much attention of seismologists, by which seismic Green's function between two points is extracted from the cross-correlation of ambient seismic noise [e.g. Campillo and Paul 2003 Science]. Hence, seismologists can calculate the Green's function or estimate subsurface structure by analyzing ambient noise, without using any natural or artificial earthquakes. For tsunami researchers, it is necessary to use correct tsunami Green's function for tsunami source inversion analysis or simulating disastrous tsunami caused by anticipated huge earthquakes. Correct tsunami Green's functions are supposed to be obtained by numerical tsunami simulation with accurate and high-resolution bathymetry data. However, we cannot always estimate correct Green's function. For example, in the 2010 Maule, Chile earthquake tsunami, there was a significant discrepancy (~ 30 min) between observed and calculated tsunami arrival around Japan [Fujii and Satake 2010 SSJ Fall Meet.]. Therefore, it would be very useful if we can synthesize tsunami Green's function from the observation, in other words, if we can retrieve tsunami Green's function from the cross-correlation of observed continuous ocean waves. This study, hence, investigates a theoretical background for the retrieval of tsunami Green's function from the cross-correlation of long-period random ocean waves. Considering that tsunami has long wavelength and sea-bottom topography acts as point-like scatterers, we employ the first-order Born approximation. The framework of this study follows Sato [2009 GJI], who dealt with the case of 3-D scalar waves with isotropic scattering. For the application to the case of long-wavelength tsunami, this study extends his approach to a case of 2-D waves with a special non-isotropic scattering.

Keywords: Tsunami, Theory

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SSS027-02 Room:105 Time:May 22 11:00-11:15

Application of auto-correlation analysis to the estimation of the seismic basement structure beneath the Noubi Plain

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Seismic interferometry is a recently established method to obtain a seismic response from auto- or cross-correlation of seismograms. Claerbout (1968) proposed that the auto-correlation of a transmitted seismogram from a source at depth and a surface receiver is equivalent to the reflected seismogram from a surface source and the receiver at the same location. Since seismic interforometry does not require artificial sources, it recently attracts attention as a new exploration method of subsurface structure. Yoshimoto et al. (2008) applied this method and obtained the basement structure beneath the Kanto Plain.

In this study, we applied the auto-correlation analysis to the strong-motion seismograms of local earthquakes observed at the seismic stations in and around the Noubi Plain in order to estimate the seismic basement structure.

The basic procedure is as follows. First, we extracted the transverse (SH-wave) component from the horizontal components of the record of each station. Then, the acceleration waveform were double-integrated to the displacement waveform after applying a high-pass filtering. At each station, the auto-correlations of the time-windowed displacement waveform were stacked to improve the S/N ratio. We investigated the frequency and the shape of the high-pass filter, the length of the time-window and the effect of normalization of auto-correlation to obtain the suitable result. In addition, we applied the deconvolution process to remove the source function of each earthquake. Two different procedures, the deconvolution before and after auto-correlation were examined.

In the synthesized seismic reflection section, we found some prominent phases with negative amplitudes. We compared the section to the 3D velocity structure model beneath the Noubi Plain which was compiled by Aichi Prefecture based on the gravity map and partially on the seismic reflection and refraction survey and borehole records. The prominent phases correspond to the reflection from the top of the seismic basement. The dip of the reflector coincides with the dip of the basement of the velocity structure model, although its depth is slightly deeper than the depth of basement of the model. The reflection section may indicate the existence of the velocity boundary in the shallow sediment unexpressed in the structure model. The auto-correlation section also agrees with the receiver function section. The auto-correlation shows higher resolution than the receiver function in the depth section. Therefore, the seismic interferometry is beneficial in exploration of the subsurface structure using natural earthquakes. In order to improve the accuracy of the subsurface structure, more dense distribution of seismic stations are needed.

We are grateful to Aichi prefecture, Nagoya city and NIED for the use of the strong-motion seismograms observed in the area of interest.

Keywords: seismic interferometry, auto-correlation analysis, Noubi Plain, basement structure, receiver function

Japan Geoscience Union Meeting 2011
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SSS027-03 Room:105 Time:May 22 11:15-11:30

Deep seismic images revealed by autocorrelation analysis of ambient noise beneath the northeastern Japan subduction zone

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We obtain seismic reflection images using autocorrelation functions (ACFs) of the ambient noise in the northeastern Japan subduction zone. ACFs with a time-window length of 120 s are calculated from the continuous seismic records obtained at each seismic station during an analysis period of 300 days. The ACFs show some distinct signals with relatively large amplitude without any significant temporal variations during the analysis period. The ACFs show the signals at a large lag time of 20?50 s as well as a small lag time of 10 s. The lag time of 10 s corresponds to the travel time of the PP reflection arrival from the continental Moho discontinuity. The signals with the large lag times between 30 and 50 s corresponding to the back-scattered signals from the mantle wedge or the plate boundary are identified clearly at stations located in the back-arc side. In the ACF records from the fore-arc side stations, weak signals interpreted as the reflection from the plate boundary are apparent in a lag time range from 20 to 30 s. These results suggest that it is possible to retrieve Green's functions reflecting seismic velocity heterogeneity related to the subducting Pacific slab from the ACFs. We construct depth migrated images using the ACFs to obtain the reflectivity profile by assuming that the ACFs represent Green's functions composed of a random wavefield excited by a stochastic sources or scatterers distributed in the vertical or near-vertical direction from stations and that they can be treated as zero-offset seismic traces recorded at each of the stations. The depth migration images show a relatively transparent structure within the subducting pacific slab, whereas a reflective structure within the mantle wedge characterized by the low velocity zones corresponding to the wedge flow imaged by 3-D seismic velocity tomography.

Keywords: Seismic interferometry, ambient noise, autocorrelation, reflection profile, subduction zone

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SSS027-04 Room:105 Time:May 22 11:30-11:45

Seismic interferometric imaging from OBS survey data in the plate subduction zone

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In marine seismic surveys, the Multi-channel reflection survey (MCS) and the ocean bottom seismograph (OBS) survey are widely used for exploring the crustal structure. In the MCS survey, detailed subsurface images are obtained from the high resolution reflection data. In the conventional OBS survey, a wide-angle reflection analysis and a tomographic refraction analysis are usually applied for deeper structures. However, it is difficult to get shallow subsurface image from the reflected waves in the OBS data because of the limitation of imaging area, even though by using the high density OBS survey with 1 km interval. In our study, we overcome this problem by applying a seismic interferometry (SI) to the OBS survey data. The SI is one of the redatuming techniques to synthesize virtual source records by crosscorrelating the seismograms. By applying the SI to the OBS common receiver records, the redatumed data are corresponding to the reflection survey data that the shot and receiver points are located at all original shot positions. Then, the redatumed seismic data can be processed to construct the depth profiles based on the reflection seismic survey. The SI imaging with the OBS survey data is a powerful technique to obtain the reflection profiles from just below the sea bottom to the deeper part of the crustal structure without the spatial imaging gaps.

We applied the SI to the high density OBS survey data acquired along a 175 km survey line crossing the Nankai Trough off the Kii peninsula by JAMSTEC in 2004. The OBSs were deployed on the line with 1 km interval in the central portion, and with 5 km or 10 km interval in the other. The air gun was fired at 200 m intervals along the survey line. In the SI stage, 30 sec OBS records including effective multiple reflections were used for the seismogram correlation, then 20 sec reflection records due to 878 virtual sources with 878 virtual receivers were synthesized. In the SI imaging result, subsurface structures from the sea bottom to the deeper part in the plate subduction zone are clearly shown on a whole survey line, forearc basin, the subduction plate boundary, and splay faults branching from the plate boundary. Because the OBS data contains low frequency energy, the SI profile is lower resolution than the profile of the MCS survey. However, our result is very important to show the advantages of SI imaging from the only OBS survey data without spatial imaging gaps. In addition, the deconvolution-based interferometry could provide the result with higher resolution and lower correlation noise in both the synthesized virtual shot records and the stacked section than the correlation-based interferometry. In another test of the OBS density, the subsurface structures were clearly shown in the depth section from the low density OBS data with 10 km intervals, although the reduction of the OBS density degraded the results with the low reflection continuity and the amplitude change especially in a shallower part.

