

Fundamental study on estimation of change in local stress field using coda-Q

OKAMOTO, Kyosuke^{1*}, MIKADA, Hitoshi¹, GOTO, Tada-nori¹, TAKEKAWA, Junichi¹

¹Graduate School of Engineering, Kyoto University

In this study, we tested a hypothesis that "coda-Q, i.e., an attenuation parameter for the part of natural earthquake seismogram (called coda-wave) after the S-wave arrival, has a relationship with the state of local stress field in the crust". In the past, it has been discussed that the coda-Q changes before a large earthquake or shows anomalous values around a volcanic zone. However the mechanism causing the change in the coda-Q has yet not been revealed since the coda-Q is considered as a parameter to reflect strong heterogeneity of the medium of seismic wave propagation. In other word, the coda-Q has not been well analyzed to obtain any change of the physical state in the subsurface since the interpretation using the coda-Q is mainly used to interpret the heterogeneity of such medium. We focus on a hypothesis proposed by Aki (2004) pointing out that the prediction of earthquakes is a difficult task since the shallow part of the crust covering earthquake sources is too inhomogeneous, and that the coda-Q could be indicating some preseismic process. In his study, he reported that the seismicity around the San Andreas Fault in California shows high correlation with the variation of the coda-Q inverse around the fault in time. When the seismicity is correlated with the variation of coda-Q, the correlation coefficient becomes higher than 0.8. Therefore, we hypothesize that "the variation of coda-Q has a relationship with the change in the local stress field, which triggers an earthquake". In fact, the coda-Q is reported to show a change before the Southern Hyogo prefecture earthquake in 1995 by Hiramatsu et al. (2000). Their results also imply that the relationship between the stochastic parameter, coda-Q and the state of subsurface medium. This study also supports the hypothesis mentioned above.

To verify our hypothesis, the variation of the coda-Q against the stress was examined using numerical simulation of seismic wave propagation. In this study, we assumed that the coda part of earthquakes would be formed by superposed scattered waves originating from cracks distributed in the medium. We then simulated the coda-wave to estimate the coda-Q for various stress loads. As Okamoto et al. (2010) already reported, the coda-Q varied with respect to the change in the direction and the magnitude of the loaded stress under the condition that the elastic displacement of crack locations were took place due to the loaded stress. The order of the change in the coda-Q against the stress, however, is much smaller than the change in the real data observed by Aki (2004). The calculated change in the coda-Q is only the order of several permill for 10 MPa change in the loaded stress, while observed were tens of percent for earthquakes in California (Aki, 2004). So there should be another mechanism to augment the change in the coda-Q much effectively than the effects of the elastic displacement of cracks. We finally assumed two types of additional effects; (1) phase velocity anisotropy induced by the selective closure and opening of microcracks, and (2) the azimuthal alignment of mezzo-scale cracks. The simulation was done for case that a plane wave travels through the bottom boundary of the model. As a result, we confirmed that the change in coda-Q had a qualitative relationship with the magnitude of the change in the mean normal stress (confining pressure). In addition, the order of the change in the coda-Q agrees with the order of the change of the real data observed in Aki (2004). This result suggests that the magnitude of the stress can be estimated from observation of the coda-Q. Unlike the qualitative relationship between the coda-Q and the crustal stress, the quantitative relationship between them can leads to a new stress monitoring method.

Keywords: Coda-Q, attenuation, anisotropy, stress field, numerical simulation

Power-Law Decay of Direct- and Coda-Wave Amplitudes and the Fractal Distribution of Intrinsic Absorbers and Scatterers

SATO, Haruo^{1*}

¹Graduate School of Science, Tohoku University

The maximum amplitude of seismic waves of a local earthquake decreases according to some power of distance for a wide range of distance. The coda amplitude of a local earthquake decreases according to some power of lapse time measured from the earthquake origin time. When intrinsic absorbers and scatterers are randomly and homogeneously distributed in space; however, the conventional theory predicts that the direct-wave amplitude exponential decreases with distance increasing and the coda amplitude also exponentially decreases with lapse time increasing in addition to the geometrical decay. The exponential decay of the direct-wave amplitude is inevitable in the case of homogeneous distribution.

This paper presents a theoretical model that leads to the power law decay of the direct-wave amplitude with distance and that of the coda amplitude with lapse time. We can formulate the scattering process in the framework of the radiative transfer theory when the spatial distribution of intrinsic absorbers and isotropic scatterers are fractally random and homogeneous. In the case that their fractal dimension is two, the theory exactly predicts power law decay for both the direct-wave amplitude with distance and coda-wave amplitude with lapse time. An exponential decay term for the fractal dimension 3 changes into a power law decay term for the fractal dimension 2. The difference between the direct- and coda-wave amplitudes and that between their powers are controlled by intrinsic absorption and scattering strength. It will be interesting to measure regional variation and depth dependence in those parameters from the analysis of seismogram envelopes of local earthquakes on the basis of the fractal model in relation with seismotectonic conditions.

