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Seismic wavefield imaging in the Tokyo metropolitan area, Japan, based on the replica exchange Monte Carlo method

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Earthquakes sometimes cause serious disasters not only directly by ground motion itself but also secondarily by infrastructure damage, particularly in densely populated urban areas. To reduce these secondary disasters, it is important to rapidly evaluate seismic hazards by analyzing the seismic responses of individual structures due to the input ground motions. Such input motions are estimated utilizing an array of seismometers that are distributed more sparsely than the structures.
We propose a methodology that integrates physics-based and data-driven approaches in order to obtain the seismic wavefield to be input into seismic response analysis. This study adopts the replica exchange Monte Carlo (REMC) method, which is one of the Markov chain Monte Carlo (MCMC) methods, for the estimation of the seismic wavefield together with one-dimensional local subsurface structure and source information. Numerical tests show that the REMC method is able to search the parameters related to the source and the local subsurface structure in broader parameter space than the Metropolis method, which is an ordinary MCMC method. The REMC method well reproduces the seismic wavefield consistent with the true one. In contrast, the ordinary kriging, which is a classical data-driven interpolation method for spatial data, is hardly able to reproduce the true wavefield even at low frequencies. This indicates that it is essential to take both physics-based and data-driven approaches into consideration for seismic wavefield imaging.
Then the REMC method is applied to the actual waveforms observed by a dense seismic array MeSO-net (Metropolitan Seismic Observation network), in which 296 accelerometers are continuously in operation with several kilometer intervals in the Tokyo metropolitan area, Japan. The estimated wavefield within a frequency band of 0.10–0.20 Hz is absolutely consistent with the observed waveforms. Further investigation suggests that the seismic wavefield is successfully reconstructed at frequencies up to 0.30 Hz in terms of the variance reduction (VR), but the VR gets rapidly worse in higher frequencies. On the other hand, the velocity response spectra of the reconstructed wavefield show good agreement with the observations even in higher frequencies up to 1.0 Hz in terms of the combined goodness-of-fit (CGOF), which measures the misfit in the velocity response spectra. In summary, the proposed seismic wavefield imaging based on the REMC method is effective <1.0 Hz, which is enough to evaluate large-scale seismic hazards in almost all infrastructures.