34 Application of Seismic Array Processing to Earthquake Early Warning

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Introduction

Earthquake early warning (EEW) systems are essential in mitigating seismic hazard by issuing warnings prior to the arrival of strong ground shaking during an earthquake. Many of the currently operating EEW systems work on the basis of magnitude-amplitude/frequency scaling for a point source, which is invalid for magnitude estimation of $M > 7.5$ earthquakes. This issue is particularly highlighted in EEW performance of the M9.0 Tohoku-Oki earthquake (Hoshiba et al., 2011). Failing to take into account the finite rupture propagation, the magnitude estimated by the Japanese EEW system saturated at M8.1. The Japanese Meteorological Agency (JMA) issued warnings of strong seismic intensity only for the Tohoku region. However, the Kanto region experienced much larger ground motions than that predicted by JMA. The example of the Tohoku-Oki earthquake demonstrates the need for characterizing the finite fault dimension in real time for EEW systems of large earthquakes to be successful.

Among the ongoing efforts to determine the finite fault extent in real time, GPS approaches provide more reliable static displacements and thus, magnitude, than do seismic methods (Colombelli et al., 2013). The FinDer approach is also proposed to determine linear fault geometry based on the amplitude difference in near/far field seismic waveform, provided dense station coverage.

Alternatively, we explore the concept of imaging the rupture process of large earthquakes in real time using clusters of dense seismic arrays located near an active fault. Back tracing the waveforms of earthquakes recorded by such arrays allows the estimation of the rupture directivity, size, duration, speed, and segmentation, which enables the EEW of $M > 6$ earthquakes. The principle is analogous to the location and tracking of moving sources by antennas in a variety of military and civilian applications. Figure 2.34.1 illustrates the concept of seismic array processing for EEW. Strong, high-frequency (HF) seismic waves usually radiate from the rupture front. Tracking the source of the HF seismic waves during large earthquakes recovers the movement of the rupture front. The trajectory of the rupture front marks the fault extent involved in the earthquake.

Method

The direction of the incoming HF waves can be determined by analyzing the phase of coherent seismic signals across an array with various array-processing techniques. For small-scale arrays, the impinging wave front can be approximated as a plane wave. The back azimuth of the plane wave is then projected onto an assumed fault plane to resolve the location of the rupture front. Here, we adopt the correlation stacking technique to perform the array analysis. The correlation stacking beamforms the normalized cross-correlation coefficients instead of the waveforms to improve robustness against scattering and multi-pathing in the shallow crustal environment (Fletcher et al., 2006). The stacked correlation $cc_{ij}$ can be calculated by:

$$cc_{ij} = \left[ \frac{\sum_i x_i(t) x_j(t - \tau_{ij})}{\sum_i x_i^2 \sum_j x_j^2} \right]^{1/2}$$

where $i, j$ are station indices, $x_i$ is the seismic signal recorded at the $ith$ station, $t$ is the time, $\tau_{ij}$ is the timing delay of a testing wave direction between the station $i$ and $j$.

The 2004 Parkfield Earthquake

We implemented the proposed methodology to the 2004 $M6$ Parkfield earthquake in a simulated real-time environment. The earthquake is one of the few big events ($M > 6$) that are recorded by a local small-scale seismic array (UPSAR array). Fletcher et al., 2006 shows that the rupture kinematics can be retrieved by...
the UPSAR array. The earthquake is dominated by a unilater-
al rupture along the San Andreas Fault towards the northwest. The rupture is composed of three subevents that radiated strong high frequency signals. The first subevent is close to the hypo-
center.

The two later subevents are closely spaced in the along-strike location near the end of the rupture. The interpretation is that these two subevents might occur at different depths consistent with the bimodal distribution of the aftershocks. In addition, we find that the dipping layer beneath the array causes the bias of the back azimuth and thus rupture length. After corrections, the estimated rupture length of 9 km is consistent with the distance between the two main subevents identified by back-projection using all local stations.

Conclusion

We explored the possibility of using seismic array processing in real time and developed an efficient methodology for rapid characterization of the earthquake rupture directivity and of the rupture area extent, using a correlation-stacking method. The strategy we propose can potentially prompt more reliable earthquake early warnings for large earthquakes. In terms of the future work, the optimal design of the array geometry and position, and real-time implementation strategy need to be further investigated.

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References