Keywords: coda, attenuation, scattering, radiative transfer theory, body waves

A comparison of finite-frequency and ray approaches in local tomography

ZHAO, Dapeng^{1*}, TONG, Ping¹

¹Department of Geophysics, Tohoku University

We determined detailed 3-D P and S wave velocity models of the crust in the 1995 Kobe earthquake (M 7.2) area in Southwest Japan using both finite-frequency and ray tomography methods. Our finite-frequency tomography technique is based on the single-scattering theory (Tong et al., 2011). The finite-frequency sensitivity kernel derived in this study reflects correctly the sensitivity of the heterogeneity off the geometrical ray path and the existence of Fresnel volume, and the kernel depends on the dominant frequency of the observed wave. The dominant frequency is estimated directly from the earthquake magnitude based on a relation that is obtained by regressively analyzing the displacement spectra of 20 earthquakes in the study area. We used a great number of P and S wave high-quality arrival-time data from the Kobe aftershocks and other local earthquakes during 2002 to 2010. Our tomographic images obtained with the finite-frequency and ray tomography methods show a high level of similarity, which is verified quantitatively by adopting the structural similarity index. Similar to the previous studies (e.g., Zhao et al., 1996), the present results show that the Kobe mainshock hypocenter is located in a distinctive zone characterized by a high Poisson's ratio and a low product of P- and S-wave velocities, which is interpreted as a fluid-filled, fractured rock matrix that may have triggered the 1995 Kobe earthquake. The crustal fluids in the Kobe hypocenter are considered to originate from the dehydration of the subducting PHS slab beneath Southwest Japan (Zhao et al., 2002, 2010).

Keywords: ray theory, finite-frequency, tomography, crustal structure, earthquakes

The mechanism of anomalous wave propagating along trench shown by 3D-FDM simulation considering topography and seawater

NOGUCHI, Shinako^{1*}, MAEDA, Takuto², FURUMURA, Takashi²

¹CRIEPI, ²CIDIR/ERI, The University of Tokyo

To clarify the mechanism of anomalous later phase which appears during shallow earthquake near a trench, we investigate the effect of heterogeneous structures around a trench on generation and conversion of seismic waves by means of numerical simulation using 3D finite difference method (FDM).

During shallow earthquake occurring near a trench (outer-rise earthquake), an anomalous later phase is observed occasionally at stations distant from the epicenter (~1000 km). From the late arrival of the phase, 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 10~20 s and the large amplitude. The initial report for the observation of such anomalous phase would be given by Nakanishi et al. (1992), which was about the observation at a station in Hokkaido during the earthquake near the Kuril Trench. After the installation of broadband network F-net, a number of such phases were observed. For example, it appeared at the F-net station AOGF in Izu Islands during 2005 off-Sanriku outer-rise earthquake (Mw 7.0) (Noguchi et al., 2011). It was also found at stations in Kanto region during 2010 Bonin Islands outer-rise earthquake (Mw 7.4). They appear at limited stations located around the junction of trenches. Also, the propagation path for these observations are along the trench. So that the anomalous phase should be attributed to particular propagation path around the trench. For the mechanism of such phenomena, Yomogida et al. (2002) discussed that these phases could be Rayleigh wave trapped along the trench by means of ray tracing. In Noguchi et al. (2011), based on 2D-FDM simulation, we showed that the slow (~1.1 km/s) solid-liquid boundary wave propagates along the deep seafloor, then converted into Rayleigh wave at the seafloor slope and finally observed as an anomalous later phase. In this result, the role of 3D structure around a trench which could trap and convert the boundary wave was not clear.

