IMPROVEMNET AND PERFORMANCE EVALUATION OF THE EARTHQUAKE EARLY WARNING ALGORITHM FOR RAILWAYS IN JAPAN

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Abstract

In Japan, railway, which is distributed throughout the country, is one of important transportation systems. Because the running trains are always in the face of earthquake risks due to the high seismicity, Japanese railway operators have installed seismometers, and have developed earthquake early warning (EEW) systems that analyze the earthquake ground motion observed by the seismometers in real time and issue an alarm to suspend running trains as soon as possible if necessary.

P-wave with the fastest propagation velocity carries effective information to suspend trains rapidly during earthquakes. Based on the initial P-wave observation, the seismometers installed for the Japanese high-speed Shinkansen railways estimate an epicenter location and a magnitude at every single observation site. Since it is impossible to know when and where earthquakes will occur, improving the performance of these seismometers is one of critical research subjects to enhance the safety of train operation during earthquakes.

Railway Technical Research Institute (RTRI) improves the algorithm installed in the seismometers in order to issue alarm more quickly and reliably. In this paper we describe the outline of the improved algorithm to estimate seismic source parameters and present a result of the comprehensive performance evaluation of the algorithm.

To examine the performance comparison between the conventional and improved algorithm in terms of alarm range, we evaluate the range sizes whether or not the system correctly performed. The result of the evaluation demonstrates that the improved algorithm increases the correct alarm ratio (i.e., an alarm is issued to the range where the running trains need to suspend) by approximately 6% and decreases the false alarm ratio (i.e., an alarm is issued to the range where the running trains need not to suspend) by approximately 87% in comparison with the conventional algorithm. Moreover, we compare the warning times issued by the algorithm, and find that the improved algorithm issues the alarms about several seconds earlier than the conventional algorithm.

We conclude that the improved algorithm is able to enhance the performance of the seismometers for Japanese railways and that the safety and operation stability of running trains during earthquakes will be progressed by introducing the improved algorithm into the seismometers.

Keywords: Earthquake early warning, Seismometer, Algorithm, Alarm issuance, Performance evaluation

1. Introduction

Earthquakes have occurred frequently around Japan. In the past, massive earthquakes caused enormous damage to railways. For example, many damage occurred to the railway structure in the Southern Hyogo Prefecture Earthquake of M_j7.3 on January 17, 1995. In addition, during the Middle Niigata Prefecture Earthquake of M_j6.8 on October 23, 2004, the Shinkansen derailed while running at a speed of approximately 200 km/h. Many countermeasures have been taken to reduce the railway damage caused by earthquakes. One of them is a system for automatically suspending running trains when an earthquake occurs. At present, earthquake early warning (EEW) systems are introduced to reduce damage from earthquakes [1-3]. The EEW system determines the impact on railway structures and running trains based on the data of seismic waves detected by seismometers installed along and near railway lines. And the seismometer automatically issues an alarm for the range to be alerted. Especially for the EEW system of Shinkansen which runs at a high-speed throughout Japan, because it is required to quickly determine whether the alarm should be issued or not, the EEW algorithm is used to estimate the seismic source parameters, such as the epicentral distance, the epicentral back-azimuth and the magnitude, based on the data for the period of several seconds at the beginning of the earthquake (P-wave data) [1, 4-10].

Railway Technical Research Institute (RTRI) is developing the EEW algorithm to estimate the seismic source parameters and make a decision for the alarm issuance earlier and with higher accuracy [8, 9]. Now the EEW system that uses seismometers developed based on the improved algorithm is being introduced [11]. In this paper, we will introduce the methods to estimate the seismic source parameters and determine whether or not to issue the alarm in the EEW algorithm of Shinkansen. In addition, we will show the result of comprehensive performance evaluation of the accuracy for the range and the required time of the alarm issuance. And we describe the effect of the introduction of the improved algorithm in comparison with the conventional algorithm [12].

2. Algorithm for earthquake early warning

Fig.1 shows a flow of a process, from a P-wave detection to the alarm issuance, by the EEW algorithm. At first, the EEW algorithm correctly detects the arrival of the P-wave at the seismometer (① P-wave detection). Then the EEW algorithm estimates the epicentral distance, the epicentral back-azimuth and the magnitude in the seismic source parameters estimation process based on the data for the period of several seconds just after the arrival of the P-wave (② Estimation of seismic source parameters). In this step, this algorithm determines whether the vibration detected by the seismometer is excited by an earthquake or not (③ Noise discrimination). Because the seismometer detects not only earthquake ground motions but also noises such as vibration induced by the running trains and excited by other transportations, this process is important to prevent a false alarm issuance for railway seismometers. At last, the algorithm determines the range of the alarm issuance according to the data of the seismic source parameters estimated in the step ② and then issues the alarm within the appropriate range (④ Alarm issuance).

