論文の内容の要旨

Advancement in Normal-Mode Method for Tsunami Computation: Simulation of Tsunami Waveforms and Characterization of Submarine Faults in the Sea of Japan

(津波計算におけるノーマルモード法の発展：津波波形計算と日本海における海底断層の類型化)

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The normal-mode method (NMM) is widely used in seismology, ocean tide and seiche studies. While most of the former NMM applications to tsunami focused on modal analysis of a bay with incoming waves, Satake and Shimazaki (1987, 1988) proposed a method to simulate tsunami waveforms based on mode superposition, which is considered to be faster than the finite difference method (FDM). They also pioneered to conduct a modal analysis of tsunami source characterization in the Sea of Japan using the NMM, where a tsunami source could be included into the model. However, their proposal was only tested in a simple ideal case which is far from the reality and few properties of NMM simulation were understood. Besides, their source characterization was qualitative due to the coarse grids and the limited number of modes.

To validate NMM in a realistic case and quantitative source characterization, high resolution normal-mode solutions of the Sea of Japan are required. In this study, I first extended the previous NMM into a spherical coordinate system and used an experiential normalization way to simplify the numerical calculation. Then linear matrix storage and matrix-vector multiplication were implemented, and a modern sparse eigenvalue solver was incorporated, which made the calculation of large scale NMM problems realistic. In addition, a parallel version of the calculation was also developed.

These improvements enabled us to obtain 6,000 modal solutions (down to a period of around 8 min) of 2-arc-min grids and 3000 modal solutions (down to around 11.5 min) of 1-arc-min grids for the Sea of Japan. By the superposition of these modes, tsunami waveforms were synthetized by the NMM, for the first time, for the 1983 Sea of Japan earthquake (Mw 7.7). Comparison with the results from the FDM and examination in both time and frequency domains confirmed the validity of the NMM when the modes cover the frequency range of the signal.

Besides the validation of NMM waveform simulation, its properties were carefully examined. Simulation time were compared with FDM and an improvement was proposed so that the time using the NMM may be faster than using the FDM by several orders, which strengthens the advantage of the NMM. In addition, a relationship between the mode order and the mode frequency was proposed so that it is possible to estimate in advance the required number of modes of a given maximum frequency.

I then conducted a novel modal analysis, utilizing the high resolution normal-mode solutions to characterize 60 potential submarine faults in the Sea of Japan. A quantitative mode grouping method using kurtosis was proposed, dividing the obtained 6,000 modes into three types: 622 basin-wide modes, 4,953 regional modes, and 425 local modes.

The excitation weights for the 60 fault models along the eastern margin of the Sea of Japan were computed, which showed that the average excitation was larger for the sources located at shallower water depth or with larger magnitude. Quantitative examinations showed that among the three types of modes, the regional modes distribute their energy more efficiently at a large costal area and therefore contribute the most to the costal tsunamis.

Finally, a symmetric construction way of NMM eigenvalue-problem was proposed, which enabled us to compute 15,000 modes of the Sea of Japan down to 5 min in period. Using these modal solutions, tsunami waveforms synthetized by mode superposition can cover the usual frequency band in the Sea of Japan, which makes it possible to simulate waveforms with high frequency energy. Besides, this approach eliminated the inaccuracy introduced by the experiential mode normalization, resulting almost no energy before the initial arrival and better agreements to FDM around the onset. These improvements further made the NMM a practical tool for the tsunami simulation in the Sea of Japan.