New Method for Estimating Earthquake Parameters for Earthquake Early Warning

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The Shinkansen Earthquake Early Warning system rapidly estimates earthquake parameters from a single station data. Epicenter locations in this system are estimated utilizing the Principal Component Analysis and the B- Δ method. This paper proposes new methods to improve the performance of epicenter estimation by introducing variable time windows, instead of the conventional fixed time window. It was found that the new method improved the accuracy and speed of the back-azimuth estimation by 28% and 0.25 seconds respectively. Speed of estimation of the epicentral distance was improved by approximately 1.32 seconds, compared with the conventional method.

Keywords: earthquake early warning, early earthquake detection, single station method, P-wave, principal component analysis, B- Δ method

1. Introduction

The Earthquake Early Warning (EEW) system is one of very effective methods to reduce earthquake hazards. In general, EEW systems can provide earthquake parameter e.g., magnitude and epicenter location, within several seconds following detection of a P-wave at the first station. Nakamura [1] developed the Urgent Earthquake Detection and Alarm System (UrEDAS) in order to stop Shinkansen safely during earthquakes, which was put into practical use approximately 20 years ago.

The Railway Technical Research Institute (RTRI) developed a new EEW system for Shinkansen, and replaced the UrEDAS with the new system in 2004-2005 [2-4]. When an earthquake is detected at a station in the new system, the epicenter location is determined by combining the following two methods (called single station method): first, by the Principal Component Analysis (PCA) [5] (Fig.1) by which the back-azimuth is estimated from the first principal component of the particle motion of the initial P-wave; and secondly by the B- Δ method [6] (Fig.2) by which the epicentral distance (Δ) is estimated from the coefficient B of a fitting function $Bt \exp(-At)$. In this procedure first the epicenter location is determined, and then magnitude is estimated from the determined epicentral distance and amplitude by using a pre-defined attenuation relation for intensity of ground motion. Improvement in accuracy and speed of the single station method to estimate the epicenter location is essential in order to make the new EEW system more stable and effective.

This study first proposes a new method to improve the accuracy and rapidness of PCA by introducing a variable-length time window instead of the conventional fixed-length time window. Secondly, another new method is proposed to improve the rapidness of the B- Δ method by using the time series characteristics of coefficients A and B .

Fig. 1 Estimation of back-azimuth using Principal Component Analysis (PCA)

Fig. 2 Estimation of epicentral distance using the B- Δ method

2. Improving back-azimuth estimations

This chapter sets out a new method to improve both the accuracy and rapidness of back-azimuth estimations by PCA [5] (Fig.1).

First, the conventional procedure for estimating the back-azimuth by using the PCA is described and its accuracy is evaluated by analyzing the waveform records observed at strong ground motion stations, K-NET, operated by the National Research Institute for Earth Science and Disaster Prevention (NIED).

The conventional method estimates the back-azimuth through the following steps:

1. Arrival time of P-wave is calculated using the STA/LTA (Short Time Average to Long Time Average) method [7].
2. Displacement data is calculated from the observed acceleration records by using the IIR (Infinite-duration Impulse Response) filter.
3. The displacement data is band-pass filtered for 1-2Hz utilizing the IIR filter.
4. The back-azimuth is determined from the first principal component of the particle motion of the initial P-wave by using PCA (Fig.1).

The first principal component is equal to the direction with the minimum variance for the sampling points of the displacement data. The length of the time window in the fourth step is set to 1.1 seconds (the start time is the P-wave arrival time point calculated in the first step). The important factor here is for the length of time window to be fixed for all data.

The accuracy of the back-azimuth estimated with the conventional method was then evaluated. 1991 waveform records were selected according to the following requirements: within the period 1995 to 2010; magnitude greater than 5.5; epicentral distance less than 300km; JMA (Japan Meteorological Agency) seismic intensity, greater than 3.5. Figure 3 shows the frequency of error in back-azimuth estimations obtained with the conventional method. In this case, errors are the absolute value of the difference between the estimated back-azimuth and the value published in JMA data. As a result, the RMS (Root Mean Square) of errors is 67.9 degrees.

The next phase was to evaluate the accuracy of errors when the fixed time windows was varied between 0.1 to 2.0 seconds by 0.1 second steps. The RMS of errors obtained in this evaluation are shown in Fig.4. When the length of the fixed-time window is set to 0.6 seconds, the RMS is found to reach the minimum (57.3 degrees). Results indicated that the time window fixed at 0.6 seconds improved accuracy by approximately 16% compared with the conventional time window (1.1 seconds). The error RMS grows as time window length increases, except in the case of the extremely short time windows (from 0.1 to 0.3 seconds) (Fig.4). This is thought to be because longer time windows are more exposed to contamination by trailing scattered waves than the shorter time windows consisting mainly of pure direct P-wave.