Keywords: seismic interferometry, OBS survey, seismic reflection survey, Nankai trough, plate subduction zone

Japan Geoscience Union Meeting 2011
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SSS027-05 Room:105 Time:May 22 11:45-12:00

Seismic wave propagation damage caused by the 1999 Chi-Chi, Taiwan earthquake: I. Repeating earthquakes observation

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Observation of three quasi-periodic M 3.8˜ 4.6 repeating earthquake sequences in eastern Taiwan from 1991 to 2007 reveals a unique temporal and spatial variation in seismic wave character associated with the 1999 Mw 7.6 Chi-Chi earthquakes in central Taiwan. The repeating events occurred after the time of Chi-Chi event reveal late-arriving phases and notable change in seismic wave character of S-wave coda. The drop of the cross correlation coefficients (ccc) between the repeating earthquake pair is significant in high-frequency wavefield. At station SSLB for example, the drop of the ccc ranges from 0.99 to 0.95 and 0.99 to 0.88 in 1 Hz and 4 Hz, respectively. Using moving window cross correlation technique, we identify delay of phases in the S-wave coda to be as large as 50 ms, corresponding to a 1% velocity decrease averaged over propagation path. Such velocity reduction is commonly considered as a result of near surface damage. However, the observed changes of seismic wave character are not localized to where the earthquake induced surface displacement or ground acceleration were larger nor where the unconsolidated deposits are located. Instead, it is found in widely distributed stations close to the Chi-Chi epicenter by a 50x80 km2 area. The near surface physical damage caused by strong shaking during the earthquake, therefore, cannot explain the change in seismic waveform character alone. The damaged zone over deep fault plane, or a combination of surface and fault zone damage may contribute to the observed Chi-Chi effect. Time delayed arrivals and decreased waveform similarity are gradually recovering to normal level as time passes, indicating a slow healing of physical damage after the Chi-Chi earthquake, though until 2007 it has not returned perfectly to the pre-mainshock level.

Keywords: repeating earthquake sequence, fault healing, Chi-Chi earthquake

Japan Geoscience Union Meeting 2011
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SSS027-06 Room:105 Time:May 22 12:00-12:15

Seismic wave propagation damage caused by the 1999 Chi-Chi, Taiwan earthquake: II. FDM simulation of the repeating earth

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Three quasi-periodic M 3.8˜ 4.6 repeating earthquake sequences occurred in eastern Taiwan from 1991 to 2007 reveals a unique temporal and spatial variation in seismic wave character associated with the 1999 Mw 7.6 Chi-Chi earthquakes in central Taiwan. The repeating events occurred after the time of Chi-Chi event reveal late-arriving phases and notable change in seismic wave character of S-wave coda as demonstrated by Chen et al. (2011).

To understand the behavior of low velocity anomaly induced by 1999 M7.6 Chi-Chi earthquake, we compute the postseismic changes in wavefield using a 2-D finite-difference method for seismic waves simulation. The simulation model covers a 200x100 km2 area and is discritized by small grid of 50 m, with a seismic source radiating seismic wave of frequency up to 8 Hz. The P- and S-wave velocity structure model is followed by studies of reflection experiments, gravity anomaly and travel-time tomography. The effect of slightly different location and focal mechanism on waveform cross-correlation coefficient (ccc) was first examined. The subtle change in source location, dip angle, and rake produce the ccc drop over the whole seismograms and in all frequencies, which is not consistent with the observed predominance of ccc reduction in high-frequency energy and in S-wave coda. The effects of near-surface damage and fault zone damage with varying depth are next examined, to compare with the spatial extent and magnitude of ccc reduction. The computed change in scattering properties correlates with the spatial extent of such influence zone only if the near-surface, low-velocity anomaly is placed in a ˜50 km wide area, or if the fault zone damage is set at 10-20 km depth. The snapshots of differential wavefield (i.e., substituting reference wavefield from the target) clearly illustrate the newborn P-to-S and S-to-S converted waves by the Chi-Chi earthquake fault. In contrast, the surface break model explains the Chi-Chi effect at the stations on the hanging wall, where the change appears at late S-wave coda. The differential wavefield illustrates strong scattering of the S wave from near surface low-velocity layer, overlapping the S-wave coda in later time. The correlation between the observation and simulation explored here point to not only pervasive damage near the surface but also the deep, along-fault damage at the time of the Chi-Chi earthquake.

Keywords: repeating earthquake, Taiwan Chi-Chi earthquake, FDM simulation

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ATMOSPHERE - OCEAN - SOLID EARTH INTERACTION FROM MICROSEISMS AND MICROBAROMS AT SYOWA STATION, ANTARCTICA

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Microseisms and microbaroms originated from the Southern Ocean are celarly recorded by both the broadband sesimograph and infrasound sensor deployed at Syowa Station (39E, 69S), East Antarctica. A continuous images are achieved for the double-frequency microseism / microbaroms (DFM) with peaks between 4 and 10 s during a whole season. The peak amplitudes of DFM reflect the large influence of winter extratropical cyclonic storms (brizzard) in the Southern Ocean. The DFM have relatively lower amplitudes during austral winters, caused by the larger amount of sea ice extent around the Lutzow-Holm Bay with decreasing the ocean wave loading effects. On the contrary, single-frequency microseism (SFM, with periods between 12 and 30 s) can be observable only by seismograph under excellent storm conditions particularly in local winter. On the infrasound data, moreover, long stand signals are identified with harmonic over tones at a few Hz to lower most human audible band. It probably related to the ice vibrations in the vicinity of the Station. Microseism measurements are a useful proxy for characterizing ocean wave climate and global storm intensity, complementing other estimates by ocean buoys or satellite measurements. A continuous monitoring both by broadband seismograph and infrasound observations firmly contribute to the Federation of Digital Seismographic Network (FDSN) and the Comprehensive Nuclear-Test-Ban Treaty (CTBTO) in southern high latitude, together with the Pan-Antarctic Observations System (PAntOS) under the Scientific Committee on Antarctic Research (SCAR).

Keywords: Syowa Station, Microseismic Noise, Infrasound Microbaroms, ocean wave climate, atmosphere-ocean-solid earth system

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SSS027-08 Room:105 Time:May 22 12:30-12:45

Seismic structure in the Northwest Pacific basin sortheast of the Ogasawara Plateau

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In the Northwest Pacific basin southeast of the Ogasawara Plateau, many Ocean Bottom Seismographs (OBSs) have showed that the P-wave phase refracted in the lower crust (Pg phase) is attenuated significantly and the signal-to-noise ratio becomes less than 1. High attenuation in the lower crust suggests low velocity zone (LVZ). The traveltime modeling has been estimated the P-wave velocity (V_P) of 6.4-6.6 km/s for the LVZ (Oikawa *et al*., 2008). In this study, we estimated the surface of the LVZ and the upper limit of the V_P in the LVZ by combining traveltime forward modeling (rayinvr, Zelt *et al*., 1992) and waveform simulation (E3D, Larsen and Schultz, 1995). We use the data of a seismic survey lines (OGr15) which lies SW-NE direction at the Northwest Pacific basin southeast of the Ogasawara Plateau. The survey is operated by Hydrographic and Oceanographic Department, Japan Coast Guard, and seismic refraction data using four component (vertical, two horizontal, and hydrophone) OBSs and Multichannel Seismic (MCS) reflection data were obtained. Many OBSs in the profile shows high attenuation of the Pg phase. As a result of the estimation using traveltime forward modeling and waveform simulation, the surface of the LVZ was estimated about 3.5-4.8 km under the seafloor, and the upper limit of the V_P in the LVZ was estimated 6.7 km/s. Estimated V_P structure in this profile under their conditions shows the V_P of 6.5-6.7 km/s in the LVZ, and it is consistent with Oikawa *et al*. (2008).

In the seismic refraction survey using OBSs and airgun system, S-wave velocity (V_S) structure in the oceanic crust or uppermost mantle could be estimated by using PS converted wave which is converted at a layer boundary such as an interface between sediments and basement. In this study, we estimated the ratio of P-wave and S-wave velocity (V_P/V_S) structure of the uppermost mantle in the Northwest Pacific basin southeast of the Ogasawara Plateau, and we calculated V_S anisotropy. We use the data of the OGr15 and the another seismic survey line which is almost orthogonally-crossed with the OGr15 at about 270 km southeast of the Ogasawara Plateau in the Northwest Pacific basin. The OBSs on the OGr15 shows that S-wave phase refracted in the uppermost mantle (Sn phase) is split into large and small apparent velocity phases. The amplitude of the large and small apparent velocity phases are larger on the parallel and orthogonal direction with shot line of the airgun, respectively. No Sn phase splitting is identified on the OGr13. MCS reflection records are indicate that the interface between sediments and basement is southeastward-dipping on the NW-SE (OGr13) direction and flat on the SW-NE (OGr15) direction. Since interface where PS conversion occur is southeastward-dipping, only SV (vibrate vertically) wave may be generated on the OGr13, and both SV and SH (vibrate horizontally) wave may be generated on the OGr15 (Xia *et al*., 2002). We estimated two V_P/V_S ratio structures for the OGr15 using large and small apparent velocity phase, respectively. The calculated V_S anisotropies from estimated V_P/V_S structures are less than 1% between the OGr13 and the OGr15 with large velocity structure, and up to about 9% between the OGr13 and the OGr15 with small velocity structure. The direction of larger velocity is consistent with OGr13 and is perpendicular to the paleomagnetic lineation. The relationship between the estimated magnitude of V_S anisotropy and the spreading rate in this study area supports the suggestion of Oikawa *et al*. (2010) that the uppermost mantle in the area where spreading rate is high may has larger magnitude of anisotropy.

