2015 Torishima tsunami earthquake: Ray tracing analysis of dispersive tsunami wave

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On 3 May 2015 (JST), an M5.7 earthquake occurred near Torishima Island and generated abnormally larger tsunami, compared to its magnitude, with heights as large as 60 cm at Hachijo Island, 180 km to the north of the epicenter. This earthquake may be regarded as a tsunami earthquake. The earthquake source is located at the shallow part near the Smith caldera, a volcanic body on the shallow ridge along the Izu-Bonin trench, where three similar earthquakes occurred in 1984, 1996 and 2006 (Satake and Gusman, 2015, SSJ). For the 1984 earthquake, Satake and Kanamori (1991, JGR) simulated tsunami propagation using the linear long-wave theory and suggested the tsunami source may be explained by a circle-shaped uplift of sea surface. The focal mechanism was explained by CLVD-type models due to volcanic activity in the shallow part, such as hydrofracture associated with magma injection (Kanamori et al., 1993, JGR) or a seismic slip on curved, cone-shaped faults (Ekström, 1994, EPSL).

Tsunami waves caused by the 2015 earthquake were recorded by a temporary ocean bottom array of water pressure gauges, 100 km to the NNE from the epicenter. The tsunami traces at the array gauges started with a positive onset and showed dispersion effects. It is notable that the measured slowness orientation of wavefront approximated by a plane wave varies as a function of frequency (Fukao et al., 2016, JpGU).

In this study, we investigated frequency-dependent ray paths of the tsunami by a ray tracing method considering the dispersion effects. We first iteratively calculated two-dimensional phase- and group-velocity fields dependent on frequency, using the theoretical formula of gravity waves and a smoothed bathymetry. These velocity fields enable us to measure travel times of both of wavefronts and wave packets. We assumed a tsunami source on the Smith caldera and applied the ray equations for seismic surface waves on spherical Earth (e.g. Sobel and Seggern, 1978, BSSA; Jobert and Jobert, 1983, GRL) to ray tracing of tsunamis.

Ray paths show that longer-period waves are more affected by bathymetry variations. We note that wavefronts toward NNE at the source change their direction to the north, furthermore to the NNW in case of longer-period waves. This trend explains well the frequency-dependent slowness orientation of wavefront at the array gauges. Travel times of wave packets are also consistent with frequency-dependent arrival times observed at the gauges. In addition, ray paths show an intensity of energy northward along the shallow ridge, regardless of frequency, which might have contributed to high amplitudes at Hachijo Island.

Our ray tracing method including dispersion effects allows us to investigate ray paths for shorter waves out of applicable range of the linear long-wave theory. Therefore we can consider path effects for shorter waves following primary longer waves. This method may be also applicable for tsunami forecasting including subsequent shorter waves due to dispersive effects with small numerical computation costs.

Keywords: tsunami, dispersion, tsunami earthquake, ray tracing, volcanic earthquake

