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Source model of the 2011 Ibaraki-oki earthquake by the empirical Green's function method using strong-motion data

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The 2011 Ibaraki-oki (M_w 7.9) earthquake occurred off the east coast of the Kanto region, the south-eastern part of Japan at 15:15 on 11 March 2011 (JST). It is the largest aftershock of the 2011 Tohoku earthquake (M_w 9.1) which occurred approximately thirty minutes before this event. Kubo *et al.* (2012) estimated the kinematic source-rupture process of the 2011 Ibaraki-oki earthquake by jointly analyzing strong-motion data (0.2-0.02 Hz) and static displacements obtained from GPS data. In this study, we estimate the source model composed of strong motion generation area (SMGA, Miyake *et al.*, 2003) for the 2011 Ibaraki-oki earthquake based on modeling of broadband strong-motion data (0.1-10 Hz) using the empirical Green's function (EGF) method, and compare it with the source model of Kubo *et al.* (2012)

The strong-motion records of the 2011 Ibaraki-oki earthquake shows that several seconds of small amplitude arrival followed by the main rupture phase. This indicates that there was an initial rupture during the 2011 Ibaraki-oki earthquake. Therefore we assume a source model that the rupture of SMGA occurred as main rupture several seconds after the initial rupture started at hypocenter.

The location of the rupture starting point of SMGA and the delay time of SMGA are estimated after the procedure of Takenaka *et al.* (2006) and Suzuki and Iwata (2007) using the arrival-time differences between the initial and main rupture phase. The source parameters of SMGA (spatial dimensions, rise time, rupture starting subfault, and rupture propagation velocity) are estimated based on broadband strong ground motion simulations using the empirical Green's function method (Irikura, 1986). The best set of the parameters is estimated by minimizing the sum of the residuals of the acceleration envelope and displacement waveform fitting (Miyake *et al.*, 1999, 2003) through a grid search. For this analysis, the records at six KiK-net stations are used. The ratios of the source dimension and the stress drop between the large and small events are obtained by the source spectral ratio fitting method (Miyake *et al.*, 1999, 2003) using observed source spectral ratios. The seismic moment ratio between the large and small events is estimated from the source spectral ratio at two F-net stations. As EGF, we adopt the records of an M_w 6.3 event, which occurred at 20:44, on October 10 2005.

The estimated location of the rupture starting point and the delay time are approximately 10 km southeast of the hypocenter and 9s, respectively. The estimated SMGA is located at the deep side of the large slip area obtained from source inversion (Kubo *et al.*, 2012) and partly overlaps with the large slip area. The spatial dimension of SMGA is 28 km$*$28 km and it is smaller than the spatial dimension of the large slip area (60 km$*$60 km). The rise time, seismic moment, and stress drop of SMGA is 2.8s, $3.4*10^{20}$ Nm (M_w 7.6), and 42 MPa, respectively. The rupture within SMGA mostly expands towards the southwest direction at 4.0 km/s. This differs from the result of Kubo *et al.* (2012) where the rupture propagates towards the southeast direction.

Based on the results of this study and Kubo *et al.* (2012), we conclude that the entire source process of the 2011 Ibaraki-oki earthquake was as follows: Approximately 10s after the initial rupture started, the main rupture started at the deeper side of the initial rupture point. At the early stage of the main rupture, short-period seismic waves are mainly radiated. The whole main rupture with a large slip extends toward the southeast direction.

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Keywords: The 2011 Ibaraki-oki earthquake, Source process, Strong motion generation area, The empirical Green's function method