17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Numerical shake prediction for earthquake early warning: Data assimilation and wave propagation simulation

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Abstract

Earthquake early warning (EEW) is a new tool for earthquake disaster prevention/mitigation, in which impending ground shaking is predicted before its arrival. Many of the present EEW systems quickly determine the hypocenter and magnitude, and then predict strength of ground motions using ground motion prediction equation (GMPE). The 2011 Tohoku earthquake (M_w 9.0), however, revealed some technical issues with such methods: under-prediction at large distances due to the large extent of the fault rupture, and over-prediction because the system was confused by multiple aftershocks that occurred simultaneously. To address these issues, we have proposed a new concept for EEW, in which the distribution of the present wavefield is estimated precisely in real time (real-time shake mapping) by applying a data assimilation technique, and then the future wavefield is predicted time-evolutionally by simulation of seismic wave propagation. Information on the hypocenter location and magnitude are not necessarily required. We call this method, in which physical processes are simulated from the precisely estimated present condition, "numerical shake prediction" by analogy to "numerical weather prediction" in meteorology.

Data assimilation technique is widely used in numerical weather prediction, oceanography and rocket control for precise estimation of the present condition. In application of the technique for EEW, the spatial distribution of the wavefield is estimated from not only actual observations but also the simulation of wave propagation based on wave propagation physics. By doing the above process, all previous observations are used for precise estimation of present condition. In the application of data assimilation to seismic wave propagation, spatial distribution of propagation direction of seismic waves is estimated in real-time manner, in addition to spatial distribution of strength of seismic wave energy. Once the present situation has been estimated precisely by the data assimilation technique, we go forward to the prediction of future situation. Because future observations are not yet available for data assimilation, the wave propagation physics are calculated without data assimilation. Thus, wave propagation is simulated from the present condition, for prediction of future distribution of seismic wave energy.

During the 2011 Tohoku earthquake (M_w 9.0), strong ground motions were radiated from multiple strong ground motion generation areas (SMGAs). The numerical shake prediction method appropriately predicts the propagation of the strong motions from the SMGAs. During the 2016 Kumamoto earthquake (M_w 7.1) M6 class earthquake was remotely triggered at around 37 s apart from 70 km from the epicenter. This method predicts well the strong shaking from the triggered earthquake. Because the numerical shake predction method makes it possible to predict ground motion without information about the earthquake hypocenter and magnitude, this method can precisely predict ground motion even when the extent of the fault rupture is large or when multiple events occur simultaneously.

Keywords: earthquake early warning; real-time prediction of strong ground motion; data assimilation

1. Introduction

Many of the present earthquake early warning (EEW) systems quickly determine the hypocenter and magnitude, and then predict strength of ground motions using ground motion prediction equation (GMPE). The M_w 9.0 Tohoku earthquake, however, revealed some technical issues with such methods: under-prediction at large distances due to the large extent of the fault rupture, and over-prediction because the system was confused by multiple aftershocks that occurred simultaneously [1]. To address these issues, we have proposed a new concept for EEW [2, 3], in which the distribution of the present wavefield is estimated precisely in real time (real-time shake mapping) by applying a data assimilation technique, and then the future wavefield is predicted time-evolutionally by simulation of seismic wave propagation. Information on the hypocenter location and magnitude are not necessarily required. We call this method, in which physical processes are simulated from the precisely estimated present condition, "numerical shake prediction" by analogy to "numerical weather prediction" in meteorology. Examples of the numerical shake prediction are presented for cases of the 2011 Tohoku earthquake and the 2016 Kumamoto earthquake (M_w 7.1).

2. Method

In the proposed method, the present wavefield is first estimated using a data assimilation technique, and then simulation of wave propagation is applied to estimate the future wavefield (Fig. 1).

