Study on rupture processes of large interplate earthquakes estimated by fully Bayesian source inversions using multi period-band strong-motion data –The 2011 Tohoku-oki and the 2011 Ibaraki-oki earthquakes–

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Contents

1 Introduction

The source process of the 2011 Tohoku-oki earthquake (M_w 9.1) has predominantly been investigated by source inversions using long-period (> 10 s) seismic waveforms and source modeling using short-period (0.1–10 s) seismic waveforms. Based on a comparison of these results, it has been suggested that this earthquake had a period-dependent spatial variation in its seismic-wave radiation. In order to investigate this period-dependent seismic radiation and the broadband source characteristics for this event from a perspective of the generation of broadband seismic motion in the period-band from 5 s to 100 s, this study attempted to construct spatiotemporal slip models for the 2011 Tohoku-oki earthquake in multi successive period-bands and discussed the spatial difference of the slip velocity function for each period-band. Using the same procedure, this study also investigated the broadband source characteristics of the 2011 Ibaraki-oki earthquake (M_w 7.9) so as to compare the rupture behaviors of these earthquakes.

Although ABIC (Akaike's Bayesian Information Criterion) based kinematic source inversions with multi-time-window methods have often been used in the estimation of spatiotemporal slip models, there are cases where conventional ABIC-based source

inversions do not work well in the determination of hyperparameters when a non-negative slip constraint is used. In order to overcome this problem, this thesis presented a newly-developed source inversion method that introduces a fully Bayesian method to the kinematic source inversion with the multi-time-window method.

2 ABIC-based source inversion with the multi-time-window method

The conventional ABIC-based source inversion method using the multi-time-window method was reviewed. Then, this source inversion method was applied to the 2011 Ibaraki-oki earthquake and the source process of this event was investigated using strong-motion and geodetic data. The derived source model demonstrates that the rupture propagation of this event was stopped by a subducted seamount and the Philippine Sea plate.

3 Fully Bayesian source inversion with the multi-time-window method

A fully Bayesian source inversion with the multi-time-window method was developed. The Metropolis algorithm, which is one of the Markov chain Monte Carlo methods, was used to directly obtain the probability distributions of the model parameters and hyperparameters. These probability distributions are useful for simply evaluating the uniqueness and reliability of the derived model. This newly-developed method was applied to the 2011 Ibaraki-oki earthquake to demonstrate its usefulness. The problem with the conventional ABIC-based method regarding the hyperparameter determination, as mentioned in Chapter 1, appeared in the spatiotemporal source inversion and it was demonstrated that the use of the fully Bayesian source inversion method can overcome this problem.

4 Construction of source models in multi period-bands for the 2011 Ibaraki-oki earthquake

A construction methodology for spatiotemporal slip models in multi period-bands using strong-motion data, 3D Green's functions, and the newly-developed fully Bayesian source inversion was proposed. The validity of the 3D velocity structure model used for the 3D Green's functions was confirmed through waveform comparisons for M ~ 6 events. The resolution of the source inversion method introduced in this thesis and the significance of the use of 3D Green's functions were ascertained through synthetic tests.

Subsequently, this multi period-band source modeling was applied to the 2011 Ibaraki-oki earthquake; source models for this event were constructed in three successive period-bands (5–10 s, 10–25 s, and 25–50 s). The estimated rupture process

in the period-band of the 5–10 s differs from those estimated in the period-bands of 10–25 s and 25–50 s. The source models in period-bands of 10–25 s and 25–50 s have large slips in the shallow area south and southeast of the hypocenter, while large slips for the source model in the period-band of 5–10 s are located in the deep area approximately 30 km west of the hypocenter. These results indicate that the 2011 Ibaraki-oki earthquake had an along-dip variation in its seismic radiation.

5 Construction of source models in multi period-bands for the 2011 Tohoku-oki earthquake

Spatiotemporal slip models for the 2011 Tohoku-oki earthquake were constructed in four successive period-bands (5–10 s, 10–25 s, 25–50 s, and 50–100 s) using the multi period-band source modeling proposed in Chapter 4. A comparison of the source models estimated for the different period-bands indicated that the shallow off-Miyagi region, which had a huge slip (approximately 30 m), strongly radiated long-period (50–100 s) waves but weakly radiated relatively short-period (5–25 s) waves. Two ruptures that occurred 40 s apart but in the roughly identical area were found in the deep off-Miyagi region. The twice ruptures were observed in all the analysis period-bands, indicating that the deep off-Miyagi region radiated not only short period (5–25 s) but also long-period (25–100 s) seismic waves during the 2011 Tohoku-oki earthquake. In addition, a difference in the dominant period of the seismic-wave radiation between the twice ruptures was discovered; the radiation of long-period (25–100 s) waves in the second rupture was stronger than in the first rupture, whereas the radiation of the relatively short-period (5–25 s) waves in the first rupture was comparable to or slightly stronger than in the second rupture. The difference in the rupture extent between the twice ruptures indicates that it was caused by the rupture of the hierarchical asperity.

6 Discussions

The similarities and differences in seismic radiation between the 2011 Tohoku-oki and the 2011 Ibaraki-oki earthquakes were discussed. It was shown that the seismic radiation for these earthquakes was segmented along the dip direction: short- and long-period seismic waves were predominantly radiated from the deep and shallow regions, respectively. However, this study also revealed that the twice ruptures of the 2011 Tohoku-oki earthquake in the deep off-Miyagi region radiated not only short-period (5–25 s) but also long-period (25–100 s) seismic waves. This implies that the properties of the seismic radiation differ from earthquake to earthquake. This is also supported by previous studies which have noted different seismic radiation

properties among other large interplate earthquakes in northeast Japan. In order to understand the spatial variation in seismic radiation in this region, the multi period-band source modeling should be applied to the other large interplate earthquakes in northeast Japan. Potential future works following on from the source-process analysis presented in this thesis were also discussed.

7 Conclusions

This thesis proposed a methodology for the construction of source models in the multi period-band as well as the development of the fully Bayesian source inversion using the multi-time-window method and the introduction of 3D Green's functions. Using this methodology, this study revealed the broadband source characteristics for the 2011 Tohoku-oki and the 2011 Ibaraki-oki earthquakes. The results indicate that the seismic radiations for both earthquakes had along-dip variations: short- and long-period seismic waves were predominantly radiated from deep and shallow regions, respectively. However this study also revealed that the twice ruptures of the 2011 Tohoku-oki earthquake in the deep off-Miyagi region radiated not only short period (5–25 s) but also long-period (25–100 s) seismic waves. This indicates that although the concept of the along-dip segmentation of seismic radiation, which had been proposed in previous studies, can explain the rough feature of the 2011 Tohoku-oki earthquake's seismic radiation, the actual seismic radiation and rupture phenomena during the 2011 Tohoku-oki earthquake are more complex than expected and further research is required.

Further applications of the methodology proposed in this thesis to other earthquakes are expected to contribute to the understanding of the occurrence and growth mechanisms for large interplate earthquakes, and to investigations of variations in their seismic radiation properties. In order to reveal the causes of the spatial variation in seismic radiation, it is necessary not only to investigate the detailed source processes of interplate earthquakes but also to obtain the knowledge of earthquake ruptures through dynamic simulations and to integrate the kinematic and dynamic earthquake information.