Based on the result, we conduct the 3D-FDM simulation for the case of AOGF during 2005 off-Sanriku outer-rise earthquake considering the seawater layer, realistic topography and 3D heterogeneous structure. We simulate the seismic wave propagation with the period of longer than 10 s in the area of 900 km x 360km around Japan Trench. We construct 3D structure model using data of the seafloor topography by J-EGG500, subsurface structure by J-SHIS and 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 introduce the calculation method for solid-fluid boundary proposed by Okamoto and Takenaka (2005). As a result, it is clearly simulated that the boundary wave propagating along the seafloor travels a long distance trapped along the Japan Trench axis. It is due to the low velocity zone for the boundary wave caused by the thick seawater along the trench. The boundary wave then escapes the trench at the triple junction at off-Chiba, converted into Rayleigh wave at the seafloor slope, and finally observed as an anomalous phase at AOGF. The result supports the mechanism revealed by 2D simulation, yet it becomes very clear newly that the boundary wave is trapped along trench axis and converted at the trench junction. It is also shown that the relative amplitude of anomalous phase compared to S or Rayleigh phase depends on the hypocentral depth or the relative position of epicenter to the trench. Similar to the other simulations considering water layer (e.g. Maeda et al., 2011), totally, the amplitude and duration of later phase observed onshore become bigger and longer compared to the case without water layer. It would be due to the slow boundary wave trapped in sea area widely for a long time. It indicates that it is necessary to consider the seawater layer when we estimate the ground motion due to the earthquake occurring in sea area.

Keywords: Ocean acoustic wave, Trench trapped wave, FDM simulation, Outer-rise Earthquake, Long period ground motion simulation

Encouragement of High Frequency Observational Seismology

OKUBO, Makoto^{1*}, Atsushi Saiga¹

¹TRIES,ADEP

Available frequency ranges for the ordinary observational seismology is limited up to about 30Hz. This limitation is controlled by seismometer's frequency response and/or sampling frequency of data logging system. Why observation frequency is limited up to 30Hz? Interesting phenomenon does not exist above this frequency?

Recently, high speed sampling data logging systems with high dynamic range were developed. In this study, we could use the two high speed sampling data logging systems, which developed by Scimorex Inc. These systems can record continuous 10kHz data sampling with 24 bits resolution, which controlled by GPS timing. We used these data logging systems to observed seismic motions with 1 Hz, 2 Hz eigenfrequency moving coiled velocity seismometers, and over-dumped acceleration seismometer, at Tono region Gifu prefecture, Japan from Dec. 2011. Data amount is not so big, only 3GB/day; for 4 channels with 10kHz sampling.

Fortunately, we could observe the earthquake, which occurred below the Tono region with $M_{JMA} = 5.1$ (2011/12/14 13:01) and its after shocks. In this study, we have verified the performance of SC-AD10K, and we concluded SC-AD10K has good for observation. Additionally, we will show some interesting observed phenomena, and introduce high frequency observational seismology, and its applicational plan, for example, detailed velocity structure estimation and its velocities monitoring.

We believe more interesting phenomena exist at these frequency ranges. The reasons that past studies did not done at these frequencies are that data logging systems was still developing and observational seismologists feared the amount of data given by high speed data sampling.

Keywords: High speed data logging system, High frequency seismogram, Detailed velocity structure, Seismic wave velocity monitoring

Time reversal analysis of seismic waves in Suruga Bay

KIKUCHI, Toshiaki^{1*}, Koichi Mizutani²

¹National Defense Academy, ²Acoust. Lab., Univ. Tsukuba

We have examined the application of time reversal in the field of the ocean acoustics. A sound pulse is radiated from a sound source set up in the sea, and the sound pulse is received by a hydrophone array set up at the remote position. The sound pulse that converges in the original source location is formed when re-emitting it from the array after time reversal processing is given to the received signal. The waveform of the sound pulse that converges in the source location becomes the same as the waveform of the sound pulse radiated there. The vibration of the hypocenter is obtained by applying this principle.

We pay attention to the earthquake of magnitude 6.5 that occurred in the Suruga Bay central part on August 11, 2009 to examine it more widely.

To obtain the propagating environment that is the most important factor for the application of the time reversal, we proposed the inverse problem method using the robustness of the time reversal.

P wave component is cut out from the received signal by the seismometer, and the time reversal processing is given to it. And, the inverted signal is transmitted in the propagating environment on the propagating simulation. And, the pulse formed in the vicinity of the hypocenter, that is, time reversal pulse is obtained.

As a result, the pulses were greatly different according to the observation station.

We paid attention to the azimuth, and the time reversal pulse was arranged in an azimuthal order. Even if the range and depth are greatly different it, the time reversal pulse of the observation station which the azimuth is near becomes a similar waveform. However, the waveform of the time reversal pulse has changed greatly when the azimuth is changed. Then, the Fourier transform was performed to the time reversal pulse, and frequency spectrum was obtained. As a result, frequency spectrum of the observation station which the azimuth was near was similar. However, the azimuthal dependence of frequency spectrum appeared greatly. Then, the peak frequency of frequency spectrum to the azimuth was obtained.

When this result is examined from an acoustics standpoint, it is clear that the hypocenter corresponds to not a fixed sound source but the maneuverability sound source.