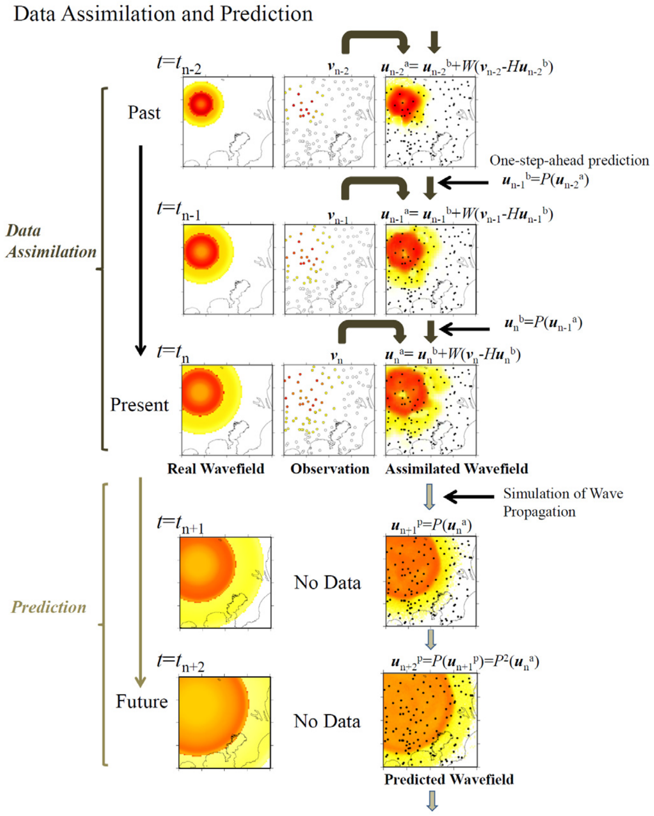

Fig. 1: Flow from estimation of wavefield using data-assimilation to prediction of ground motion. This figure is from [2].

2.1 Data assimilation for estimation of present situation

Data assimilation technique is widely used in numerical weather prediction, oceanography and rocket control for precise estimation of the present condition [4]. The technique is a kind of spatial interpolation. Fig. 1 (upper part) illustrates data assimilation procedure, in which the spatial distribution of the wavefield is estimated from not only actual observations but also the simulation of wave propagation based on wave propagation physics. In Fig.1, $\boldsymbol{v}_n$ indicates the actual observation at time n, $\boldsymbol{u}_n^b$ $(=P(\boldsymbol{u}_{n-1}^a))$ means the wavefield at time n predicted from the wavefield at one-time-step-before (n-1) using simulation of wave propagation, and $\boldsymbol{v}_n - H\boldsymbol{u}_n^b$ indicates the discrepancy between the actual observation and the one time-step prediction, where H is called "observation matrix" which means the interpolation of grid points onto the location of the observation points. $W(\boldsymbol{v}_n - H\boldsymbol{u}_n^b)$ indicates the correction of the one-step prediction in the wave propagation simulation, where W is called "weight matrix". Matrix W controls how much actual observation is reflected into the estimation of $\boldsymbol{u}_n^a$. By doing the above process of data assimilation, all previous observations are used for precise estimation of present condition. In the application of data assimilation to seismic wave propagation, spatial distribution of propagation direction of seismic waves is estimated in real-time manner, in addition to spatial distribution of strength of seismic wave energy.

2.2 Radiative transfer theory for simulation of seismic wave propagation

For seismological applications, some simulation methods have been proposed such as finite difference method, finite element method, boundary integral equation method, and so on. Radiative transfer theory (RTT) is based on ray theoretical approach, so that it is an approximation for high frequency waves. In RTT, peaks and troughs of waveforms are neglected, and energy propagation is considered instead of wave propagation. RTT is based on Boltzmann equation, and it has been widely used to interpret seismogram envelopes of high frequency seismic waves [5]. Because of the approximation, much less computational time is required compared with the finite difference method and boundary integral equation method.

