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

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

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

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

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

SSS027-07 Room:105 Time:May 22 12:15-12:30

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

Japan Geoscience Union Meeting 2011
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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

Japan Geoscience Union Meeting 2011
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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

Tatsunori Ikeda[1*], Toshifumi Matsuoka[1]

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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

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

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

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

SSS027-11 Room:105 Time:May 22 14:45-15:00

Time reversal of seismic waves in Izu peninsula

Toshiaki Kikuchi[1*], Koichi Mizutani[2]

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

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

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

Japan Geoscience Union Meeting 2011
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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

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

SSS027-14 Room:105 Time:May 22 15:30-15:45

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

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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

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

SSS027-15 Room:105 Time:May 22 15:45-16:00

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

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

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

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

SSS027-17 Room:105 Time:May 22 16:30-16:45

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

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It is well known that the double-planed deep seismic zone is observed within the Pacific slab subducting beneath the north-eastern 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 inter-plate earthquakes.

Keywords: oceanic lithosphere, intraplate earthquake, S coda wave

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

SSS027-18 Room:105 Time:May 22 16:45-17:15

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

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

SSS027-19 Room:105 Time:May 22 17:15-17:30

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

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

SSS027-20 Room:105 Time:May 22 17:30-17:45

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

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

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

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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

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

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

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

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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