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

Inhomogeneous structure inferred from reflected S waves beneath the Bungo channel, southwest Japan.

MIYAZAKI, Masahiro^{1*}, MATSUMOTO, Satoshi², SHIMIZU, Hiroshi², UEHIRA, Kenji²

¹Grad. Sch. Sci., Kyushu Univ., ²SEVO, Kyushu Univ.

Analysis of reflected phases provides accurate image of structure in deeper region than use of refracted waves. The depth of upper boundary of the Philippine Sea plate subducting beneath the Bungo channel, southwestern Japan has been estimated from the travel time data of the reflected or converted phases observed in the seismic record of the intraplate earthquake (Oda et al., 1990; Miyoshi and Ishibashi 2007). In the seismograms of the crustal earthquakes observed at the stations near the Bungo channel, we found many reflected phases. In this study, we attempted to reveal the inhomogeneous structure in detail by using data of an earthquake cluster in the shallower part of the crust.

After the normal moveout correction, we found the reflected phases in most of the observed seismogram from reflectors in depth range from 15 to 20 km depths under assumption of horizontal reflectors. The waves from the reflector deeper than 30 km depth, which is close to the plate interface, were also seen in some traces.

In order to improve the estimation of the location and the shape of the reflector, we developed a method that minimizes both residuals of travel time data and amplitude ones. Applying the method to the data at SIKH where the distinct phases are observed, we determined the reflector lying not on the plate boundary but near the hypocenter of the non-volcanic tremors. The estimated reflection coefficient implies that the reflector has high impedance contrast to the crustal material. However, the coefficient does not always reliable due to the large variance of data in the estimation. In further study, we should improve the estimation by adding new data set.

Keywords: the Bungo channel, slow earthquakes, amplitude data of reflect phases

The characteristics of the surface wave propagation for the 2011 off the Pacific coast of Tohoku earthquake

ARISUE, Maho^{1*}, KAWAKATA, Hironori¹, DOI, Issei¹

¹College of Science and Engineering, Ritsumeikan University

In the past decade or so, very dense arrays of strong ground-motion instruments such as the K-NET and the KiK-net have been developed across Japan by the NIED. These networks enable us to visualize the behavior of the seismic wave propagation from large earthquakes. Furumura et al. (2003) examined the seismic radiation and regional propagation characteristics during the 2000 Tottori-ken seibu earthquake (Mw6.6) by means of visualization of wave propagation using data recorded at the K-NET and KiK-net stations. Recovering broadband seismograms from short-period seismograms for the Hi-net data, Maeda et al. (2011) visualized the surface wave propagation for the 2007 Sumatra earthquake. They took into account not only amplitude information but phase information, and found the interference of two surface waves incoming from slightly different arrival directions. The visualization of wave propagation with phase information may have a great potential for revealing the details of wave propagation. In this study, we tried to visualize surface wave propagation with phase information for the 2011 off the Pacific coast of Tohoku earthquake. We used the acceleration waveform data recorded at 525 stations of the K-NET and 628 surface stations of the KiK-net. Considering the mean interval of these stations, we applied a bandpass filter from 0.05 Hz to 0.1 Hz to seismograms and integrated them into velocity waveforms. Then, we made snapshots every one second for each component, and combined them into animation. It was confirmed that some large wave packets concentrically propagated.

In time traces, wave packets with their maximum amplitudes propagated at an apparent group velocity around 3 km/s, which is equivalent to surface wave velocities for such a frequency band. These wave packets were radiated from the source region at ~50 s after the initial rupture, which implies that they were surface waves produced at the second large wave source. Focusing on the wave packets, we found a tear of a surface wave on snapshots at Tohoku region. In order to reveal the cause of this tear, we examined their particle motions. Before making particle motions, we corrected the installation azimuth of accelerographs when needed. From the particle motions, it was revealed that transverse components were predominant in the northeastern area to the tear, whereas radial components were predominant in the southwestern area. Hence, Love wave should be predominant in the northeastern area, and Rayleigh wave in the southwestern area. This result is consistent with theoretical radiation pattern of Love wave and Rayleigh wave (Lay and Wallace, 2002).

Acknowledgment: The strong motion records of K-NET and KiK-net (NIED) were used for the analysis. We thank Prof. Tomotaka Iwata and Dr. Kimiyuki Asano (DPRI, Kyoto Univ.) and Dr. Takuto Maeda (CIDIR, Univ. of Tokyo) who provided the helpful information.