2.3 Prediction

Once the present situation has been estimated precisely by the data assimilation technique, we go forward to the prediction of future situation (Fig. 1, lower part). Because future observations are not yet available for data assimilation, the wave propagation physics are calculated without data assimilation. Thus, wave propagation is simulated from the present condition for prediction of future distribution of seismic wave energy.

3. Results

3.1 The 2011 Tohoku earthquake (M_w9.0)

Fig. 2a shows time evolution of seismic moment growth of the Tohoku earthquake [6], and Fig. 2c indicates slip distribution on the fault from analyses of low frequency waveforms (0.01-0.15 Hz). Rupture duration is estimated to be 180 s. Asano and Iwata [7] identified four strong motion generation areas (SMGAs) from analyses of high frequency waveforms (0.1-10 Hz) as shown in Fig. 2. Source model from low frequency and that from high frequency are different both spatially and temporally. In Fig. 2b, accelerograms at stations indicated in Fig. 2c are shown. Propagation of strong motions (S1-4) from the four SMGAs is observed. In Tohoku region, S1 and 2 are main contribution to determine peak ground acceleration (PGA) and S3 and S4 add little effects, but in Kanto region S3 and 4 are main and S1 and S2 are little. This suggests that PGA is determined by nearby instantaneous local process, rather than whole process of rupture [8]. These strong motions, especially S1 and 2, appear much earlier than the end of fault rupture. Prediction of these impending strong motions, such as S1-4, before its arrivals is the main subject for useful EEW.

Fig. 3 shows distribution of seismic intensity of real-time shake-mapping and prediction of future distribution, in which frequency dependent site amplification factors are corrected in real-time manner [9], so that all locations have virtually the common site amplification factor as the same as that of Ohte-machi, Tokyo. Fig. 3a indicates distribution the seismic intensity after data assimilation. Thus, Fig. 3a shows real-time shake-maps. Fig. 3b and 3c show the predictions of 10 s and 20 s ahead, respectively. As shown in Fig. 3a, at 157 s of elapse time, strong ground motion is observed to be propagating in northern Kanto, and the strong motion is predicted to reach Tokyo 20 s later. At 177 s of elapsed time, strong shaking is actually observed around Tokyo.

Monitoring of propagation of strong motions, such as Fig. 3a (real-time shake-mapping), gives us a direct evidence of impending strong motions to be predicted in EEW.