RTRI developed the improved methods for the processes of ① P-wave detection, ② Estimation of seismic source parameters and ③ Noise discrimination for the EEW algorithm to improve the safety and stability of railway transportation during earthquakes. Table 1 lists the upgraded points of the improved EEW algorithm. The major points that have been improved and added are represented in red. The main improvements to estimate the seismic source parameters are described below.

- Epicentral distance estimation: To estimate the epicentral distance, the empirical relationship between an epicentral distance and an increasing ratio of acceleration of the initial P-wave is used. At the improved algorithm, the function expressing an increasing ratio of the initial P-wave is simplified ($y(t)=Ct$) compared with the conventional method ($y(t)=Bt \cdot \exp(-At)$), and the method uses only the first 0.5 seconds of P-wave data (Fig.2 (a) and (b)).

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- Epicentral back-azimuth estimation: The back azimuth is determined through the Principal Component Analysis (PCA) for the displacement of the P-wave initial phase. In the conventional algorithm, the length of the time window for the analysis is fixed for all data. On the other hand, we introduced a variable-length data time window which is determined by the first half cycle of the wavelength of the initial P-wave at the improved algorithm (Fig.3).
- Magnitude estimation: Magnitude is calculated using an empirical attenuation relationship of observed amplitude, an epicentral distance and magnitude. We improved the method so that the magnitude is determined using the acceleration amplitude, in addition to the displacement amplitude conventionally used. And we improved the relational expression of amplitude, the epicentral distance and magnitude ($M_j = Pm1 \cdot \log_{10} A + Pm2 \cdot \log \Delta + Pm3 + Pm4 \cdot \Delta$).

The time required for estimation has been reduced and the estimation accuracy has been improved in all the methods. The algorithm combined these methods is able to reduce the time until the alarm issuance by one second due to the default parameters compared with the conventional algorithm [8, 9].

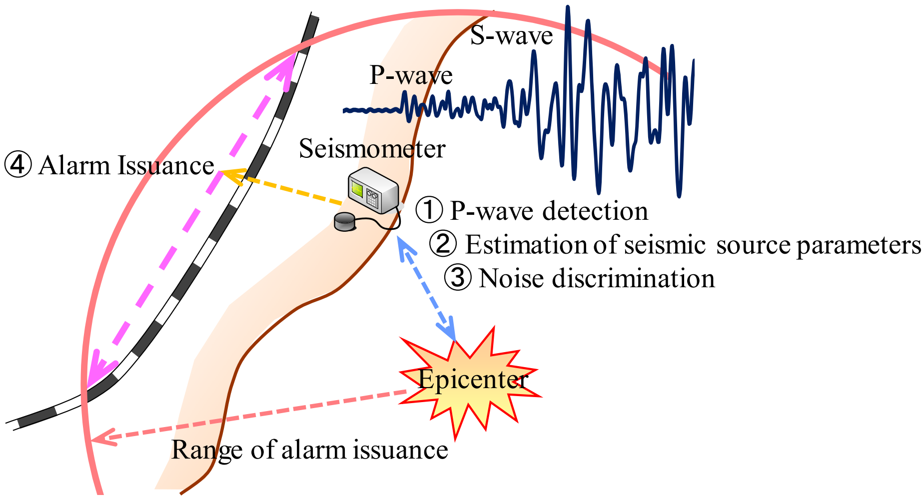

Fig. 1 – Flow of the alarm issuance by the EEW algorithm

Table 1 –Upgraded points of the improved EEW algorithm

	Conventional algorithm	Improved algorithm
P-wave detection	STA/LTA method	STA/LTA method + Level trigger method
Epicentral distance	B-Δ method (2.0 sec.)	C-Δ method (0.5 sec.) C-Δ level Considering viscous damping
Epicentral back-azimuth	Fixed window mehod (1.1 sec.)	Variable window method (Less than 1.0 sec., Averaged 0.58 sec.)
Magnitude	Disp. Mag	Disp. Mag + Acc. Mag (OR operation) Addition of the estimation timing Considering viscous damping
Noise discrimination	Amplitude	Amplitude + Frequency
Alarm issuance time	Minimum 2.0 sec. (Default)	Minimum 1.0 sec. (Default)