Keywords: surface wave, visualization, the 2011 off the Pacific coast of Tohoku earthquake, radiation pattern

Seismic interferometry in exploration geophysics: a review from practical aspect

SHIRAISHI, Kazuya^{1*}

¹JGI, Inc.

This is a brief review of the seismic interferometry (SI) in an exploration geophysics. The SI has highly developed and become multifunctional in this decade. Many theoretical and application researches have been published. In a view point of the exploration, an interferometric redatuming from a controlled-source seismic observation is one of the most important use. For example, a walkaway VSP survey can be changed to a reflection survey with sources and receivers on a well, which could image vertical structures clearer than a conventional surface reflection survey. Additionally, extracting signals from a passive seismic data is also useful to estimate subsurface structures or rock properties. The ambient noise surface wave tomography is based on the SI technique to generating Green functions from passive seismic data. A pseudo reflection survey from local earthquakes has capability to profile regional subsurface structures using not only S-wave coda but also P-wave coda.

The basis of the SI is an amplitude summation at stationary points after phase shift by crosscorrelating the seismic traces of the data with many sources or of the long passive seismic data. I summarize key terms at four practical aspects for effective use.

[1] Seismic source

- (a) Controlled-source (air-gun, vibrator, dynamite, and so on)
- (b) Natural earthquake
- (c) Natural/artificial ambient seismic noise

[2] Method

- (a) Cross-correlation
- (b) Deconvolution
- (c) Multi-dimensional deconvolution
- (d) Cross-coherency
- (e) Convolution

[3] Function

- (a) Redatuming
- (b) Data interpolation/extrapolation
- (c) Signal extraction

[4] Objective

- (a) Reflection seismic imaging
- (c) Surface wave tomography / inversion
- (d) Rock property estimation
- (b) Data processing; signal enhancement, noise elimination

Keywords: seismic interferometry, exploration geophysics, controlled-source, redatuming, passive seismic, signal extraction

Discussion on the significance of seismic interferometry to estimate inclined layered medium

ZHANG, XINRUI^{1*}, MORIKAWA, Hitoshi¹

¹Tokyo Institute of Technology

In a case where the spatial auto-correlation (SPAC) method (Aki, 1957) is used to estimate phase velocity, the underground structure is assumed to be horizontal layers, which confine the estimation accuracy. On the other hand, according to seismic interferometry theory, in an elastic medium the Fourier transform of azimuthal average of the cross correlation of motion between two sites is proportional to the imaginary part of the exact Green's function between these site (SanchezSesma, 2006). It means that it is possible to introduce the concept of Green's function to SPAC method because we calculate out many Fourier transform of cross correlation as intermediate results. Actually, there was a successful example combining the H/V method and seismic interferometry by Sanchez-Sesma before. Hence, we propose a method combining the conventional SPAC method and the concept of Green's function, which is known as the seismic interferometry in frequency domain. It is expected to obtain more accurate model of ground structure like inclined layered medium.

Afterwards, we take the ratio of power spectra of center of the array and one site on the circular array to calculate the ratio of imaginary part of Green's functions of these sites. Therefore, in practical observations, we calculate the ratio of power spectra of center of the array and one site on the circular array to obtain the ratio of imaginary part of Green's function of these sites. The ratio of Green's function can be obtained without any additional calculation, because the power spectra are just intermediate results in the process of the SPAC method. Then, we can modify the structure, such as the thickness of each layer, to satisfy the ratio of the imaginary part of Green's function. Therefore, more detailed information of ground structure such as inclination can be obtained from the combination of the SPAC method and seismic interferometry. The condition to satisfy this method is the diffusive wavefield.

In order to examine the validity of the proposed method, we do the sensitivity analysis and numerical simulation. In sensitivity analysis, we calculated the ratio of imaginary part of Green's function between varieties of 2-layered models with different thicknesses and see how the ratio varies with the thickness. Through 36 comparisons between 36 pairs of models, it is found that the shallower ground structure is, the more sensitive the ratio is with respect to the thickness. In numerical simulation, we use certain finite difference method-based program to simulate the diffusive wavefield by random sources and see how the ratio of power spectra matches the ratio of imaginary part of Green's function. Through 12 comparisons, it is found that the critical frequency which gives the peak value of ratio matches quite well. Through error analysis, it is found that the shallower structure is, the smaller error is.

In conclusion, the validity of proposed method is primarily confirmed. It has best accuracy in estimating shallow structure.