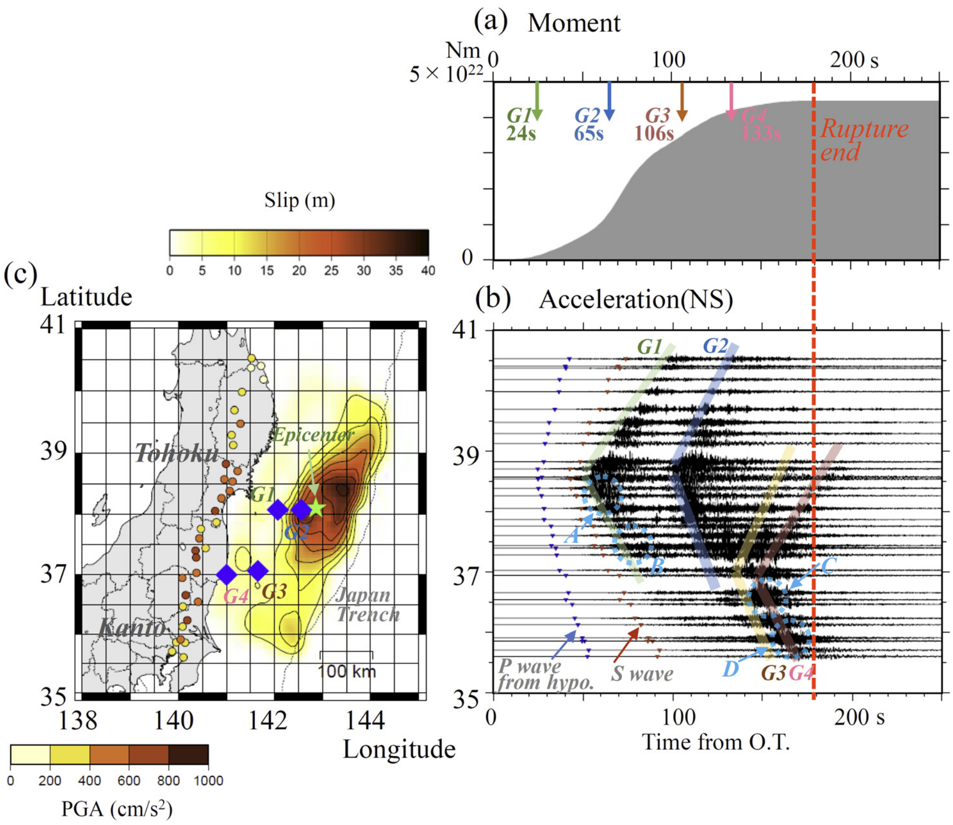

Fig. 2: (a) Time evolution of seismic moment growth and time of strong motion generation of the 2011 Tohoku Earthquake [6]. (b) Accelerograms (NS component) observed at stations indicated in Fig. 2c. (c) Slip distribution estimated from low frequency [6] and four areas of strong motion generation (blue diamonds) identified by Asano and Iwata [7]. Small circles are stations used for Fig. 2b. (After [6,7])

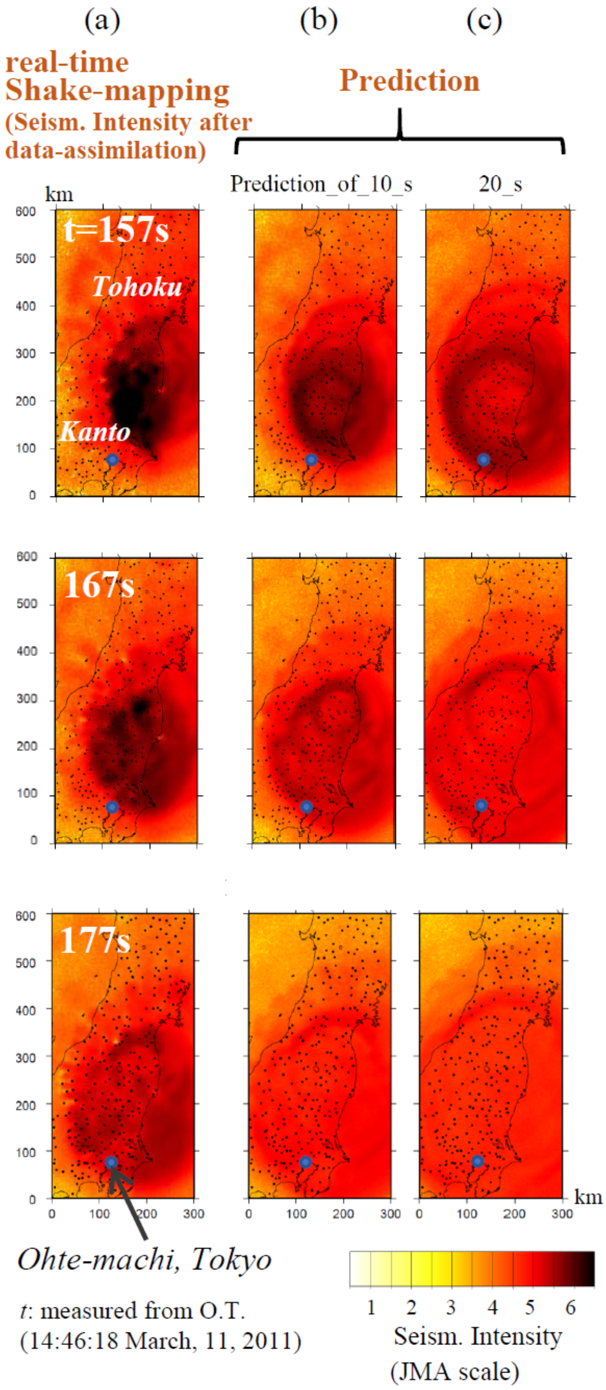

Fig. 3: Example of prediction of seismic intensity using data from the 2011 Tohoku earthquake (M_w9.0). Fig. 3a shows the assimilated distributions, that is, the real-time shake maps. Fig. 3b and c indicate the prediction of 10 s and 20 s, respectively. Modified from [2].