Keywords: PS converted wave, Vp/Vs, seismic anisotropy, ocean bottom seismograph, low velocity zone

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SSS027-09 Room:105 Time:May 22 14:15-14:30

Computation of Rayleigh wave dispersion on anisotropic media by compound matrix method

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The surface wave dispersion on isotropic media can be calculated by the Haskel method. However, it is well known that the phase velocity in the high frequency cannot be calculated for computing error. As the calculation method to overcome this problem, the compound matrix method was proposed.

In this study, we calculated Rayleigh wave dispersion on anisotropic media by applying the compound matrix method. In conclusion, the compound matrix method can be available for calculation of Rayleigh wave dispersion in the higher frequency than the Haskel method.

Keywords: dispersion curve, anisotropic media, compound matrix method, surface waves

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SSS027-10 Room:105 Time:May 22 14:30-14:45

Testing equi-partition in S-wave coda using borehole seismograms

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Equi-partition is a state in which energy of all possible wave modes becomes equal due to multiple scattering among the modes. This is important to identify the scattering regime (e.g. Shapiro et al., 2000) and constitutes the basic principle underlying seismic interferometry (e.g. Sanchez-Sesma and Campillo, 2006).

In this study, we calculate relative contributions of the horizontal and vertical components to the kinetic energy, similar to horizontal to vertical (H/V) ratio, for S-wave coda of 60 local earthquake records at three borehole stations in Japan. S-wave coda in lapse times of 40-80sec and 2-16 Hz band is used. On the surface receivers of the two rock sites of IWTH13 and IWTH17, contribution of horizontal components is dominant and gradually increases with frequency. At a softer site of IWTH02, the contributions show much stronger variations with frequencies reflecting low velocity layers. Subsurface receivers at a depth of about 100m show larger contribution in horizontal components irrespective of site conditions.

We quantitatively explain the observations by synthesizing wavefields under equi-partition in horizontally layered structures estimated from well-logging. Through the modeling, we test there different assumptions on the equi-partition. Subsurface receivers play a critically important role to distinguish the assumptions. For S-wave coda in frequencies lower than about 5Hz, equi-partition holds among both body and surface waves. For higher frequencies, equi-partition holds among only body waves. The results suggests that the contribution of horizontal and vertical kinetic energies serves as a useful tool for estimating subsurface layered velocity structures as an alternative to or in conjunction with the H/V method using ambient noise.

Acknowledgments
I used seismograms registered by the Kik-net, NIED, and an integrated event catalogue by the Japan Meteorological Agency and the Ministry of Education, Culture, Sports, Science and Technology in Japan.

Keywords: equi-partition, coda, borehole seismograms

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Time reversal of seismic waves in Izu peninsula

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The time-reversal process is performed to the seismic wave that occurred in Izu peninsula central part on December 18, 2009, and vibration on the hypocenter is obtained. There are many difficulties that should be solved for the application of the time-reversal process to the seismic wave. Acquisition of detailed propagation environment in underground is difficult, and the number of elements of the array is limited. To obtain the propagation environment that is the most important factor on the application of the time reversal, we proposed an inverse problem method using robustness of the time reversal. First of all, velocity of seismic wave was obtained from the relation between the range and the propagation time from the hypocenter to the observation station. The velocity of the P wave was 5633 m/s. This value is the average velocity from the hypocenter to the observation station, and the average value is insufficient for the time-reversal process. The time reversal pulse formed on the hypocenter is theoretically shown by the product of Green function from the hypocenter to the observation station, the conjugate Green function from the observation station to the hypocenter, and the spectrum of the hypocenter vibration. The product of Green function from the hypocenter to the observation station and the spectrum of the hypocenter vibration are reflected in the signal received at the observation station. On the other hand, the product of the signal to which the received signal is time-reversed and the conjugate Green function from the observation station to the hypocenter is reflected in the pulse formed on the hypocenter. However, Green function from the observation station to the hypocenter is unknown. Then, the robustness of the time reversal is used. First, the pressure fluctuation on the hypocenter is obtained by assuming the propagation environment to be a uniform layer that consists of the average velocity, and using the propagation model for Green function. Parabolic equation method is used here for the propagation model. The rise time of the formed pulse approaches time axis 0 as it approaches the hypocenter. That is, the principle of the time reversal has been obviously approved. However, a systematic change in the time reversal pulse was not seen for the change in the velocity structure. That is, it is necessary to grasp a more detailed propagation environment. The contributing parameter is pressure in the same in all sea areas though the sound speed structure in the sea changes by the temperature, salinity, and the current. Underground velocity is assumed to subject the effect of pressure, and the velocity is increased monotonously in depth from surface of the earth to 7000 m. The velocity gradient is assumed to be a parameter, the propagation environment is changed, and the amplitude change of the time reversal pulse is obtained. The amplitude of the pulse became the greatest at a certain gradient. When the velocity gradient is 0.14 in observation station Shimoda, the amplitude became the greatest. The transmission path from the hypocenter to the observation station was obtained by the propagation environment with this velocity gradient. The wave horizontally radiated from the hypocenter reaches the surface of the earth of the range 17 km. The wave radiated from the horizontal up reaches the surface of the earth at the range that is shorter than 17 km. From the results, future tasks are obtaining the detailed propagation environment corresponding to the range between the hypocenter and the observation station. In this paper, data from Hi-net of National Research Institute for Disaster Prevention was used. We express our gratitude.

Keywords: Time reversal, Phase conjugation, hypocenter vibration, Seismic wave propagation, Underwater acoustics

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SSS027-12 Room:105 Time:May 22 15:00-15:15

Frequency Dependency of Elastic Wave Speed and Attenuation - in seismic wave range -

Hironori Kawakata[1*], Issei Doi[1], Nana Yoshimitsu[1], Naoki Takahashi[2]

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Major rock properties such as elastic wave speed and attenuation are essential for estimating Earth's internal structure. Generally, laboratory measurements are held using a frequency band between 100 kHz and a few MHz, which is far from seismic frequency band. It is not cleared whether these properties are constant over such a wide frequency range. Kawakata et al. (2010, SSJ) studied the elastic wave speed from 100 kHz to 2 MHz using elastic wave radiation. In this study, we carried out cyclic loadings using a Westerly granite sample, and estimated elastic wave speed and attenuation through complex elastic modulus using stress-strain relationships between 0.1 Hz and 10 Hz. The amplitude of complex elastic modulus showed weak positive correlation with frequency, while phase shift showed no remarkable dependence on frequency.

Keywords: laboratory experiment, cyclic loading, elastic wave speed, elastic wave attenuation, frequency dependence

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SSS027-13 Room:105 Time:May 22 15:15-15:30

Square waves - application for the rock mechanics

Makoto OKUBO[1*]

[1]TRIES

Rock properties, which are rigidity and energy loss, can be estimated from the attenuation of acoustic waves (Q) or the velocity of propagation. Many velocity estimation studies have been done, by the pulse transmission method (eg. JGS2110-1998) and the frequency modulated continuous wave transmission method (eg. ACROSS). However, these methods can not evaluate attenuation and frequency response, or complicates measurement and analysis. In this study, I propose a continuous square wave method for estimating the rock properties. My method can easily applicate to existed measure system, and give more information on rock properties.

Continuous square wave method that introduced in this paper, was used to actual velocity measurements at Mizunami. These studies will be presented at S-TT55 session by Ishii *et al*. and Sano *et al*. See also these presentation.

