Source characteristics and resonant amplification of the 2016 Fukushima earthquake tsunami in Sendai Bay, Japan

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1. Introduction: A large Mw6.9 earthquake occurred offshore Fukushima Prefecture, Japan on 22 November 2016 (05:59:47 JST). Japan Meteorological Agency (JMA) estimated the epicenter of this earthquake at 37.392 °N, 141.403 °E. Following the earthquake, a small tsunami was generated and instrumentally recorded at several tide gauges along East Japan coast. The JMA initially issued the tsunami warning at 06:02 JST for a tsunami up to 3 m along the coast of Fukushima and an advisory message for a tsunami up to 1 m elsewhere along the East Japan coast from Aomori Prefecture to Chiba Prefecture. At 08:09 JST, a large tsunami height of 1.5 m was observed at Sendai port which was unexpected from the issued advisory. Therefore, JMA upgraded the emergency level from advisory to warning for Miyagi Prefecture. The tsunami warning was downgraded to advisory level at 09:46 JST, and totally cleared at 12:50 JST.

The amplification of the 2016 Fukushima earthquake tsunami in Sendai port has been considered as a mystery as the large tsunami of 1.5 m was unexpected from the initially issued advisory by the JMA. Relevant earlier studies have been made to explain the earthquake source and the tsunami issues. Nevertheless, the resonance patterns around semi-enclosed waterbody of Sendai Bay needs to receive more attention. The objective of this study is twofold: (1) to investigate the source properties of the 2016 Fukushima earthquake, and (2) to investigate the resonance response of the 2016 Fukushima tsunami inside Sendai Bay. Our study is the first attempt to study the resonance patterns in Sendai Bay. We also indicated the source properties of the 2016 Fukushima earthquake from tsunami perspectives.

2. Data and Methods: In this study, we collected observed raw data at seven JMA tide gauge stations along the East Japan coast: Ofunato, Ayukawa, Sendai port, Soma, Onahama, Oarai, and Choshi. The collected raw data contained observations from 21 November 2016 to 26 November 2016, with a sampling rate of 15 seconds. The method of data processing is described as follows. Firstly, we applied quality control to the raw data of coastal tide gauges to ensure the quality of the data for analysis. Following this, we applied a high-pass filter with a corner frequency cut at 0.000138 Hz (2 hours) to remove the low frequency component from the observed signals.

We applied the Fourier analysis to estimate the tsunami spectra of observation tsunami and background signals. The observation tsunami and background signals of 5 h were employed for the Fourier analysis at each station. The background signals indicate the tide gauge recorded before the arrival of the tsunami. Based on the spectrum of tsunami and background signals, we calculated the spectral ratio and reconstructed the tsunami source spectrum of the 2016 Fukushima earthquake.

In addition to analyzing observed records, we applied numerical tsunami simulation to replicate the synthetic tsunami wavefield of the 2016 Fukushima earthquake tsunami. The tsunami simulation was conducted based on a nonlinear shallow water equation. For the initial tsunami wavefield, we adopted the source model of Adriano et al. 2018. The improved source model of Adriano et al. 2018 is based on fault geometries proposed by USGS and slip distribution inverted with tsunami observations. The tsunami simulation is applied based on bathymetric data with a grid resolution of 405 m. We applied modal analysis to the synthetic tsunami wavefield simulated around Sendai Bay and evaluated the resonant amplification and the oscillation patterns of the 2016 Fukushima earthquake tsunami.

3. Reconstruction of Tsunami source spectrum: Figure 1 shows the results of Fourier analysis at each JMA tide gauge. A large gap between tsunami spectra (solid red lines) and the background spectra (solid black lines) indicates the spectral energy triggered by the arrived tsunami. In general, it is expected that tsunami can trigger various oscillation modes inside Sendai Bay. A semi-enveloped waterbody such as Sendai Bay typically has several fundamental modes depending on its dimension and water depths. Therefore, it is expected that the tsunami source periods of the 2016 Fukushima earthquake to be mixed with the fundamental modes of Sendai Bay. The energetic periods of the tsunami spectra represent the tsunami source spectrum or fundamental modes. To exclude such effect, the tsunami spectra is calculated as a ratio of background spectra. The spectral ratio at each coastal tide gauge were plotted in Figure 2. According to the study of Rabinovich 1997, the tsunami source periods mostly appeared at the spectral ratio of coastal tide gauges. Here, we calculated the mean of spectral ratio of all seven stations, which was drawn in solid red line in Figure 2.

Based on the study of Rabinovich 1997, the tsunami source periods (T) of mode n can be approached based on the tsunami wavelength (λ) and sea depth (h) of source region. Accordingly, the source periods can be calculated from equation (1).

$$T_n = \frac{\lambda}{n\sqrt{gh}} \tag{1}$$

g is the gravitational acceleration of 9.81 m s^{-2}, the tsunami wavelength of λ is normally twice of the width dimension of tsunami source. Based on the source model proposed by Adriano et al. 2018, we calculated the theorical solution of tsunami source periods with tsunami source width of 32 km and water depths of 700 m around the source region. The comparison of theoretical and observational source periods was listed in Table 1. We also calculated the discrepancy between theorical and observational source periods. From the comparison, our estimation (applying spectral ratio to observations) showed good performance in estimating the source periods with discrepancy less than 10 %. This method demonstrates a rapid and stable approach on constraining the source properties (in source dimension) for tsunami source estimation.