Keywords: Seismic Interferometry, Green's function, Cross spectrum, layered medium, SPAC method

Structure imaging by cross-correlation of local earthquake records: Simulation on source distribution and artifacts

TSUJI, Takuma¹, WATANABE, Toshiki^{1*}

¹Nagoya University

Seismic interferometry synthesizes a seismic response (often called a virtual shot record) that would be recorded at one receiver as if there was a source at the other receiver location by cross-correlating the seismic traces observed at two receivers. This operation is equivalent to retrieving surface-related reflections. By applying the method to natural local earthquake records observed at a dense receiver array, we can simulate a seismic reflection survey of crustal scale without any artificial sources. Subsurface imaging can be accomplished by adopting highly advanced data processing and imaging technology of reflection seismology to the virtual shot records. In order to synthesize virtual shot records with sufficient accuracy, the assumption of seismic interferometry that sources are distributed densely and uniformly in space should be satisfied. However, the lopsided distribution of the hypocenter of natural earthquakes may result in lowering signal-to-noise ratio of the synthesized virtual shot records and generating artifacts on the seismic profiles.

In this study, numerical experiments were conducted regarding the accuracy and reliability of seismic interferometry using local earthquake records for imaging crustal structure. Following three points were investigated: 1) the influence of lopsided source distribution of natural earthquakes on the virtual shot records and the imaged profiles, 2) the source-receiver geometry that is effective for imaging the target crustal structures, and 3) the origin of artifacts and the way to suppress them. A 2-D model simulates subsurface structures beneath Tokai region in central Japan including crustal structures and subducting oceanic plate. The model is defined by 100 km x 50 km in the horizontal and the vertical direction. The survey line is subparallel to the convergence direction of the Philippine Sea plate. Using the sources distributed in shallow crust, deeper crust, oceanic slab and continental slab, 125 SH-wave seismograms were calculated in total.

As the results, the accuracy of the virtual shot records improves as the number of the sources (earthquakes) increases. The quality of the records depends on the spatial relation among the sources, the receivers and target reflector. Particular combinations of the sources and the receivers were found effective to synthesize virtual reflection records with fewer sources. Such source-target-receiver geometry is consistent with the concept of stationary phase that has been theoretically derived by previous studies. Imaging the target structures is possible as long as the geometry is retained even if the earthquake sources are not necessarily distributed uniformly, nor the range and number of the receivers are limited. The depth-migrated profile obtained using earthquakes distributed in the continental slab and oceanic slab shows good illumination to the target structures from shallow to deep area. The study shows that some particular type of artifacts are dependent on the source depth. Such depth-dependent artifacts in the migrated profiles can be suppressed by increasing the source depth variation.

Keywords: seismic wave, scattering, interferometry, crustal structure, imaging, simulation

Seismic anisotropy from the interferometric analysis of seafloor records

TAKEO, Akiko^{1*}, NISHIDA, Kiwamu¹, ISSE, Takehi¹, KAWAKATSU, Hitoshi¹, SHIOBARA, Hajime¹, SUGIOKA, Hiroko², SUETSUGU, Daisuke², ITO, Aki², KANAZAWA, Toshihiko¹

¹Earthquake Research Institute, the University of Tokyo, ²IFREE, JAMSTEC

The seismic interferometry is now widely applied to the ambient noise source in continental regions [e.g. Shapiro et al., 2005] and in an oceanic region, the East Pacific Rise (EPR). Harmon et al. [2007] used the vertical components of ocean bottom seismometers deployed in the EPR region for analyzing the Rayleigh wave. In this study, we apply similar method to the three-component record of broadband ocean bottom seismometers (BBOBSs) deployed in (i) the Shikoku Basin (SB) region by the Stagnant Slab Project and (ii) the French Polynesia (FP) region by the TIARES (tomographic investigation by seafloor array experiment for Society hotspot) project. The spacing of the stations is about 100-200 km. For each region, we obtain the phase velocities of (i) the fundamental mode of Rayleigh wave (14-29 sec), (ii) the first higher mode (5-11 sec) of Rayleigh wave, and (iii) the fundamental mode of Love wave (2.5-14 sec) by the SPAC method [Aki, 1957]. The propagation of the first higher mode of Rayleigh wave appears (i) in the horizontal component (7-11 sec) for the SB region, (ii) in both vertical and horizontal components (5-10 sec) for the FP region, and (iii) in the vertical component (3.5-7 sec) for the EPR region. The difference between EPR and SB regions can be interpreted by the difference between the periods of analysis. To account for the difference between FP and SB regions, on the other hand, we need to discuss other causes such as the difference of sedimental thickness and the source intensity of ambient noise.