Keywords: Square waves, P-wave velocity, Rock mechanics, Odd numbered-overtone, Frourier analysis

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Numerical simulation of wave propagation in the media based on MRI measurement of partially frozen brines (Part2)

Jun Matsushima[1*]

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We used partially frozen brine as a solid-liquid coexistence system to investigate attenuation phenomena in laboratory experiments. Attenuation results measured from experimental data are not entirely due to the intrinsic properties of the ice-brine coexisting system; a component of attenuation due to scattering effects is also included in the estimate. The level of scattering attenuation is related to the magnitude heterogeneity of acoustic impedance between ice and unfrozen brine. We obtained a series of two-dimensional apparent diffusion coefficient (ADC) maps of the ice-brine coexisting system using a diffusion-weighted magnetic resonance imaging (DW-MRI) technique. A series of two-dimensional MR slices of the ice-brine coexisting system exhibits strongly heterogeneous characteristics. The purpose of this study is to characterize scattering phenomena on synthetic data generated from the information of the microstructure of an ice-brine coexisting system. We constructed a synthetic seismic data set propagating through two-dimensional media based on the ADC maps, and generated synthetic data with a second-order finite difference scheme for the two-dimensional acoustic wave equation. Quantitative characterization of heterogeneities of two-dimensional MR slices and correlation with scattering attenuation results is helpful to understand the variation of attenuation with azimuth. We quantified the microstructure of an ice-brine coexisting system using spatial autocorrelation functions (ACF) whose shape is directly related to microstructural spatial changes.

Keywords: seismic scattering, seismic propagation simulation, seismic attenuation, heterogeneity, MRI

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Effect of seismic wave scattering due to the heterogeneous topography on the high-frequency seismic wavefield

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Introduction

High-frequency seismic wavefield would be significantly affected by the seismic wave scattering due to small-scale heterogeneity in the lithosphere and heterogeneous surface topography. In order to reproduce and understand the characteristics of the high-frequency wavefield, the detail distributions of small-scale heterogeneity are required [e.g. Takahashi et al., 2009]. In previous our works, we conduct FDM simulation and compare these results with observed feature derived from dense seismic array [e.g. Takemura et al., 2009; Takemura and Furumura, 2010 SSJ]. In this study, we conduct FDM simulation for seismic wave propagation including surface topography. We compare the both effects of seismic wave scattering due to topography and small-scale heterogeneity using each simulation result.

FDM Simulation including heterogeneous topography

Our simulation model covers a zone 128 km by 128 km by 64 km, which has been descretized with grid size 0.1 km in horizontal direction and 0.05 km in vertical direction. In order to conduct such large scale simulations, we use a parallel staggered-grid FDM simulation technique. We assume the heterogeneous surface topography using the 50 m mesh topography data provided by the Geospatial Information Authority of Japan. In order to include the effect of seismic wave scattering due to small-scale heterogeneity, we also assume the stochastic random heterogeneity characterized by exponential auto-correlation function with correlation distance a = 5km and rms value e = 0.05.

We put the explosion (P-wave) source at the center of model, depth h = 10 km. In the case of homogeneous media, P-wave amplitude can be observed in the radial and vertical components only. However, in the case of heterogeneous media, P-wave amplitude would be observed in transverse (T) component due to seismic wave scattering and diffraction. Therefore some researchers have estimated the structure of small-scale heterogeneity using the P-wave amplitude of T component [e.g. Kubanza et al., 2007; Takemura and Furumura, 2010 SSJ]. In this study, using simulated three component waveforms, we examine the P-wave Energy Partition (EP), which is evaluated as the ratio mean P-wave energy of T component to sum of all components. We compare P-wave EP value as a function of distance for each simulation result.

Simulation results

We conduct FDM simulation for seismic wave propagation in the three models, 1) flat surface model with stochastic random structure, 2) uniform velocity structure model with surface topography and 3) uniform back ground velocity model with both heterogeneities. In the model 1, P-wave EP increases with increasing distance, at 50 km, P-wave EP is 005. On the other hand, in the model 2, P-wave EP value is 0.02 on overall distance. In the model 3, the P-wave EP value increases by the effect of both heterogeneities and at 50 km it is 0.07. This values is corresponding to the observed EP value at Chugoku Shikoku region.

In the FDM simulation for the high-frequency seismic wavefield, we should include the surface topography effect on the seismic wavefield.

Acknowledgement

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

Keywords: Seismic wave propagation, body wave, seismic wave scattering, numerical simulation, surface topography

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SSS027-16 Room:105 Time:May 22 16:00-16:15

Analyses of transverse component of teleseismic P-waves recorded at Hi-net stations

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Short-wavelength heterogeneities of the structure beneath Japan has been recently well studied by many kinds of analyses such as coda-Q, multi lapse time window analyses, peak time delay analyses and so on. In the present study, we evaluate the heterogeneity by analyzing transverse component amplitudes of teleseismic P-waves. Using teleseismic P-wave has a merit in that the structure of all Japan are evaluated almost at once, using the same earthquake. Radiation patterns are not necessarily considered. We analyze the data from 2002 to 2009 recorded at Hi-net station by NIED. We measure the ratio of the energy in transverse component to the total energy of the P-waves, which is theoretically related to the strength of short-wavelength heterogeneity (Kubanza et al., 2006). The earthquakes with a magnitude of 5.5-6.6 at depth $>$ 300 km are analyzed, and signals of P-waves from these earthquakes are band-pass filtered at 0.25-0.5, 0.5-1.0, 1.0-2.0, 2.0-4.0, 4.0-8.0 Hz. We select the data with a large signal to noise ratio (more than 5), and average the ratios for each station at the five frequency bands. The results obtained at these frequency bands show the following characteristics: Large ratios, which represent strong heterogeneity, are recognized mainly at around the Fossa Magna in the central Japan and the Kanto region. The western boundary of the large ratio to small ratios almost correspond to the Itoigawa-Shizuoka tectonic line. We also find large ratios along the volcanic front in the Tohoku region, and around active volcanoes in Kyushu regions. Small ratios representing week heterogeneity are observed mainly at the northern part of Hokkaido, along the Sanriku coast. The western Japan such as Chugoku and Shikoku districts are mostly characterized by week heterogeneity. Slightly large ratios may be recognized along the Median tectonic line in the Shikoku island. The spatial changes of the ratios, which reflect the generation of transverse component in P-wave, are well matched with the geological settings of Japan island.

Keywords: P-wave, transeverse component, scattering, heterogeneous structure

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Envelope broadening of S-waves from the inter- and intraplate earthquakes in the northeastern Japan forearc

Shoko Koga[1*], Yoshihiro Ito[1], Ryota Hino[1], Masanao Shinohara[2], Norihito Umino[1]

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It is well known that the double-planed deep seismic zone is observed within the Pacific slab subducting beneath the northeastern Japan arc. Recently, the double-planed structure is also found in the shallow inter- and intraplate seismicity beneath the NE Japan forearc region. Appearances of observed seismograms are remarkably different between the earthquakes in the upper plane and those of the lower planes: Seismograms of the upper plane events show 1) indistinct direct P- and S- waves, 2) many later phases following direct P- and S-waves, and 3) comparatively low frequency. In contrast, seismograms of the lower plane events show 1) distinct direct P- and S- waves, 2) almost no later phases, and 3) comparatively high frequency. In this study, we evaluated the difference in the seismograms by measuring a time difference between the onset and the peak amplitude of S-wave envelope, a peak delay time. The peak delay time is mostly controlled by the strength of multiple forward scattering and diffraction due to the heterogeneous structure of short wavelength along a seismic ray path.

We analyzed seismograms recorded at the seismic stations in the forearc side of the NE Japan arc. Focal depths of the target earthquakes, the earthquakes belonging to the double-planed shallow seismic zone, were determined by using arrival times of sP depth phases recognized clearly on the seismograms. We calculated root means square (rms) envelopes of velocity seismograms of horizontal components in four frequency bands 2 - 4, 4 - 8, 8 - 16, and 16 - 32 Hz to measure the peak delay time (PDT). The measured PDTs grow as hypocentral distances increase. In order to evaluate the dependence of the PDTs on the hypocenter locations, we corrected the distance dependence of the PDT by taking deviations from a linear regression line of log-PDT against log-travel time (delta log PDTs) in each frequency band.

As a result, it turns out that the earthquakes belonging to the shallow double seismic zone can be divided into two groups according to the delta log PDTs. The delta log PDTs measured for the interplate earthquakes are significantly large and show no noticeable frequency dependency. In contrast, the intraplate events are characterized relatively small delta log PDTs. The PDTs measured for the intraplate earthquakes show positive frequency dependence: PDTs are larger for the higher frequency band. Conspicuous difference in S-wave envelopes between interplate and intraplate earthquakes indicates that the envelope shape is strongly dependent on the hypocenter locations in relation to the plate boundary. We suggest that formation of guided wave through the low velocity layer along the plate boundary contributes to considerable broadening of S-wave envelopes of the interplate earthquakes.