Figure 5 shows the error frequency in back-azimuth estimations with a fixed 0.6 second time window. Comparison of Fig.5 (fixed 0.6 seconds time window) and Fig.3 (fixed 1.1 second time window), shows that data with

Fig. 3 Frequency of errors in back-azimuth estimations with the conventional method utilizing the fixed 1.1 second time window

Fig. 4 RMS of errors in case of fixed time windows with lengths of between 0.1 to 2.0 seconds varied at 0.1 second intervals

Fig. 5 Frequency of errors in back-azimuth estimations in the case of a fixed 0.6 second time window

errors within 60 degrees increase, whereas there is a decrease for other data.

The abovementioned results demonstrate the importance of reducing the influence of trailing scattered waves in order to make back-azimuth estimations by PCA more accurate. Consequently, a variable time window approach (Fig.6) is adopted in which pure P-waves are extracted as the input data for PCA. The variable time window in this case means the length of the first half of the wavelength cycle of an initial P-wave in the band-pass displacement data (Fig.6). More specifically, its length is equal to the time from the P-wave arrival to the first zero-cross point. A key factor in this new method is that

the time-window lengths vary depending on the characteristics of each data set. Figure 7 shows the frequency of variable time window lengths for the dataset described above. The average length is 0.85 seconds. It is important for this average length to be shorter than the length of the conventional time window.

The frequency of errors caused when utilizing a variable time window is shown in Fig.8. Consequently, comparing Fig.8 (variable time window) with Fig.5 (fixed 0.6 second time window), reveals that there is an increase in data with errors of less than 30 degrees whereas there is a decrease for other data. The error RMS is 49.0 de-

Fig. 6 Comparison between the conventional fixed time window and the proposed variable time window

Fig. 7 Frequency of the lengths of variable time windows

Fig. 8 Frequency of back-azimuth estimation errors in the case of variable time windows

grees when the variable time window is applied. These results demonstrate that utilization of a variable time window improves accuracy by approximately 28% in relation to results obtained through the conventional method or by 14% compared with application of the fixed 0.6 second time window (which achieves the highest level of accuracy among fixed time windows). Other detailed analyses about improvements reached by using variable time windows are discussed in reference document [8].

It was deemed that the new proposed back-azimuth estimation method would be quite effective for the EEW system. This approach offers the following competitive advantages:

1. In addition to improving the accuracy of back-azimuth estimations it also shortens the estimation time compared with the conventional method, because the average length of the variable time window is shorter than that of the conventional time window.
2. It is so simple that CPU load scarcely increases even for real-time processing.
3. Only a handful of lines of code are required in addition to the conventional method source code, in order to calculate the length of the first half of the wavelength cycle of the initial P-wave.

3. Improvement of epicentral distance estimation

This chapter sets out a proposal for a new method to improve the speed of epicentral distance estimation obtained through the B- Δ method [6] (Fig.2).

The conventional method estimates the epicentral distance by applying the following steps:

1. Arrival time of P-wave is calculated through the STA/LTA method in the same way as for the back-azimuth estimation.
2. Observed acceleration data is band-pass filtered for 10-20Hz by using the IIR filter.
3. The epicentral distance (Δ) is estimated from the coefficient B which is determined by fitting the equation,

$$y = B \exp(-At) \quad (1)$$

to the UD-component envelope of the band-passed acceleration data of the initial P-wave.

Coefficient B has a good correlation with the epicentral distance ($\log_{10}\Delta = -0.498 \log_{10}B + 1.965$). The coefficient B is almost independent of magnitude, because coefficient A is related to the total shape of the envelope mainly affected by magnitude and coefficient B is related to the slope of the initial part of P-wave mainly affected by epicentral distance respectively. We call the conventional method "2 seconds B- Δ method," since the length of the time window in the third step is often set to 2 seconds. The RMS of the difference between $\log_{10}\Delta_{JMA}$ and $\log_{10}\Delta_{2s}$ is approximately 0.32 (Δ_{JMA} and Δ_{2s} represent the epicentral distance as published by JMA and that estimated through the 2 seconds B- Δ method, respectively). The dataset in this chapter is the same as in the previous chapter.

