High-performance computing for understanding seismic sources

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Slip inversion using seismic waveform data has become a popular method to investigate the source process of large earthquakes. This is fundamental information to understand physical process related to earthquake rupture and to assess the possibility of future earthquakes. However, the results usually include large errors, which is mainly due to the limitation of our ability to compute seismic wave field between the source and stations. There are actually two problems: the lack of information about underground structure and technical difficulty to solve elasto-dynamic equations in complex structures. The latter can be tackled with state-of-art high-performance computing.

In practical data analyses of earthquake rupture process, the availability of data is limited to avoid the source of large model errors. We often assume, without guarantee, that near-field strong-motion records are well approximated by 1-D layered structures, and that PREM and the ray theory are sufficient for teleseismic data in the hypocentral distance range from 30° to 100°. Data between 2° and 30° were not used, usually. These data are plenty and have sufficient signal-to-noise ratio, but the wave propagation is complex and information about structure is insufficient in this intermediate range.

A breakthrough to this problem might be provided by the combination of high-performance computing and high-resolution structural information. Several studies have attempted to compute seismic wave fields with complex structural information. Tsuboi et al. (2016) calculated seismic waves up to 1.2 s, using a global 3D heterogeneous model. Ichimura et al. (2016) computed deformation of a space of about 3000 km, with a realistic underground structure around Japan, and suggested that similar computation for seismic field is also possible. Seismic waveforms using realistic Earth structure will become popular in near future.

Although seismic wave field in global heterogeneous Earth is currently too expensive, significant improvement is expected just by introducing realistic shape of subducting slab and seafloor topography. The shape of subducting slab is clearly resolved around Japan. However, in some subduction zones, the uncertainty of hypocenter locations is too large to image slab shape. Near-filed seismic stations are rare, though many stations are available in the intermediate range. In such a region, theoretical waveforms calculated considering slab and see-floor topography may be useful.

In medium scale, and in a well-studied region with dense observation networks, like Japan, more detailed study including a complex underground structure may be meaningful. It would be helpful to know how the result of seismic tomography and receiver function analyses improve the resolution of the seismic source imaging. Starting from the low-frequency limit, i.e. static deformation, we will be able to model complete seismic wave field around Japan, which will reduce the uncertainty of seismic source models.

Very informative, but challenging data for seismic source imaging are the records of ocean bottom seismograms, which have been installed in many places around Japan. In addition to complexity due to seafloor topography and water layer, appropriate modeling of thick sediment layers is necessary to explain complicated observed seismograms. This was a realistic problem when an earthquake of Mw 6.5 occurred in the Kumano-Nada region on April 4, 2016. Because of our inability to model seismic waves in this region, we could not distinguish whether the earthquake was inter- or intra-plate earthquake, immediately after the earthquake. In this region, active tectonic tremors and slow slip events were observed by DONET1, and underground structure is relatively well-known. If accurate theoretical waves are available using high-performance computing, these are helpful for studying both large disastrous earthquakes and

diverse slow earthquakes.

Keywords: Earthquake source process, Theoretical waves, subduction zones

Moment tensor inversion of 2016 Southeast Off Mie earthquake via numerical simulation using a three-dimensional velocity structure model

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On April 1, 2016, Mw 5.8 earthquake (2016 Southeast Off Mie earthquake) occurred near the epicenter of the 1944 Tonankai earthquake. To investigate seismic activity around the Tonankai area, source mechanism of the 2016 Off Mie earthquake should be required. However, since seawater, accretionary prism (low-velocity sediments) and subducting Philippine Sea plate exist beneath the epicenter region, it is difficult to obtain accurate source mechanism via conventional one-dimensional analysis (Nakamura et al. 2015; Takemura et al. 2016). Thus, in this study, we conduct moment tensor (MT) inversion using Green’s function via finite-difference method (FDM) simulations of seismic wave propagation in a 3D heterogeneous velocity structure model (hereafter, simply called “3D Green’s function”). Recent developments of computer system and calculation technique enable us to evaluate 3D Green’s functions practically.

The model of 3D simulation and technical details are same as in Takemura et al. (2016). The 3D heterogeneous velocity structure, including topography, sedimentary layer, crust and subducting Philippine Sea plate, is referred from the Japan Integrated Velocity Structure Model (JIVSM; Koketsu et al., 2012). By using displacement waveforms for periods of 30-100 s, we estimate an MT solution of this earthquake. The result with minimum variance reduction is the optimal solution with source mechanism and centroid depth.