Keywords: oceanic lithosphere, intraplate earthquake, S coda wave

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Random Heterogeneity of the Earth Revealed from the Analysis of Short-Period Seismograms

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In short period seismograms of local earthquakes, long lasting coda waves follow the direct S arrival and the apparent duration of S waves is often much larger than the source duration time. For P-waves of teleseismic events, their envelopes are broadened longer than the source duration and waves are excited in the transverse component. Analyzing those seismogram envelopes on the basis of stochastic scattering models, we are able to quantify the random heterogeneities distributed in the earth's lithosphere: one is the scattering coefficient which phenomenologically characterizes the scattering power per unit volume for the radiative transfer theory; another is the power spectral density function (PSDF) of the fractional velocity fluctuation, which is more appropriate for the wave theoretical description of random media. Stochastic characterization and deterministic imaging such as tomography are complimentary to each other to enrich our understanding of the structure and the evolution of the solid Earth. Here we briefly review recent measurements by using statistical envelope syntheses and analytical methods.

Scattering coefficients in the lithosphere at various areas in the world are estimated to be from 0.001/km to 0.05/km and 0.01/km on average in the 1-30Hz range. Scattering coefficients beneath volcanoes are two order larger and those in the mantle at lower frequencies are two or three order smaller than those in the lithosphere.

Envelope broadening is well explained by multiple forward scattering due to random velocity inhomogeneities. When the wavelength is smaller than the correlation distance of random media, wave propagation is governed by the parabolic type equation. The Markov approximation, which is a stochastic extension of the split step algorithm, directly derives the mean square envelopes in random media. According to this approximation, the PSDF of fractional velocity fluctuation controls the frequency dependence and distance dependence of the envelope broadening. From the inversion analysis of S envelopes of microearthquakes, the PSDF is found to be larger and the spectral decay rate is smaller beneath Quaternary volcanoes compared with those between them and those in the fore-arc side of the volcanic front.

By using the Born approximation for random elastic media, we can derive nonisotropic scattering coefficients, which is a function of the PSDF of fractional velocity fluctuation. By using the raditiave transfer theory with the Born scattering coefficients, we are able to synthesize vector wave envelopes. The analysis of P wave envelopes of teleseismic events revealed that the PSDF in the lower mantle is smaller than that in the lithosphere and the upper mantle.

Keywords: coda waves, heterogeneity, lithosphere, random media, scattering, envelope

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The mechanism of anomalous seismic wave propagating along trench revealed by FDM simulation

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During shallow earthquake occurring near the trench (outer-rise earthquake), an anomalous later phase is observed occasionally at stations distant from the epicenter (around 1000 km). From the late arrival of the phase (hundreds of seconds after S-wave), the propagation speed of the phase is estimated as 1˜1.5 km/s. The phase has the particle motion like Rayleigh wave, the dominant period of around 12˜20 s and the large amplitude. About such phase, the report by Nakanishi et al. (1992) would be the initial, which was about the observation at a station in Hokkaido during the earthquake near the Kuril Trench. Following this, Yomogida et al. (2002) discussed that these phases could be Rayleigh wave trapped along the trench by means of ray tracing. After the installation of broadband network (F-net), a number of such phases were obtained. For example, it appeared at Izu Islands during 2005 off-Sanriku outer-rise earthquake (Mw 7.0) (Noguchi et al., 2010; 2011). It also found at stations in Hokkaido during the aftershocks of 2007 Kuril outer-rise earthquake (Mw 8.1) and at stations in Kanto region during December 2010 Bonin Islands outer-rise earthquake, etc. They appear at limited stations whose propagation path is along the trench. They will not appear during the earthquakes nearer to land. From such relative positions of the epicenters and stations, there is no doubt on that the anomalous phases are generated on the long way along the trench. Because the phases appear around the kink of trench, off-Tokachi junction or off-Chiba triple junction, such particular structures with thicker seawater and sediments also could play a role on the generation of the phase. To investigate the mechanism of the phase, we conduct the 2D- and 3D- finite difference method (FDM) simulations using various model structures.

First, we conduct 2D-FDM simulation considering the case of F-net AOGF during 2005 off-Sanriku outer-rise earthquake using model structure along Japan Trench which is made from the seafloor topography by J-EGG500, subsurface structure by J-SHIS and subducting plate structure by Special Project for Earthquake Disaster Mitigation in Urban Areas. To take the interaction between the seawater and seafloor into account properly, we introduced the calculation method for solid-fluid boundary proposed by Okamoto and Takenaka (2005). As a result, the mechanism of the anomalous phase is clearly shown; the ocean acoustic wave coupled with the seismic wave propagating along the seafloor (boundary wave) is excited and propagates slowly (around 1 km/s), then be converted to Rayleigh wave at the seafloor slope to the land and observed as an anomalous phase. It represents that the slow propagation of boundary wave in deep sea area along trench and the conversion at seafloor slope are important for the generation of the phase.

Then we investigated the roles of seawater, sediment and seafloor topography using the various cases of simplified 2D models. It is shown that the depth of seawater affects on the travel time and the dominant period of the phase. The travel time also depends on the thickness of sediment. The angle of seafloor slope controls the ratio of conversion and reflection of boundary wave and affect on the amplitude of the phase.

Finally, we conduct the 3D-FDM simulation to investigate the role of 3D structure containing trench and its junction on the phase. As the result, it is shown that the boundary waves are trapped along the trench because of low velocity zone due to thick seawater. Then a part of them are converted at the seafloor slope which faces the kink of trench, and reach on the land as a Rayleigh wave. From the results, the mechanism in the case of off-Sanriku outer-rise earthquake can be explained as below; the boundary wave trapped along Japan Trench is converted into Rayleigh wave at off-Chiba triple junction, then be observed as anomalous later phase at AOGF.

We used the continuous seismic data recorded by F-net, NIED.

Keywords: ocean acoustic wave, trench trapped wave, Rayleigh wave, FDM simulation, outer-rise earthquake

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Finite-difference calculations of near-field long-period seismograms with 3D lakes at Taal volcano, Philippines

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Taal volcano, Philippines, located 60 km south of Metro Manila, has experienced mainly phreatic and phreatomagmatic explosions with a typical recurrence interval of 30 years. More than 30 years have passed since the last eruption in 1977, increasing a risk of near-future explosion. In order to better monitor and understand this volcano, an observational network was upgraded in the last November, including 5 new broadband seismometers, in cooperation with some other organizations including PHIVOLCS.

A problem to be solved in seismic analysis at Taal volcano may be an effect of lakes on the Green's functions. Taal holds a caldera filled with a lake (Taal Lake) with horizontal dimensions of 15 km (east-west) x 25 km (north-south) and with a maximum depth of 200 m, in which an active volcanic island exists. The island itself has another lake (Main Crater Lake), with a diameter of 1.2 km and a maximum depth of 80 m. A significant effect of a shallow low velocity layer on moment-tensor inversions of long-period (1-2 s) volcanic events have been indicated by Bean et al. (2008, JGR). Since the lake is regarded to be a special case of low velocity layer, the effect of the lake on calculations of the Green's functions is an important issue for seismic analysis at Taal volcano.

In order to investigate this problem, the finite-difference method (FDM) code of Maeda et al. (2011, GJI) was improved to deal with water domains such as lakes and the sea. The FDM code has the advantage in the following two points; (1) arbitrary 3D topography and structure can be considered, and (2) efficient absorbing boundary layers known as the perfectly matched layer (PML) are used. We used the algorithm of Okamoto and Takenaka (2005, J. Seism. Soc. Jpn.) to deal with the water domains.

Synthetic seismograms were generated by the improved code, using a 3D Digital Elevation Model (DEM) of Taal volcano, in which the lake-floor topographies of the both lakes were included. Calculations and comparisons were made among three cases, namely: the lake domain is filled with water (hereafter called "waterlake"), the lake domain is filled with solid having the same property as surroundings ("solidlake"), and the lake domain is dealt as a part of the vacuum domain ("vacuumlake"). Numerical tests were conducted for isotropic ricker wavelet sources with typical source durations of (a) 2 s, (b) 5 s and (c) 10 s at a depth of 500 m, and of 5 s at depths of (d) 200 m and (e) 2000 m under the crater center. Maximum differences between the results of waterlake and vacuumlake, within epicentral distances of 10 km, for calculations (a)-(e), were 43, 9, 3, 10 and 5 %, respectively. Those between waterlake and solidlake were 63, 21, 14, 24 and 13 %, respectively. These results indicate that the synthetics generated by shorter and shallower sources are more seriously affected by the lake. Although the presence of the water layer has a negligible effect on the waveforms generated by 5 s or longer sources, the lake-floor topography should not be neglected even for the source of as long as 10 s.

Additional tests to estimate their effects on the moment-tensor inversion results are now going on. In this presentation, the results of these calculations are presented.

