Fault slip distribution of the 2016 Fukushima earthquake estimated from tsunami waveforms

*Aditya Gusman[1], Kenji Satake[1], Masanao Shinohara[1], Shin'ichi Sakai[1], Yuichiro Tanioka[2]

1. Earthquake Research Institute, The University of Tokyo, 2. Institute of Seismology and Volcanology, Hokkaido University

A large earthquake occurred on 21 November 2016 UTC offshore Fukushima prefecture approximately 40 km to the east from the dismantled Fukushima Daiichi nuclear power plant and 120 km to the southeast of Sendai city. Based on the JMA earthquake catalog, the hypocenter of the earthquake is located at 37.355° N, 141.604° E, and 25 km of depth and the magnitude (Mjma) is 7.4. There are four moment tensor solutions available for the event from Global CMT, JMA (two solutions), and USGS. All of these moment tensor solutions suggest that the earthquake is a normal faulting event and has a moment magnitude (Mw) of 6.9. The depths of the centroids are all at 12 km, which is shallower than the hypocenter depth provided in the JMA catalog. The earthquake generated a tsunami that was clearly recorded at tide gauges in Iwate, Miyagi, Fukushima, Ibaraki, and Chiba prefectures, and five cabled-pressure-gauges offshore Iwate (TM1, TM2, YTM1, YTM2, and YTM3).
The simulated tsunami waveforms from GCMT, JMA-CMT, JMA-WCMT, and USGS-WCMT solutions generally underestimate the observations. The tsunami waveform of USGS-WCMT northwest dipping (Normalized RMS error = 1.21) and GCMT southeast dipping (Normalized RMS error = 1.26) solutions better fit the observations compared to those from the other solutions. The centroid locations of JMA-CMT and JMA-WCMT are located on the edge of the aftershock region, that of USGS-WCMT is located outside and to the northwest of the aftershock region, and that of GCMT is located inside the aftershock area. Because the centroid and hypocenter depths are significantly different, we also run simulations with depths of 8, 12, 20, and 25 km. The results show that the simulated tsunami waveforms at offshore pressure gauges are more sensitive to the fault depth than those at tide gauges.
The fault geometry with the southeastward dipping of GCMT solution (strike = 45°, dip = 41°, rake = -95°) is chosen for tsunami waveform inversion because it gives small misfit to tsunami waveforms and the centroid is located within the aftershock area. We distributed 4 ×3 sub-faults with sub-fault-size of 10 km ×10 km, which cover the aftershock area. The estimated fault slip distribution has a large slip of 6 m at depth of 12 km (Figure 1). The seafloor displacement is estimated to be subsided by 1.3 m at the lowest point (Figure 1d). From the fault slip distribution, the calculated seismic moment by assuming a rigidity of 4×10^{10} N/m^2 is 2.21×10^{20} Nm or equivalent to Mw = 7.5, which is significantly larger than that from moment tensor solutions.
Using the estimated fault slip distribution, we run a numerical simulation to analyze the behavior of the tsunami propagation. The tsunami wave hit the coast of Fukushima and the coast reflected the wave back to the open ocean. The reflected wave is then refracted to the north direction and clearly observed in the later phase of tsunami waveform at Sendai port, TMs and YTMs stations. This propagation behavior is mainly due to the configuration of bathymetry off the east coast of Japan (from Chiba to Iwate prefecture). This effect of bathymetry is further confirmed by a numerical experiment of tsunami simulation using artificial bathymetry with seafloor deeper than 500 m as flat in which the reflected tsunami was spread in all directions in front of the coast without being refracted to a particular direction. Larger tsunami amplitudes in the later phases of tsunami waveform are observed and modeled at Sendai port, Ishinomaki, Ayukawa, and Ofunato. At Sendai port, the peak of the second arriving wave is larger (1.4 m) than the peak of first arriving wave (0.9 m). We also found that accurate and precise bathymetry around the ports is required in order to get a reliable coastal tsunami prediction.

Figure 1. Earthquake fault model estimated by tsunami waveform inversion. a) Focal mechanism, aftershock distribution, and subfault boundary. b) Cross-section of fault slip distribution along the dip. c) Map of fault slip distribution. d) Estimated seafloor displacement from the fault slip distribution.

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