By further using the phase velocities measured by array analysis of teleseismic waveforms, we obtain one-dimensional radially anisotropic structures at the uppermost mantle beneath SB and FP regions. Both structures show that the velocity of horizontally propagating shear-wave with horizontal polarization (V_{SH}) is 3 % higher than that with vertical polarization (V_{SV}). We also focus on the azimuthal anisotropy. By the analysis of teleseismic waveforms, the phase velocity (30-50 sec) beneath the FP region is revealed to depend on the back-azimuth, τ , in a form with $\sin(2\tau)$ and $\cos(2\tau)$. We obtain consistent pattern at shorter periods (20-30 sec) by the ambient noise interferometry with assuming homogeneous structure beneath the array. We will discuss the effects of inhomogeneous structure and inhomogeneous source distribution, and will estimate the azimuthal dependence at shorter periods.

Keywords: Seismic interferometry, ambient noise, anisotropy

Detecting Temporal Evolution of the Subsurface Structure Associated with the 2011 Tohoku Earthquake Using Ambient Noise

OHMI, Shiro^{1*}

¹Disaster Prevention Research Institute, Kyoto University

Temporal variation of the seismic wave velocity in central - eastern Japan associated with the 2011 off the Pacific coast of Tohoku Earthquake was preliminarily investigated using ambient seismic noise. Vertical components of the continuous seismic waveforms recorded by the seismic networks operated by NIED (Hi-net), JMA (Japan Meteorological Agency), and DPRI (Kyoto Univ.) were used for analysis. Cross-correlation functions (CCF) of 0.1Hz - 1.0Hz and 1.0 Hz - 2.0Hz frequency bands among station pairs whose separations are less than 120 km are calculated. CCFs from January 2011 to June 2011 are calculated and the temporal change of the lag times of the Rayleigh wave arrivals are compared. Auto-correlation functions (ACF) of 2.0Hz - 10.0Hz frequency band are also calculated for each single day for each station. Preliminary result of the CCFs show that the regions of velocity decrease are observed along the Pacific coast in the NE Japan, where experienced the strong ground motion at the mainshock, especially in the 0.1Hz-1.0Hz frequency band. However, CCFs in the Chubu district, where experienced no strong ground motion, exhibit no clear velocity changes in the CCFs of both frequency bands. Theoretical static strain change associated with the mainshock in the studied area is more than 10^{-5} large and velocity change associated with strain change was expected. The observed facts probably indicate that lagtime change in CCFs are caused by strong ground motion rather than strain changes. On the other hand, ACFs at several stations in both NE Japan and Chubu district clearly exhibit lagtime change that indicate subsurface velocity decrease. Observed feature in the ACFs in rather remote area are likely caused by not direct effect of strain change but indirect effect such as ground water level change caused by strain change, which is previously reported by Savage and Ohmi (2010, AGU FM).

Keywords: 2011 off the Pacific Coast of Tohoku Earthquake, Cross-correlation of ambient noise, Temporal change of subsurface structure

Seismic velocity reduction after the 2011 Tohoku-Oki earthquake using repeating earthquake

TAKAGI, Ryota^{1*}, UCHIDA, Naoki¹, OKADA, Tomomi¹, HASEGAWA, Akira¹

¹RCPEV, Graduate School of Sci., Tohoku Univ.

We used repeating earthquakes data to estimate velocity change in the overriding plate from Kanto to Hokkaido region associated with the 2011 M9.0 Tohoku-Oki earthquake. Because repeating earthquakes occur as the repeating slips on the same patch on the Pacific plate with the same source mechanism at different time, waveform data of repeating earthquake is suitable for detecting temporal change in subsurface structure.

First, we performed the moving window cross-spectral analysis for vertical component of seismograms of 54 repeating earthquake sequences. Before the analysis, data were filtered with a band-pass window of 1-10Hz. To align the arrival time of P-wave, we used cross-correlation for the P-wave in a 5-sec time window centered by computed arrival time according to the 1-D structure of JMA2001 [Ueno et al., 2002]. After aligning the P-wave, we computed cross-spectra for the moving time window with a length of 2-sec at every 0.1 sec to measure time-shift between a pair of repeating earthquakes. For pairs of repeating earthquakes that are both before the 2011 Tohoku-Oki earthquake, the time-shifts are almost zero from direct P-wave to S coda. In contrast, for pairs before and after the earthquake, the time delay gradually increases with lapse time. This result indicates the velocity decrease after the 2011 Tohoku-Oki earthquake. For example, at a Hi-net station (N.KAKH) near the Oshika Peninsula, the time delay linearly increase just after P arrival to about 0.02 sec in 40 sec for an repeating earthquake sequence of which epicentral distance is 232 km. From the slope of the time delay, the amplitude of velocity reduction is about 0.05 %. The time delay does not always show linear increase with lapse time. The behavior of the time delay seems to depend on the location of event-station pair, which means heterogeneous distribution of velocity change.