Keywords: Taal volcano, Green's function, FDM, lake-floor topography

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SSS027-21 Room:105 Time:May 22 17:45-18:00

Comparison of global synthetic seismograms calculated by the spherical 2.5-D finite-difference method with observed wave

Genti Toyokuni[1*], Hiroshi Takenaka[2], Masaki Kanao[1]

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We have been developing accurate and efficient numerical schemes using the finite-difference method (FDM) in spherical coordinates to simulate global seismic wave propagation thorough laterally heterogeneous realistic Earth models. The so-called axisymmetric modeling is known as a traditional approach which efficiently solves the 3-D elastodynamic equation in spherical coordinates on a 2-D cross-section of the Earth assuming structures to be invariance with respect to the axis through the seismic source, although it essentially contains a severe demerit that asymmetric structures about the axis cannot be incorporated. Our scheme is based on the framework of the axisymmetric modeling but has extended to treat asymmetric structures (Toyokuni et al., 2005, GRL), arbitrary moment-tensor point sources (Toyokuni & Takenaka, 2006, EPS), anelastic attenuation (Toyokuni & Takenaka, 2008, AGU Fall Meeting), and the Earth's center which is a singularity of wave equations in spherical coordinates (Toyokuni & Takenaka, 2009, AGU Fall Meeting). All of this kind of schemes which solve 3-D wavefields on a 2-D model cross-section are classified into the 2.5-D modeling, so that we call our scheme spherical 2.5-D FDM.

In this presentation, we compare synthetic seismograms calculated by our FDM scheme with three-component observed long-period seismograms including data from stations newly installed on Antarctica in conjunction with the International Polar Year (IPY) 2007-2008. Seismic data from inland Antarctica is expected to bring images of Earth's deep interior with enhanced resolution due to the high signal-to-noise ratio and wide extent of this region, in addition to rarity of their sampling paths along the rotation axis of the Earth. We will show some numerical examples with the standard Earth model PREM and more realistic Earth models with lateral heterogeneity using a moment-tensor point source which has the same mechanism as a November 9, 2009 Fiji earthquake (Mw=7.3).

Keywords: seismology, synthetic seismogram, finite-difference method (FDM), global modeling, IPY2007-2008, Antarctica

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SSS027-22 Room:105 Time:May 22 18:00-18:30

Our numerical simulation studies: bridges connecting theory and practice in quake seismology

Hiroshi Takenaka[1*]

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In this presentation I review our numerical simulation studies on wave propagation in quake seismology. Jon F. Claerbout mentioned ”I hope to illuminate the gaps between theory and practice which are the heart and soul of exploration seismology, as they are of any living science.” in one of his text books for exploration seismology ”Earth Sounding Analysis: Processing versus Inversion” (Blackwell Scientific Pub.,1992). What a wonderful sentence it is! I hope that our numerical simulation studies become bridges connecting theory and practice in quake seismology.

Keywords: numerical simulation, seismic wave

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SSS027-P01 Room:Convention Hall Time:May 23 16:15-18:45

Approximate calculation of group velocity of anisotropic media in the shortest path method

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Shortest path method calculates travel times between sources and receivers by searching the shortest travel time path connecting nodes distributed in the target area. In order to apply this method to anisotropic media, group velocity between two nodes should be calculated. The other part of program is almost same as in isotropic media. In the anisotropic media, phase velocity and group velocity is different. Phase velocity vector and group velocity vector are also different. In weak anisotropic media, the differences are negligible and the difference of ray path due to it is also neglected in general. In this study, we take the difference into account.

At each media node, we calculate group velocity vectors as well as phase velocities in many directions around the node by solving Christoffel equation. We assume six planes around the node. Two components of unit direction vector at the node, parallel to the plane, are two local coordinates on the plane. Grid points are distributed at cross points of the local coordinates. The direction vector is obtained by the group velocity vector, not the phase velocity vector. We fit the group velocities with spline function on each plane and interpolate group velocities at the grid points. The interpolated group velocities are stored and group velocity at the node in arbitrary direction is obtained by linear interpolation of the stored data. In strong anisotropic media, the fitting fails, so that we cannot use this approach.

We add this process into our shortest path method program and apply it to the anisotropic velocity structure of the low velocity layer of PREM model. We get travel times at receivers in horizontal and vertical directions from the source location. The travel tines are same as theoretically expected. The ray paths are little deviated from those in isotropic media. The reason will be that the anisotropy of the PREM is weak.

Keywords: shortest path method, anisotropy, group velocity

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SSS027-P02 Room:Convention Hall Time:May 23 16:15-18:45

Seismic anisotropy apparently caused by contamination of P-S or S-P converted wave

Yoko Tono[1*], Yoshio Fukao[1], Seiji Tsuboi[1]

[1]JAMSTEC

Shear wave splitting measurement is a powerful tool for characterizing anisotropy of the crust and mantle. Analysis of shear wave splitting requires records of well-isolated shear waves little contaminated by other phases. Contamination occurs, for example, by sP or SP wave arriving around the expected arrival time of direct s or S in a wide epicentral distance range for a source depth greater than 25km. The consequent waveform distortion of s or S is examined using synthetic seismograms calculated by the Direct Solution Method [Takeuchi et al., 1996] for the model of PREM [Dziewonski and Anderson, 1981]. The synthetics are accurate to a period of 10 sec.

We calculate the synthetics for vertical-dip slip sources placed at 8 depths of 25, 100, 300, 400, 450, 500, 550 and 600 km. For example, the s waveform in an epicentral distance range less than about 5 deg, calculated for the depth of 100 km is contaminated by not only sP but also Rayleigh waves. The waveforms show the arrival of the weak sP and distortion of the radial component by Rayleigh waves. The S arriving at distances larger than about 20 deg is contaminated by SP. The synthetics calculated for the other source depths also show the similar contaminations, the detail of which changes complexly according to the epicentral distance and the source depth. It is difficult to analyze the anisotropy using the direct s or S at periods longer than 10s.

We also examine the cases of ScS and ScS2. For a source depth between 450 and 600 km, the ScP and ScSScP arrive almost simultaneously as the ScS and ScS2, respectively. We use a correlation method for the synthetic ScS and ScS2 phases for the shear wave splitting measurement to see the effect of the ScP and ScSScP. The effect is found to be minor at epicentral distances less than 20 deg, where the amplitudes of ScP and ScSScP are very weak. The effect can be large at the epicentral distances greater than 25 deg. For the shear wave splitting measurement, we have to examine the vertical component and check against the synthetics test more carefully.

Keywords: anisotropy, Shear wave splitting

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Excitation and propagations of seismo-acoustic waves with an open boundary condition

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We developed an efficient numerical method to calculate normal modes of elasto-gravitational planetary bodies with atmosphere and any mechanical dissipation (Kobayashi 2007). Using the method, we can easily calculate eigenfunctions of a solid mode in the atmosphere and those of an atmospheric mode in the solid earth. To show the performance of the method, we calculated a million of acoustic modes including the solid earth and synthetic waveforms of acoustic waves excited by Iwate-Miyagi Nairiku Earthquake (Nagao et al. 2008). We also discussed an effect of zonal winds on the acoustic wave propagations and their waveforms (Kobayashi 2009).

In such a medium, seismic wave energy can escape through the atmosphere and an eigenfrequency of a mode is inevitably a complex number, and any two normal modes are never orthogonal each other even if we use a perfect elastic earth model in calculations. In this presentation, we discussed about excitation problem of normal modes of one dimensional acoustic system as such a dissipative system in the 2010 SSJ fall meeting (Kobayashi 2010). In this presentation, we apply the theory to a realistic coupled system of the solid earth and the atmosphere, and report effects of the open boundary conditions on wave propagations.

Keywords: seismoacoustic waves, excitation, wave propagation, coupling, open boundary, zonal winds

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The Earth's background free oscillation recorded by the laser strain meter beeing in operation at the Kamioka Mine

Wataru Morii[1*], Akito Araya[2], Akiteru Takamori[2], Yasuyuki Kano[1], Hideaki Hayakawa[3], Shuzo Takemoto[4]

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The observations with the two orthogonal laser strain meter of 100m length have carried out since 2003 and are still continuing in a deep tunnel at the Kamioka Mine, Gifu prefecture. Analyzing the laser strain meter record and the barometer record, we investigated the characteristics of the Earth's background free oscillation. We will report the relation between the signal intensity of the Earth's background free oscillation and the atmospheric pressure change.

