Earthquake detection based on deep learning

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Earthquake detection, identifying the presence of an earthquake and determining its hypocenter, is challenging, because it requires the correct detection and association of seismic phases across different seismographs while also precisely picking the arrivals of P and S waves. Yet, this effort is essential for producing the earthquake catalog that provides important insights into many studies of observational seismology, such as the spatiotemporal distribution of Gutenberg-Richter's *b*-value, the geometry of faults, and foreshock behavior. Better catalog also enables us to use more event data for the determination of source parameters, such as focal mechanisms.

Despite several separating automatic methods are continuously developed to resolve each step of earthquake detection, seismic analysts still strive to identify earthquakes or calibrate the result proposed by automatic method manually for the superior accuracy and reliability of expert-made estimation. Accompanying with the explosion of seismic waveform data caused by the development of high sensitivity seismograph network, however, comprehensively identifying earthquakes from such massive data is becoming increasingly difficult, especially for earthquakes which are small yet dominate the overwhelming majority of earthquakes.

We integrate earthquake detection procedures into an efficient, sensitive, and coherently end-to-end framework. The framework extends Mask R-CNN, which is the de-facto standard method for instance segmentation in deep learning, by training it on multi- and single-seismograph waveform data separately to construct a detector branch in parallel with a picker branch, and afterwards both branches are concatenated together. The detector branch efficiently detects the time spans in which seismic phases originating from a common causative earthquake are included in a 120-second multi-seismograph waveform window while segmenting the preliminary tremors (waveforms from P- to S-arrivals) observed at each seismograph roughly. The picker branch subsequently generates high-quality segmentation masks that covers preliminary tremors further precisely to pick P- and S-wave arrival times. The framework, in addition, predicts confidence scores of distinguishing seismic phases from ambient noise for each earthquake and each preliminary tremor respectively, which can be used as the criterion of monitoring the quality of earthquake identification and phase picking.

We evaluate the framework on an unseen test dataset of 3,591 discrete earthquakes accompanying with the target labels of expert-picked P- and S-wave arrival time from Japan Meteorological Agency (JMA) earthquake catalog. After discarding some prediction scored with low confidence, the framework has successfully recalled and relocated 97.61% of the test earthquakes with small errors both in the phase arrival times and the hypocenter location, showing a near-human-level detection accuracy and great generality. We then apply the framework to a set of one-month continuous waveform data that have been

recorded by a temporary seismograph network operated by Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST) in northern Ibaraki, Japan. While trained on the seismic waveform data from a different seismic network, the framework generalizes well and has identified more microearthquakes beyond JMA earthquake catalog over the certain area around the temporary network, which allows us to demonstrate its robustness and detection sensitivity.

We hope our effective approach will serve as a general automatic method of earthquake detection to help ease monitoring earthquake activities and provide new information to facilitate further researches in seismology.

Keywords: Deep learning, Neural network, Instance segmentation, Earthquake catalog, Time-series analysis, Computational seismology