The optimal result is characterized by a low-angle dipping faulting at a depth of 11 km, where the upper surface of the Philippine Sea plate exists closely. Obtained result reproduced not only long-period displacement waveforms but also polarity of short-period (˜ 2 s) *P* waves. Observed *P*-first arrivals at land stations show apparent velocity of approximately 7 km with up polarizations, which propagate along oceanic Moho of the Philippine Sea Plate

Since our FDM simulations evaluated seismic wave propagation for periods longer than 1.4 s, calculation of one element moment tensor at a certain depth requires 1.3 TB of computer memory and a wall-clock time of 1.5 hours by parallel computing using 256 nodes (1,024 cores) of the Earth Simulator.

Acknowledgement

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

Keywords: Nankai Subduction zone, Earthquake, three-dimensional velocity structure, Moment tensor inversion, Numerical simulation of seismic wave propagation

Global seismic wave computation on the K computer

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We present high-performance simulations of global seismic wave propagation with an unprecedented accuracy of 1.2 seconds seismic period for a realistic three-dimensional Earth model by using the Spectral-Element Method on the K computer. Our seismic simulations use a total of 665.2 billion grid points and resolve
1.8 trillion degrees of freedom. To realize these large-scale computations, we optimize a widely used community software code to efficiently address all hardware parallelization, especially thread-level parallelization to solve the bottleneck of memory usage for coarse-grained parallelization. The new code exhibits excellent strong scaling for the time stepping loop, i.e. parallel efficiency on 82,134 nodes relative to 36,504 nodes is 99.54%. Sustained performance of these computations on the K computer is 1.24 petaflops, which is 11.84% of its peak performance. The obtained seismograms with an accuracy of 1.2 seconds for the entire globe should help us to better understand rupture mechanisms of devastating earthquakes.

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Keywords: seismic wave ppropagation, spectral element method, K computer

Modeling crustal deformation with mechanical models and geodetic data

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Over the past two decades, development of dense and continuous geodetic networks makes it possible to capture transient crustal deformation at high resolution in both space and time. A primary example of geodetically observed transient deformation in plate boundary zones is postseismic deformation following large earthquakes. Postseismic deformation observed at the surface reflects mechanical properties of faults, crust, and upper mantle. Thus mechanical models that are designed to fit the observed postseismic deformation may provide insights into these mechanical properties at depth.

Two primary processes that are responsible for postseismic deformation are viscoelastic relaxation of coseismic stress changes in the upper mantle and afterslip on the plate interface surrounding the coseismic rupture. Viscoelastic relaxation is governed by the rheological properties of the crust and upper mantle, while afterslip is governed by frictional properties of the plate interface. Both of the processes are initiated by stress changes due to coseismic slip. Therefore, geodetic observations of postseismic deformation could be used to constrain the frictional properties on the plate interface and upper mantle rheology.

In this talk, we present a three-dimensional coupled model of stress-driven frictional afterslip and viscoelastic stress relaxation for postseismic deformation following the 2011 Mw9.0 Tohoku-oki earthquake. In this model, we assume that afterslip is governed by a velocity-strengthening friction law that is characterized with a friction parameter (a-b) σ. Viscoelastic relaxation of the upper mantle is modeled with a biviscous Burgers rheology that is characterized with the steady-state and transient viscosities. We calculate the evolution of afterslip and viscoelastic relaxation using an assumed coseismic slip model as the initial condition.

We examine the effects of the friction parameters, mantle viscosities, elastic thickness of the slab and upper plate, and coseismic slip distribution on the model prediction and find that these parameters significantly affect the predicted surface postseismic displacements. Postseismic deformation following the 2011 Tohoku-oki earthquake has been captured by both on-land GNSS and seafloor GPS/Acoustic networks. We thus explore the range of the model parameters that can fit the postseismic observations. At this moment, we employ a trial-and-error approach to estimate the parameters. However, given the complexity of the model and the abundance of the observations, it is difficult to completely characterize uncertainties and trade-offs between the parameters by the trial-and-error approach, although such information is critically important for better understanding of the postseismic processes. A more complete model that fully accounts for uncertainties and trade-offs between the parameters could be obtained by building posterior probability distributions of the parameters using Bayesian inverse methods. Such Bayesian methods, however, require many forward calculations and thus it would not be easy to implement those methods with our model within a realistic computation time. It is therefore essential to reduce the computational costs of the forward model simulations and Green’s functions calculations, as well as to develop more efficient Bayesian methods to estimate posterior probability distributions, in order to develop more advanced models of geodetically observed postseismic deformation.