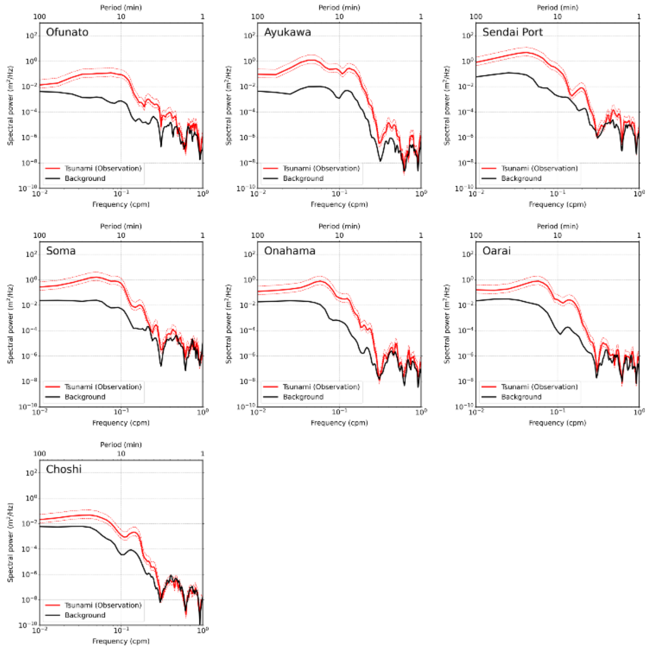

Figure 1. The results of Fourier analysis at each tide gauge.

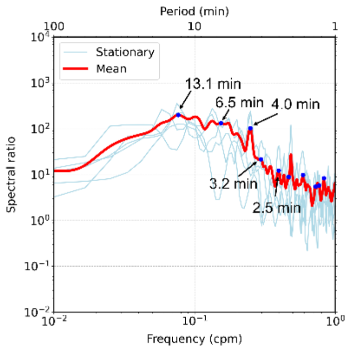

Figure 2. The tsunami spectra calculated as ratio of background spectra.

Table 1. Comparison of tsunami source periods.

Mode n	Theorical periods (min)	Observational periods (min)	Discrepancy (%)
1	12.9	13.1	1.5
2	6.4	6.5	1.5
3	4.3	4.0	7.5
4	3.2	3.2	0
5	2.6	2.5	4

4. Resonant amplification: To evaluate the resonant amplification associated with the tsunami source of the 2016 Fukushima earthquake, we applied modal analysis to identify tsunami source periods of 13.1 min (mode 1) in the region of our interest. The spatial distribution of the resonant amplification and phase angle were plotted in Figure 3. The spatial distribution of spectral amplitude and phase angle reveal the resonant process and its oscillation patterns along the continental coast of East Japan. In Figure 3, several nodes and antinodes were distinct with notable energy amplification distributed over the continental shelf from the source region into Sendai Bay. This indicates that the tsunami oscillation from the source period did not propagate along the coastline but formed a system of standing wave along the coastline and the bay. Also, the continuous change of the phase angle revealed that the tsunami wave has been refracted and trapped into Sendai Bay after generation. The resonant process of the trapped waves with the fundamental modes of the continental shelf and inside Sendai Bay resulted in energy amplification. Thus, the amplified tsunami inside the Sendai Bay may be attributed to the coupling of the shelf resonance and the bay oscillation due to the effect of wave trapping. The synthetic assessment based on the 2016 Fukushima earthquake tsunami demonstrated the resonant feature of Sendai Bay to tsunamis. The findings of this work suggested that the coastal communities around Sendai Bay should be aware of the larger waves following the arrival of the first wave in future tsunamis because of the magnification.

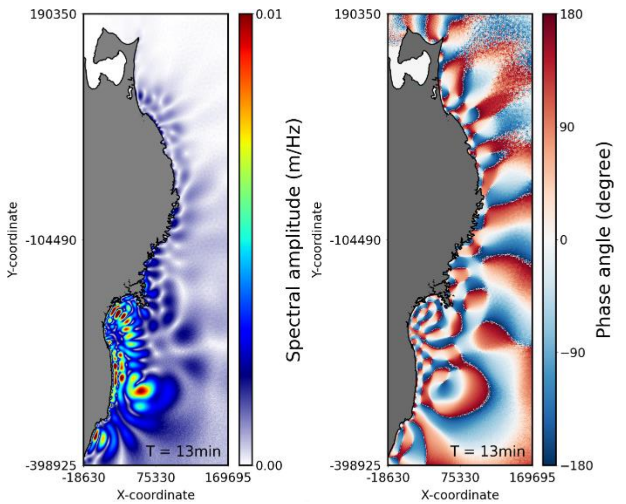

Figure 3. The spatial distribution of spectral amplitude and phase angle at period 13 min.

5. Conclusions: In this study, we investigated the source properties of the 2016 Fukushima earthquake, and the resonance response of the tsunami source periods inside Sendai Bay using Fourier analysis and numerical tsunami simulation. The main findings are shown as follows:
(1) The tsunami source periods of the 2016 Fukushima earthquake are estimated at periods of 13.1 min (mode1), which is well consistent with the width dimension (32 km) of the source model proposed by the study of Adriano et al. 2018.
(2) The tsunami resonance analysis revealed that fields of the standing wave were formed over the continental shelf and Sendai Bay associated with the tsunami source period. Therefore, we concluded that the amplified tsunami in Sendai Bay during the 2016 Fukushima earthquake tsunami might be attributed to the coupling of shelf resonance and Bay oscillation.

References:

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