論文の内容の要旨

Tsunami data assimilation for early warning

（早期警報のための津波データ同化）

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The tsunami data assimilation approach has been proposed for tsunami early warning. It estimates the tsunami waveform by assimilating observed offshore data into a numerical simulation without considering the source based on Optimal Interpolation method. However, previous data assimilation approach has a relatively high computational cost as it is necessary to run numerical simulations to obtain the entire tsunami wavefield during the assimilation process. The previous approach also requires a dense offshore observation network, making it difficult to conduct data assimilation in regions with sparse observations.

In this thesis, I first proposed Green's Function-based Tsunami Data Assimilation (GFTDA) to reduce the computation time for assimilation. It can forecast the waveform at Points of Interest (PoIs) by superposing Green's functions between observational stations and PoIs. Unlike the previous assimilation approach, GFTDA does not require the calculation of the tsunami wavefield for the entire region during the assimilation process because Green's functions are calculated in advance. A simple matrix manipulation can allow the calculation of the forecasted waveforms. I applied this

method to data from the 2012 Haida Gwaii earthquake, the 2004 off the Kii Peninsula earthquake, and the 2015 Torishima volcanic tsunami earthquake. GFTDA achieved an equivalently high accuracy of tsunami forecasting as the previous approach, while saving sufficient time to achieve an early warning. It also enabled the application of a more complicated tsunami propagation model to data assimilation, such as the linear dispersive (DSP) model, which predicts the tsunami arrival time more accurately.

Next, I proposed a modified tsunami data assimilation method for regions with a sparse observation network. The method uses interpolated waveforms at virtual stations to construct the complete wavefront for tsunami propagation. The artificial tsunami waveforms at the virtual stations between two existing observational stations could be estimated by shifting arrival times with linear interpolation of observed arrival times and by correcting the amplitudes using water depths. This was based on the assumption that tsunamis propagate as a plane wave, and that the wavefront is nearly a straight line. After computing the waveforms for virtual stations, the data assimilation algorithm was applied to real and virtual stations. Its application to the 2004 Sumatra–Andaman earthquake, the 2009 Dusky Sound, New Zealand earthquake, and the 2015 Illapel earthquake revealed that adopting virtual stations greatly improved the tsunami forecasting accuracy for regions without a dense observation network.

Additionally, I proposed a real-time tsunami detection algorithm using Ensemble Empirical Mode Decomposition (EEMD). EEMD adaptively decomposes a time series into a set of Intrinsic Mode Functions (IMFs). The tsunami signals of the Offshore Bottom Pressure Gauge (OBPG) can be automatically separated from the tidal components, seismic waves, and background noise. Unlike traditional tsunami detection methods, the new algorithm does not require tidal predictions. The application to the actual data of cabled OBPGs off the Tohoku coast showed that it successfully detected the tsunami from the 2016 Fukushima earthquake (M 7.4). The method was also applied to the extremely large tsunami from the 2011 Tohoku earthquake (M 9.0) and extremely small tsunami from the 1998 off Sanriku earthquake (M 6.4). The algorithm detected the former, which caused devastating damage, whereas it did not detect the latter micro tsunami, which was not noticed on the coast. The algorithm was also tested for a month-long OBPG data, and no false alarm occurred. Hence, the algorithm could detect tsunami arrival with a short detection delay and accurately characterize the tsunami amplitude.

Furthermore, I combined the tsunami data assimilation approach with the real-time tsunami detection algorithm. The tsunami of the 2016 Fukushima earthquake was recorded by the offshore pressure gauges of the Seafloor Observation Network for Earthquakes and Tsunamis (S-net). I used 28 S-net pressure gauge records for tsunami data assimilation and forecasted the tsunami waveforms at four tide gauges on the Sanriku coast. The S-net raw records were processed using two different methods. In the first method, I removed the tidal components by polynomial fitting and applied a low-pass filter. In the second, I used the real-time tsunami detection algorithm based on EEMD to extract tsunami signals, imitating real-time operations for tsunami early warning. The scores of forecasting accuracy of the two detection methods were 60% and 74%, respectively, for a time window of 35 min, which improved to 89% and 94%, respectively, if stations with imperfect modeling or insufficient offshore observations were omitted. Hence, the proposed tsunami data assimilation approach can be put into practice with the help of the real-time tsunami detection algorithm. Finally, I proposed a tsunami early warning system using data assimilation of offshore data for Japan.