Keywords: laser strain meter, Earth's background free oscillation, atmospheric pressure change

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Latitude and longitude dependencies of the eigen frequency in core moeds of the earth's free oscillation

Hironobu Shimizu[1*], Yoshihiro Hiramatsu[2], Ichiro Kawasaki[3]

[1]Natural Sci and Tec., Kanazawa Univ., [2]Natural System Kanazawa Univ., [3]Reserach Center for DMUCH

Seismological studies revealed that the inner core had axisymmetric anisotropy(Morelli et al., 1986; Woodhouse et al., 1986).Kawasaki (2009) pointed that the eigen frequency of the core modes changed with the latitude for the axisymmetric anisotropy. In this study, we use waveform data of the 2004 Sumatra-Andaman earthquakes recorded by superconducting gravimeters and STS-1 seismometers. We calculate the power spectrum of the waveform data using discrete Fourier transformation to identify excited core modes and to discuss the latitude and longitude dependencies of the eigen frequency. In addition, we apply Sompi method to excited core modes. Sompi method estimates the eigen frequency and the quality factor of the free oscillation simultaneously.

We identify ${}_0S_0$, ${}_1S_0$ and ${}_3S_2$ as the excited core modes from the power spectrum. We can find the latitude and longitude dependencies in ${}_1S_0$ and ${}_3S_2$, but we can find no dependencies in ${}_0S_0$. From the comparison of the results of Sompi method with those of Fourier transformation, we suggest that the attenuation of the free oscillation affect little the estimation of the eigen frequency.

Because ${}_3S_2$ is sensitive mainly to the boundary between the inner core and the outer core, we suggest that observed dependencies in ${}_3S_2$ are caused in this region. ${}_1S_0$ is sensitive mainly to the outer core.It is unlikely assumed that there is anisotropy in the outer core, because it is difficult to expect lateral variations in density larger than one part in 10^5 in the fluid outer core (Stevenson, 1987). Therefore, the very small dependencies in ${}_1S_0$ may be caused in other sensitive regions that are the core mantle boundary and the inner core. No dependencies in ${}_0S_0$ may result from little sensitivity to the anisotropy of the core and mantle.

Keywords: the earth's free oscillation, spectral analysis, the inner core, anisotropy

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Waveform effects of the thinning or tearing of the subducting Pacific plate beneath Japan

simanchal padhy[1*], Takashi Furumura[1], Takuto Maeda[1]

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We studied the detailed distorted structure of the subducting Pacific plate near Honshu in the Kanto district by the use of waveforms from deep earthquakes recorded at fore-arc Hi-net and F-net stations in Japan. Such waveforms confirm most of the earlier observations like dominance of low-frequency onset and following high-frequency energy due to the stochastic waveguide effect of the subducting plate, proposed earlier by Furumura and Kennett (2005). However, new observations for most of the source-receiver paths show the distortion of body waves, when signals traverse the Pacific slab at depths more than 350 km. They include the loss of high frequency energy in P-coda, loss of low-frequency precursor and presence of converted phases in P-coda. Such complexities in the observed waveforms are difficult to explain by existing slab model, indicating sudden lateral change in the wave guiding properties of the subducting slab such as caused by the thinning or tearing of the slab in deeper part.

To explain the observations, we employ two-dimensional finite-difference method (FDM) simulations of complete high-frequency P-SV wave propagation taking thinning of Pacific slab into account. We expect that the observed guided wave energy must decouple from waveguide where the slab is deformed or thin. Low frequency energy leaks out of the slab and travels to the receivers along paths in the low velocity mantle surrounding the slab. Taking into account the tomographic evidence of weak velocity anomaly of the Pacific slab beneath Honshu and the observations of slab tear in the Pacific plate (Obayashi et al., 2009; Kennet and Furumura, 2010), we expect a local velocity anomaly or thinning in the oceanic lithosphere along the Izu-Bonin arc that would be compatible with the observations. The preliminary results, which suggest that the Pacific slab is strongly deformed beneath Honsu, is the cause of the complicated waves from deep events with strong source location dependencies. These effects need to be tested further with a 3-D FDM simulation employing high-performance computers with a variety of possible slab geometries.

Keywords: slab tears, subducting plate, waveguide, wave propagation

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Waveforms of seismic events followed by the 2008 Iwate-Miyagi Inland Earthquake

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It is reported that the 2008 Iwate-Miyagi Inland Earthquake (Mj 7.2) had foreshock activity 40 minutes before the mainshock which occurred at 8:43 on June 14. Two foreshocks at 8:01 (Mj 0.6) and 8:11 (Mj 1.3) less than 1 km apart from the mainshock epicenter are listed in the JMA hypocenter catalog. In this study, we check the waveforms carefully which were recorded at the nearest Hi-net station (Ichinoseki-Nishi, epicentral and hypocentral distances are 3 km and 8 km, respectively), and investigate the foreshock sequence of this earthquake.

We used the waveform of updown component recorded at the Ichinoseki-Nishi station from 7:45 to 8:45 on June 14. We detected by eye 13 events whose initial phases are clear and have large amplitudes compared to noises. Each event has quite similar waveform: every phase such as P, S and reflection phases at the ground arrive at the same time when arranged at the P time. Normalized amplitudes of these phases by those of first P waves are classified into at least two groups by their magnitudes. This fact is thought to reflect that there are various types of focal mechanisms of foreshocks. These features of foreshock waveforms suggest that foreshocks occurred at almost the same place but had more than one fault plane. We will extract the information on change of hypocenter location or heterogeneity structure from the recorded waveforms.

Keywords: 2008 Iwate-Miyagi Inland Earthquake, foreshock, focal mechanism, later phases

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An attempt to detect the inhomogeneous structure beneath the Bungo channel using reflected waves

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In the seismograms observed by stations near the Bungo channel, southwestern Japan, many reflected phases are found. In the previous studies, the shape of the Philippine Sea plate subducting beneath the Bungo channel and the structure of crust have been estimated by using reflected phases in the records of the interplate earthquake (Oda et al., 1990; Ohkura, 2000; Miyoshi and Ishibashi, 2007). We attempted to reveal the inhomogeneous structure from data of a earthquake cluster in the shallower part of the crust.

Assuming horizontal reflectors, we estimated the depth distribution of the reflectors from the differences in travel time between a direct S wave and reflected S wave. The hypocenters were determined by the relative hypocenter determination method (Ito, 1985) in order to reduce some errors. We analyzed only the seismograms having impulsive direct S wave. We use the data at 18 stations including 1 temporal station.

As a result, we recognized the reflected phases in most of the observed seismogram from reflectors in depth range from 15 to 20 km depths. Reflected waves from reflector deeper than 30 km depth were also seen in some traces.

Long-term slow slip events (Hirose et al., 1999; Ozawa et al., 2004) and nonvolcanic deep tremors occurred beneath the Bungo channel. Our result indicates a possibility that the reflected waves from deeper parts have a relationship with these slow earthquakes.

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Keywords: reflect waves, the Bungo channel

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Detecting Subsurface Reflections in Southwestern Japan, Using Ambient Seismic Noise

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We demonstrate to detect several subsurface reflectors in Kinki district, southwestern Japan, using ambient seismic noise. In this area, several subsurface reflectors are reported in previous studies. We computed the auto/cross-correlation functions (ACF/CCF) of continuous short period UD components seismograms obtained from Hinet (NIED), JMA (Japan Meteorological Agency), and DPRI (Kyoto Univ.) seismic networks. We divided the seismic record into 1 hour segments and applied 'running absolute mean normalization' (Bensen et al., 2007, GJI) and band-pass filtering (0.5 - 1.0 Hz). Then we calculated ACFs/CCFs and stacked them for at least 15 months long. At borehole stations whose depths are more than 1000 m, clear 'exotic' phases other than surface waves are observed.

We assumed a 1D model based on the previous result of seismic exploration survey in Kinki district (Hirose and Ito, 2007) and calculated theoretical travel times from Moho and other several crustal discontinuities as well as group velocity of the Rayleigh waves. Travel times of the observed 'exotic' phases are generally explained as signals from subsurface reflectors. At the 2000 m borehole, Moho reflection (PmP) is well identified within 100 km distance as well as other crustal reflections. At station pairs of which distance ranges are greater than 100 km, travel time of 1-st higher mode Rayleigh wave well explains the travel time of the observed exotic phase, however, the amplitude of the observed phase is much larger than that expected from theoretical calculation, which requires further investigation to identify the origin of the phase.

Keywords: Ambient Seismic Noise, Seismic Interferometry, Subcrustal Reflector, Moho discontinuity

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Monitoring of the Nojima Fault structure using ACROSS

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To research the healing process of the Nojima Fault structure which ruptured in the 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake, Mw 6.9), ACROSS was set near the boreholes by the Nojima Fault-zone Probe Project and has been operated intermittently since 2000 to monitor temporal variations of the fault structure. In this study, we investigate the long-term change in the travel time, the amplitude and the anisotropy of the transfer function propagating in the fault fracture zone. The result that the travel time variations in both P- and S-wave arrivals proceed about 2 ms since 2000 are consistent with a healing process of a fault. However, the amplitude does not show interpretable variation. As for the anisotropy, estimated from S-wave splitting, we found that the anisotropy is stable since 2000. The leading S-wave polarized direction (LSPD) in the shallow zone indicates that cracks in this zone are orientated to the strike of branch fault, not the direction of the regional horizontal compression (E-W). The degree of anisotropy in the deep zone is smaller than that in the shallow zone and the cracks in deep zone is close and/or not selectively orientated.