3.2 The 2016 Kumamoto earthquake (M_w7.1)

Fig. 4 show the case of the numerical shake prediction for the 2016 Kumamoto earthquake (M_w 7.1). During the rupture of the mainshock, M 6 class earthquake was remotely triggered at around 37 s apart from 70 km from the epicenter (Fig. 4). This method predicts well the strong shaking from the triggered earthquake.

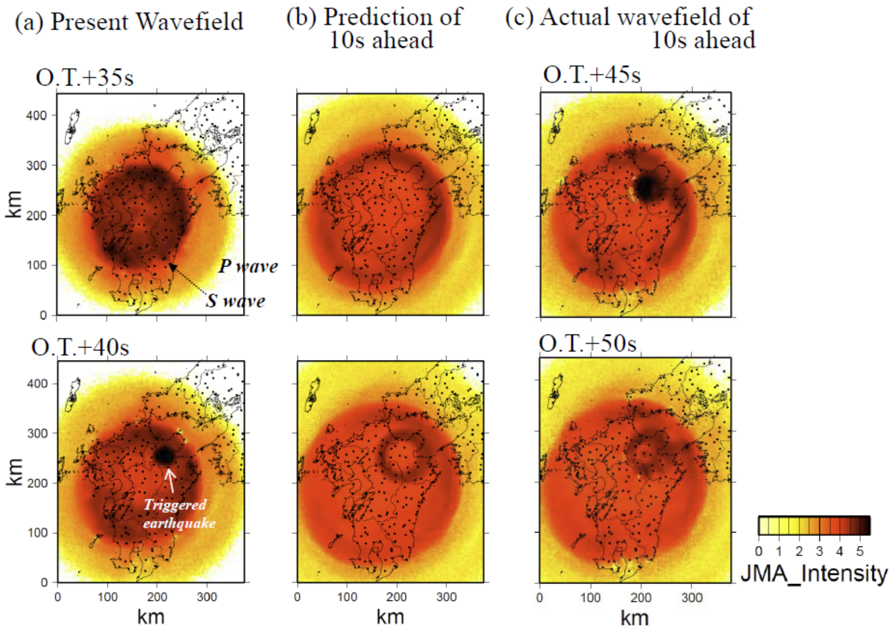

Fig. 4: Example of the numerical shake prediction for the 2016 Kumamoto earthquake (M_w 7.1). (a) Wavefield at O.T.+35s and 40s from the origin time, (b) prediction of 10s ahead, (c) Actual wavefield of 10s ahead. The triggered earthquake occurred at around O.T.+37 s.

4. Conclusion

A new method is proposed for real-time prediction of ground motion using data assimilation, real-time shake mapping, and simulation of wave propagation. The method makes it possible to predict ground motion without information about the earthquake hypocenter and magnitude. This method can precisely predict ground motion even when the extent of the fault rupture is large or when multiple events occur simultaneously.

Kodera et al. [10] developed a method known as the propagation of local undamped motion (PLUM) which is a simplified version of the numerical shake prediction method. PLUM issues an alert to a region around a station where observed ground motions are above a defined threshold (after correcting for site effects). PLUM was introduced into the operational JMA EEW system in 2018. Moreover, the data assimilation technique is applied for real-time prediction of long period ground motion [11].

5. Acknowledgment

I used waveform data from K–NET and KiK-net of National Research Institute for Earth Science and Disaster Resilience (NIED), and from JMA.

6. References

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