Secondly, we only used the information of direct part of a seismogram to estimate the location of the velocity reduction. This is because the time-shift in direct part simply reflects the velocity change only along a direct ray path in contrast to the complex path of coda waves. One problem for using the direct part is an error of origin time. However, because the errors of origin times are identical at all stations, we can estimate the relative delay in many stations for a pair of repeating earthquakes that can be used for the estimation of the spatial variation of time-shift in direct part. In order to evaluate the spatial variation of time-shift for a pair of repeating earthquakes, we subtract a median of the time-shifts of direct P-wave for all stations from the time-shifts of P and S-wave at every station. From the result of all repeating earthquake sequences, we can recognize clear relative time-delay of about 0.01 sec for S-wave by in both the fore-arc and back-arc region from Fukushima to Iwate prefecture. Furthermore, we estimated spatial distribution of the S-wave velocity change by a tomographic inversion method using the time-shift as input data. In this inversion method, we solved slowness changes in three-dimensional blocks and the errors of the origin times simultaneously. The ray path is computed by using the JMA2001. As a preliminary result, a major slowness increase (velocity decrease) of 0.05 % is estimated in upper crust in Tohoku region from Fukushima to Iwate prefecture. The receiver-side velocity reduction can be interpreted as the damage in near surface due to strong motion or the static stress change due to coseismic slip on the fault.

Temporal change in shallow subsurface structure detected by coda wave interferometry

YAMAMOTO, Mare^{1*}

¹Geophysics, Science, Tohoku University

Understanding of shallow subsurface structure is important for prediction of earthquake strong motion, elucidation of transport process of underground water, and so on. On the other hand, recent progress in theoretical and observational researches on seismic interferometry reveal the possibility to detect subtle ($< 1\%$) change in subsurface seismic velocity. This high sensitivity of seismic interferometry to the medium properties may thus be one of the important ways to directly observe the time-lapse behavior of shallow crustal structure. In this presentation, we report the long-term variation of subsurface velocity and co-/post-seismic change associated with the 2011 off the Pacific coast of Tohoku earthquake revealed by applying the coda wave interferometry to the NIED KiK-net data.

In this study, we use the acceleration data recorded at KiK-net stations operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). Each KiK-net station has a borehole whose typical depth is about 100m, and two three-component accelerometers are installed at the top and bottom of the borehole. To estimate the very shallow subsurface velocity between two sensors and its temporal change, we apply the coda wave interferometry (e.g., Schuster et al., 2004). Although, recently, Nakata and Snieder (2012) apply the deconvolution method to KiK-net data, in this study, we adopt cross-correlation method to obtain stable results. In the data processing, we select 1005 earthquakes that occurred between January 2004 and December 2011, and compute the cross-correlation function between surface and downhole records using five 2sec-long successive time windows starting from twice the S-wave travel time for each earthquake. Because the seismic coda wave, which appears after the body wave arrivals, are considered to be composed of multiply-scattered waves, the ensemble average of cross-correlation functions can be regarded as the Green function between two sensors. From the averaged cross-correlation functions, we estimated the near-surface velocity at frequency bands of 2-4, 4-8, 8-16Hz, and we also measure the temporal velocity change using time-stretching method.

Each obtained averaged cross-correlation function shows a clear wave packet traveling between borehole sensors, and its travel time is almost consistent with that of S-wave calculated from the borehole log data. During the period we analyze, two remarkable temporal variations are observed in the averaged cross-correlation functions: One is the co-/post-seismic change associated with large earthquake, especially the 2011 off the Pacific coast of Tohoku earthquake occurred in March 2011, and another is seasonal/annual variation. It has been widely known that the strong motion due to large earthquakes causes rapid decrease and long-term recovery of shear wave velocity (e.g., Sawazaki et al., 2009). Our results also show the similar behavior with sudden velocity decrease of typically about 5-15% and gradual recovery which still continues at the end of 2011. In contrast, the observed seasonal/annual variation is about one order of magnitude smaller than the co-/post seismic change. Obtained near-surface velocity is smallest in the summer season, and the fraction of velocity change shows negative correlation to the precipitation, which is indicative of the effect of underground-level and corresponding change of effective pore-pressure at the shallow subsurface. These results demonstrate that the seismic interferometry is a useful tool to monitor shallow subsurface structure.

Acknowledgment: We used KiK-net data provided by the National Research Institute for Earth Science and Disaster Prevention.

Keywords: Seismic interferometry, Shallow subsurface structure, Temporal change