Keywords: ACROSS, monitoring, Nojima fault, S-wave splitting

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Temporal changes of auto-correlation functions accompanied by crustal deformation for the eastern off-Izu seismic swarms

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In December 2009, a seismic swarm occurred off the east coast of Izu Peninsula, central Japan. The largest earthquakes during the swarm were two events with MJMA ˜ 5.0. For the whole period of the swarm, tilt record changes were observed at stations in the area. Such seismic swarms, accompanied by crustal deformation, occurred often in the region and are likely caused by magma intrusion from depth into the seismogenic crust [e.g., Okada et al., 2000]. NIED has started to record continuous seismic waveforms since 1990s. Recently, temporal changes of auto- and cross-correlation functions were reported before and after seismic and volcanic events in Japan [e.g., Wegler et al., 2009; Maeda et al., 2010] with continuous waveform data. Here we analyzed continuous auto-correlation functions (ACFs) to infer temporal changes of the velocity structure in the eastern off-Izu Peninsula region, before and after seismic swarms accompanied by crustal deformations. We then compare the velocity changes with tilt records, GPS measurements, and seismicity.

We used Hi-net stations to monitor ACFs of continuous seismic records. We divided the continuous waveform data of 100 Hz sampling into segments of 5 minutes length, removed the mean and trend, and applied 1-3 Hz band-pass filtering and one-bit normalization. The ACFs were calculated for each of the 5 minute segments and stacked for time intervals of one week to obtain stable records. The temporal changes of the ACFs versus time are analyzed by considering a reference ACF, which is the mean of the ACFs for a time period without major seismic swarms. The temporal changes of the ACFs were used to calculate the relative fluctuations of the velocity structure (dv/v) following a similar approach with Wegler et al. [2009]. The tilt records were obtained using high sensitivity acceleration seismographs, having the same locations as the Hi-net stations. The records were corrected for the tidal components using the BAYTAP-G software (Tamura et al., 1991). GPS data for this area were provided by GEONET of the Geospatial Information Authority of Japan.

By using the continuous waveform data, we have obtained ACFs since 2002. The record section of ACFs shows that there is a stable phase around 10 s in lag time. The dv/v estimations show a clear decrease associated with significant earthquake swarm activity. The decrease of the dv/v appears to have gradually recovered in several years. Because the noise level did not have specific changes associated with swarm activities except for a short period of several weeks after large events, the systematic velocity fluctuations for a long period detected using ACFs were not caused by changes in the noise characteristics. Crustal deformations detected with tilt record and GPS-measurement also appeared during the earthquake swarms and they correlate with the seismic activity. The processes of the decreases of the dv/v and its recoveries associated with seismic swarms and crustal deformations appeared in the 2006 and the 2009 eastern off-Izu seismic swarms. We interpret the velocity degrease as being caused by magmatic intrusions that are consistent with the crustal deformation measurements. The recovery process after the velocity decrease seems to have a longer time-span compared to the gradual return to the background level of seismicity and crustal deformations. The longer period of velocity recovery might be related to magma cooling processes.

Keywords: Auto-correlation function, temporal change, Izu Peninsula, seismic swarms, crustal deformation

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Detection of seismic velocity changes associated with the 2005 M7.2 Miyagi-Oki Earthquake, NE Japan revealed from seismi

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Seismic intererometry is a one of techniques used to estimate the detailed properties of the Earth interior using vast number of seismic records; a pair of seismic traces is correlated with one another to estimate a Green's functions as a response of subsurface elastic properties (e.g. Campillo and Paul, 2003). Some previous works for seismic interferimetry of ambient noise showed that auto-correlation functions (ACFs) and cross-correlation functions (CCFs) have temporal changes associated with strong motions due to local large earthquakes (e.g. Wegler et al., 2009). Here, we show changes of ACFs calculated from ocean bottom records accompanied with the occurrence of large earthquake. The five ocean bottom seismometers (OBSs) were deployed off Miyagi Prefecture before the 2005 M7.2 Miyagi-Oki Earthquake. All of the OBSs used in this study are a free-fall/pop-up type with a three-component geophone of natural frequency of 1 Hz. We computed ACFs with time-window length of 120 s. Filtered one-hour traces at the frequency band of 0.5?2 Hz were used to compute correlation by one-bit correlation technique. By taking ensemble average of ACFs among 24 hours, the one-day ACFs were computed from June 2005 to February 2006 including the Miyagi event at each station. Computed ACFs showed some common coherent phases throughout observing period. We assumed that computed ACFs reflected subsurface structure just below OBSs.

The phases between 10 s and 15 s in lag time showed slightly delay of approximately 0.1s after the 2005 Miyagi-Oki Earthquake, which are observed at some OBSs. Interestingly, the delayed phases at 15 s in lag time are restored gradually. The delay time of the 0.1 s corresponds to the rate of seismic velocity decrease of 1% if seismic velocity would be uniformly changed around stations after the 2005 Miyagi-Oki Earthquake. The observed seismic velocity change is comparable with the velocity decrease of 1.5% at inland seismic stations, which was reported by Nakahara et al (2007) after the 2005 West Off Fukuoka Prefecture Earthquake (Mj7.0).

Keywords: seismic interferometry, OBS, ACF, the 2005 M7.2 Miyagi-Oki Earthquake

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Search for seismic velocity changes due to the 2009-2010 Bungo-Channel slow slip event with seismic interferometry

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Recently, seismic velocity structures and their temporal changes have been investigated with seismic interferometry, where green function waveforms propagating between two stations are constructed by producing ambient noise correlations of waveform data observed at two stations. Rivet et al. (2010) have reported a possible velocity change of 0.3 % due to the 2006 slow slip event in Guerrero, Mexico. Inspired by their study, we try to detect the possible velocity change due to the 2009-2010 Bungo-Channel slow slip event occurring in southwest Japan with seismic interferometry.

We analyze continuous vertical waveform data obtained at 28 Hi-net stations operated by NIED in the Shikoku region, southwest Japan. Applying band-pass filtering of 0.1-0.5Hz, we first produce 1-day stacked cross-correlation functions (CCFs) for each pair of stations following the running-absolute-mean normalization method (Bensen et al.,2007) to enhance the ambient noise portions. Each 1-day CCF has a similar waveform but the amplitude is changing. Therefore, we produce 1-month stacked CCFs. Stacked CCFs during the whole period for respective pairs show a prominent Rayleigh wave packet propagating with the group velocity of 2.5 km/s. Then, we produce a cross-correlation function between the corresponding phase portions for the 1-month stacked CCF and for the reference CCF, and examine the temporal changes in the arrival time of the phase in 1-month CCF for each station pair.

Even if CCFs are relatively stable in time, say CCFs for stations N.OOTH and N.MISH, they have asymmetry in the CCF delay time, and the phases of Rayleigh wave portion appear in the positive and the negative delay times depending on the season. As previous studies pointed out, this seems to be caused by the temporal change in the distribution or the strength of noise sources. We compare the CCFs for the western and the eastern Shikoku station pairs with those for the northern and the southern ones. The CCFs for the western and the eastern ones show the arrival time seasonal changes of 1 %, and the larger delays appear in winter than in summer if the reference stations are take to be the western ones. Such seasonal delay changes, however, cannot be seen in CCFs for the northern and the southern station pairs. Furthermore, differently from seasonal changes, in some northern and southern station pairs, the CCFs show rapid delays of arrival times amounting to 0.3-0.5 % around January in 2010. The paths between these station pairs sample the region where the 2009-2010 Bungo-Channel slow slip occurs. And the amount of arrival time delays, namely, the reduction of seismic velocity, is comparable to those reported in previous studies. Therefore, the changes in delay times might be related to the slow slip event, though we need further to examine the details in the changes, to distinguish the seasonal changes and to investigate CCFs in some different frequency bands.

In this paper, in addition to the data at the stations in Shikoku, we analyze the data recorded at the Hi-net stations in Ooita and Miyazaki prefectures, the Kyushu region, which give us the CCFs for station pairs whose paths are crossing the Bungo-Channel and well sampling the source region of the slow slip event.

Keywords: Seismic interferometry, ambient noise, cross-correlation, Bungo-Channel slow slip event