Keywords: crustal deformation, mechanical model, geodetic data

A Bayesian hierarchical model for a seismic source inversion

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The earthquake rupture processes of earthquakes are diverse reflecting the heterogeneous distribution of fault constitutive properties and stress, and fault geometry. Kinematic source parameters constrained by data provide the information related to the fault rupture dynamics and statistical properties of rupture processes. It is also used as an input for the calculation of Coulomb stress changes, the calculation of tsunami waveforms and the estimation of slip deficit.

A source inversion analysis using spatio-temporal displacement field data is able to be formulated as a discrete linear inverse problem when the Green function and the source fault are known. However, it is difficult to calculate an accurate Green function due to the lack of the accurate Earth structure model. Effects of the uncertainty of the Green function on the result of an inverse analysis increases with the improvement of the quality and the increase of the amount of data. Some of previous studies approximated the effects of the uncertainty of the Green function by introducing a new correlated and/or uncorrelated error term, which is added to data. The approximation, however, fails to capture important characteristics of the effects of the uncertainty of the Green function such as peak shift and heavy tails of the likelihood function under the uncertainty of the Green function.

To address the issue, we propose a hierarchical Bayes model for a seismic source inversion analysis. The model is targeted to the multi-data analysis with the multi-time-window finite fault source parameterization. We assume Gaussian observation errors and a Gaussian prior distribution for model parameters. In the model, a Green function is treated as a realization of a random variable G. We approximate the posterior distribution of the model parameters by approximately marginalizing G and the hyperparameters, which control the variance of the prior distribution of the model parameters and the variance of the observation errors. The marginalization of the hyperparameters is approximated by plugging in the maximum a posteriori hyperparameters given G. The marginal likelihood function for G is approximated by the Laplace approximation to the conditional posterior distribution of the hyperparameters given G. The marginalization of G is approximated by a Monte-Carlo integration method. The precisions of the two approximations are able to be improved by increasing the amount of data and number of samples of G.

We applied the method to synthetic data for far-field vertical P-wave displacement waveforms. We set a 1-D velocity structure consisting of two layers at the source region. We set the P-wave velocity, the S-wave velocity and the density of each layer to follow uniform distributions. We also set the depth of the interface of the layers to follow a uniform distribution. We made the true velocity structure by randomly sampling the 25th percentile point or the 75th percentile point for each random variable. We drew thousands of velocity structure samples from the probability density function (PDF), and then calculated the corresponding Green functions. For reference, we also conducted a conventional inversion, which used only a reference velocity structure (50th percentile point of the PDF of the velocity structure). We found that the conventional inversion result suffers artifacts especially at the later shallow part of the rupture process, while the result with the proposed method does not suffer from the artifact. Note that the mitigation of the artifact was not possible with the simple mean-of-the-posterior-mean approach. We also found increase of the Variance of the posterior distribution of the potency due to the marginalization of G.

The method could be a reasonable counterpart for the recent increase of Bayesian approaches with Monte-Carlo methods to study velocity structures.

Keywords: Bayesian hierarchical model, Seismic source inversion

Creating future of solid Earth science with HPC: Discussion

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Due to the development in computer science and computational science, large-scale or many times forward simulations and/or inversion analyses have become available recently. In solid Earth science, large-scale seismic wave propagation and crustal deformation with high fidelity model based on high resolution observation data have been demonstrated; uncertainty in crustal deformation caused by material properties and structures can be investigated based on many-time calculations for different material properties and structures; fault slip inversion analyses for non-Gaussian error distribution, etc. Thus, we invited researchers who are facing problems in forward simulations and inversion analyses. In this talk, we will discuss how to solve such problems by the collaboration between computer & computational sciences and solid Earth science.

Keywords: high performance computing, high fidelity model, data analysis