This study focuses on the time series of coefficients

A and B in order to improve the speed of the B- Δ method. Coefficients A and B are calculated for time window lengths of between 0.1 to 2.0 seconds in 0.1 second increments in the third step.

Consequently, the A and B time series have two important characteristics:

1. A and B are highly correlated.
2. A converges to each constant value as time progresses.

Figure 9 illustrates the first characteristic. The average and standard deviation of the correlation coefficient between the time series of A and that of $\log_{10}B$ are 0.85 and 0.15 respectively. Figure 10 demonstrates the second characteristic. Fig.10 (a) and (b) show the time

Fig. 9 Examples of A and B coefficient time series

- (a) Recorded results from station code AKT020 (epicentral distance of 8km) for event (M5.1) occurring at 14:18, 26 Feb 1999, in Akita prefecture
- (b) Recorded results from station code WKY006 (epicentral distance of 180km) for event (M6.9) occurring at 19:07, 5 Sep 2004, on the Southeastern Kii peninsula
- (c) Recorded results from station code NIG013 (epicentral distance of 53km) for event (M6.8) occurring at 17:56, 23 Oct 2004, in mid-Niigata prefecture
- (d) Recorded results from station code MYG006 (epicentral distance of 50km) for event (M7.2) occurring at 8:43, 14 Jun 2008, in Iwate-Miyagi prefecture

Fig. 10 Time series of the coefficient A (a) and its differential value (b)

series of A and its differential value respectively. Although all data used in the analysis is plotted in these figures, A converges clearly within 2 seconds. These characteristics reflect the suitability of fitting equation (1) to the initial P-wave envelope.

These characteristics give rise to a possible new method to improve the rapidness of the B- Δ method, i.e. ability to estimate the epicentral distance from coefficient B when the convergence of A is confirmed (we call this time point “the convergence time”) with almost the same accuracy as the 2 seconds B- Δ method. Therefore, the proposal is for a method which monitors the convergence of coefficient A by using two parameters, for real-time processing (Fig.11). The first parameter is Tad which is the threshold for the differential value of A ; the other parameter is Dd which is the threshold for the duration in which the differential value of A is less than Tad . This new method was named the “Variable B- Δ method.”

Figure 12 shows the relationship between Dd and the RMS of the difference between $\log_{10}\Delta_{2s}$ and $\log_{10}\Delta_{var}$ (Δ_{var} means the estimated epicentral distance by using the Variable B- Δ method); Fig.13 shows the relationship between Dd and the average convergence time. The figures illustrate that the smaller Tad are and the longer Dd are respectively (signifying that the judgment of convergence is more severe), the later the convergence time and the smaller the RMS of the difference between $\log_{10}\Delta_{2s}$ and $\log_{10}\Delta_{var}$ are, respectively as well. In other words, this result indicates a trade-off between convergence time and accuracy of the Variable B- Δ method as opposed to the 2 seconds B- Δ method.

The speed of the B- Δ method can be improved while keeping the accuracy of the 2 seconds B- Δ method, by appropriate selection of parameters (Tad and Dd) from the Variable B- Δ method. For example, when $Tad=30(1/s^2)$ and $Dd=0.3(s)$ are chosen, the average of the convergence time is approximately 0.68 seconds and the RMS of the difference between $\log_{10}\Delta_{JMA}$ and $\log_{10}\Delta_{var}$ is approximately 0.30. This RMS value is almost equal to the value obtained using the 2 seconds B- Δ method, as described above. The conclusion therefore is that the Variable B- Δ method is quite effective for the EEW system, because speed can be improved by approximately 66%

Fig. 11 Schematic illustration of the Variable B- Δ method

Fig. 12 Relationship between Dd and the RMS of the difference between $\log_{10}\Delta_{2s}$ and $\log_{10}\Delta_{var}$

Fig. 13 Relationship between Dd and average convergence time

while retaining epicentral distance estimation accuracy, by comparison with the 2 seconds B- Δ method.

4. Conclusion

This study proposed two methods to improve performance in estimation of epicenter locations. In the estimation of the back-azimuth, the accuracy and rapidness were improved by 28% and 23% respectively, by introducing variable-length time windows. For epicentral distance estimation, speed was improved by 66% while maintaining the same level of accuracy, by using the time series characteristics of coefficients A and B .

Applying the methods proposed in this study to the EEW system is expected to produce more robust and faster earthquake warnings.

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