Earthquake early warning based on wavefield estimation approaches incorporating P-waves and ground motion prediction equations: toward the improvement of the PLUM method

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A major technical challenge of earthquake early warning (EEW) systems is to provide ground motion predictions with high accuracy and timeliness for complex earthquake scenarios such as occurrences of earthquakes with large finite faults and multiple simultaneous events. To address this issue, the Japan Meteorological Agency introduced the Propagation of Local Undamped Motion (PLUM) method (Kodera et al., 2018) into its operational system in March 2018. PLUM is one of wavefield estimation approaches that predict seismic intensities directly from observed ground shaking. PLUM calculates a predicted intensity Ir_{pred} by $Ir_{\mathrm{pred}} = \max\left\{Ir_{\mathrm{obs}}^{(1)}, \cdots, Ir_{\mathrm{obs}}^{(N)}\right\}$, where $Ir_{\mathrm{obs}}^{(i)}$ is an observed real-time seismic intensity (Kunugi et al., 2013) at station i within 30 km from the target site (each intensity should be converted into the intensity on bedrock by correcting its site amplification factor). This equation assumes that ongoing ground shaking will propagate without attenuation if the propagation distance is as short as ≤30 km. PLUM exhibits high robustness for complex events because source parameters are not required to be estimated.

On the other hand, PLUM has a shortcoming in terms of timeliness. Long lead times are not expected because PLUM only uses observed intensities within 30 km from target sites so that high intensities are not predicted until strong motion reaches at a close distance. The theoretical maximum time is 10 s, assuming that the S-wave velocity is 3 km/s. To enhance the timeliness, we have improved the prediction procedure focusing on (1) the use of P-waves and (2) ground motion prediction equations (GMPEs).

(1) Incorporation of P-waves

One of ways to improve the timeliness is to incorporate P-waves that arrive before S-waves. The original equation of PLUM relies on direct observation of strong motion caused by S-waves. Therefore, available lead times would be lengthened if on-site predictions are made using P-waves that appear before the corresponding S-waves.

To perform the on-site prediction, P-waves are identified from continuous waveforms based on a particle motion analysis. A P-filter value (Ross and Ben-Zion, 2014) is calculated from the principal component analysis. If the value exceeds a threshold, the waveform is classified into a P-wave. After the detection, the seismic intensity of the corresponding S-wave is predicted. The on-site prediction Ir_{onsite} is obtained from $Ir_{\mathrm{onsite}} = Ir_{\mathrm{obs}}[\mathrm{UD}] + \Delta Ir_{PS}$, where $Ir_{\mathrm{obs}}[\mathrm{UD}]$ is the intensity calculated only from the

UD component, and ΔIr_{PS} indicates the difference in seismic intensity between P and S waves. For the PLUM prediction, Ir_{onsite} is used instead of $Ir_{\mathrm{obs}}^{(i)}$ if Ir_{onsite} is available and $Ir_{\mathrm{onsite}} > Ir_{\mathrm{obs}}^{(i)}$.

When this approach was applied to the 2011 Tohoku-Oki earthquake (Mw 9.0) using KiK-net stations, P-waves were detected not only from the initial rupture point but also from strong motion generation areas. Compared to the original method, the new approach lengthened warning times by several seconds for sites close to the source region without largely decreasing the prediction accuracy.

(2) Incorporation of GMPEs

Another approach to enhance the timeliness is to use intensities observed at more distant sites. This could be done just by expanding the radius from 30 km; however, a longer radius will cause overprediction since PLUM assumes plain waves that do not attenuate. Therefore, a certain distance attenuation model is required to be incorporated.

We have introduced GMPEs used in conventional point-source algorithms to imitate the distance attenuation. First, pseudo point sources with various fixed depths ($d = d_1, \cdots, d_M$) are assumed to be located just below each observation point. The magnitudes are estimated from the observed intensity at the observation point. The most appropriate source is selected by comparing expected shaking (intensities predicted from the assumed sources and GMPEs) to intensities actually observed at surrounding sites (within R_1 from the observation point). Then, ground motion predictions are made for sites within R_2 based on the best-fit point source. This procedure is repeated over all observation points in a single calculation cycle. In general, a site is given multiple predictions by surrounding observation points; the maximum among the predictions is chosen as the final result.

We applied this method to the Tohoku-Oki earthquake using KiK-net and K-NET stations. The parameters were set as follows: R_1 = 45 km, R_2 = 300 km, d = 1.00, 1.46, 2.14, 3.13, 4.58, 6.71, 9.82, 14.36, 21.02, 30.75, 45.00 km. Compared to the original PLUM method, available lead times by the new method were ~10 s longer for sites with low intensities (i.e., distant sites from the source region) although those for sites with high intensities were shorter than those by PLUM. The short lead times were due to the intensity comparison using the circular region with the radius of R_1; the appropriate point source was not estimated until ground motion passed over the region. The entire prediction accuracy was better than that of PLUM.

These results indicate that (1) the use of P-waves can improve the timeliness for sites near source regions and (2) introducing GMPEs is effective for lengthening lead times for distant sites. Introducing P-waves and GMPEs would improve the entire performance of EEW systems based on wavefield estimation approaches.