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Synthesis of Broadband Ground Motions Using Embedding and Neural Networks

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Ground motions of earthquakes cause fatal damages on buildings and infrastructures. Accurate knowledge on ground motions of prospective earthquakes is indispensable for seismic hazard and engineering applications. Physics-based numerical simulations have been developed to generate precise ground motions and building responses, but it is limited only to long periods, e.g., down to 1 sec due to heavy computational costs, and the lack of detailed knowledge of the source rupture process the subsurface structure. A hybrid approach was proposed to combine numerical simulations for long periods with stochastic approaches for short periods to generate broadband motions. But it still has drawbacks that generated short period motions do not reflect source and path effects, and resulting building responses can be inconsistent over the joint periods between the long and short periods.

In Japan, a large amount of observation data have been collected by K-NET over the past 20 years. Then machine learning approaches would be effective to estimate broadband ground motions from simulated long period motions. From this perspective, we propose a ground-motion synthesis method based on the state-of-the-art machine learning techniques, i.e. embeddings and neural networks, and apply it to an M7.0 earthquake in Japan to evaluate its performance.

In our method, the time property (envelope of accelerogram) and frequency property (Fourier amplitude spectrum) of broadband motions are separately estimated. The time property is estimated using embeddings. A common embedded space representing both long and broadband period motions is built by an extended version of t-SNE, so that neighbor identities of envelopes are preserved. Then, unknown broadband envelopes for test data can be interpolated in this space. The similarity of envelopes is measured by the Wasserstein distance of the optimal transport theory, which captures the time dependence of waveforms. We discuss the seismological implications of the embedded space.

The frequency property is estimated using deep neural networks. The Fourier spectrum of the short period motion are estimated from that of the long period motion. In order to increase the number of training data and while keeping the properties of observation site, we train the network in the following two steps. We first train the network with large data from all sites to model a general frequency property, and then retrain it with small data from a specific site to model a site-specific frequency property. We found that this approach could avoid overfitting and improve the accuracy.

Finally, the estimated time and frequency properties are combined to synthesize broadband ground motions. We show that the resulting broadband ground motions could match the ground-truth observations well, and examine the consistency of waveforms in terms of building response properties.