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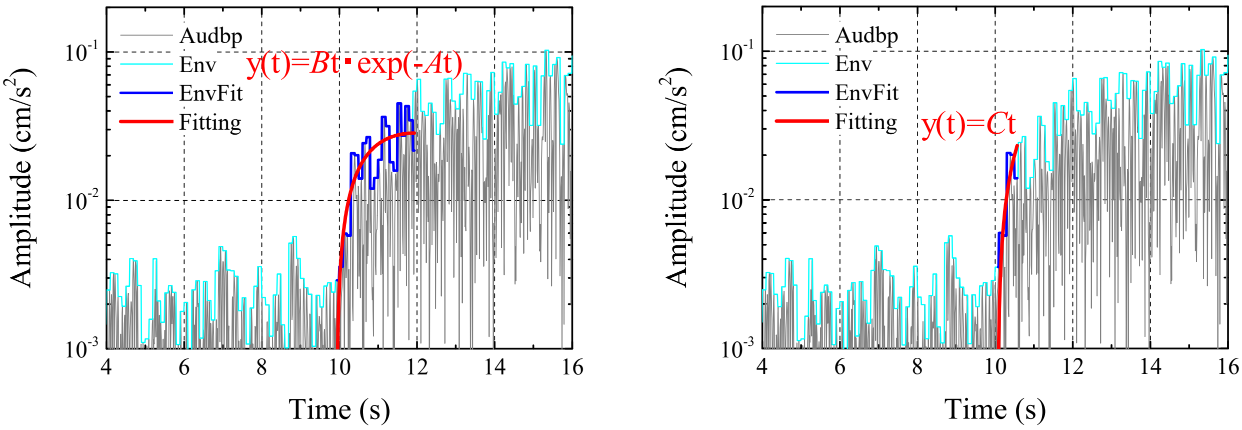

(a) The conventional algorithm

(b) The improved algorithm

Fig. 2 –The fitting function to estimate epicentral distance

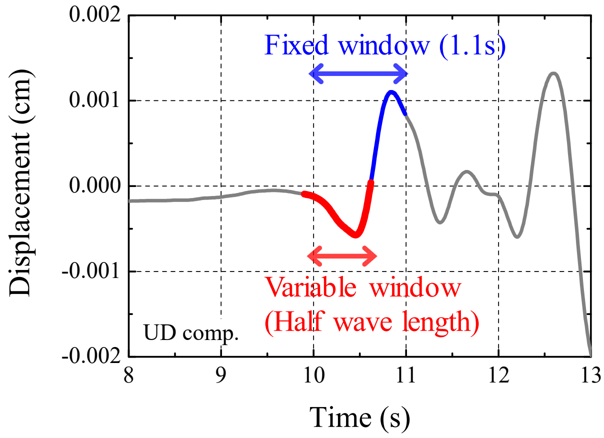

Fig. 3 –Comparison between the Fixed window and the variable window to estimate epicentral back-azimuth

3. Simulations using actual earthquake data

To validate the estimation result of seismic source parameters in practice, the improved algorithm is applied to actual earthquake data. Waveform data was recorded at K-NET stations operated by National Research Institute for Earth Science and Disaster Resilience (NIED) [13]. This offline simulation used default parameters and recorded data from the Northern Osaka Prefecture Earthquake of M_j6.1 on June 18, 2018. Fig.4 (a) and (b) show the estimated epicenters locations by the conventional and improved algorithm respectively. In these figures, the star marks denote the epicenter determined by JMA, and cross marks denote the epicenter estimated by the EEW algorithms. Observation stations within 200 km from the epicenter were selected for this evaluation. The circle represents the region within a radius of 200 km, and triangle marks denote the subject stations where the P-wave was detected. As a result of the simulations, 127 stations detected P-wave applying the conventional algorithm, also 142 stations detected it applying the improved algorithm. Comparison of both algorithms demonstrated that improved algorithm has better P-wave arrival detection performance.

The estimated epicenter locations under the improved algorithm are more densely distributed around the JMA epicenter than the estimated locations under the conventional algorithm. This result confirms that the estimation accuracy for the epicenter locations can be better by the improved algorithm.

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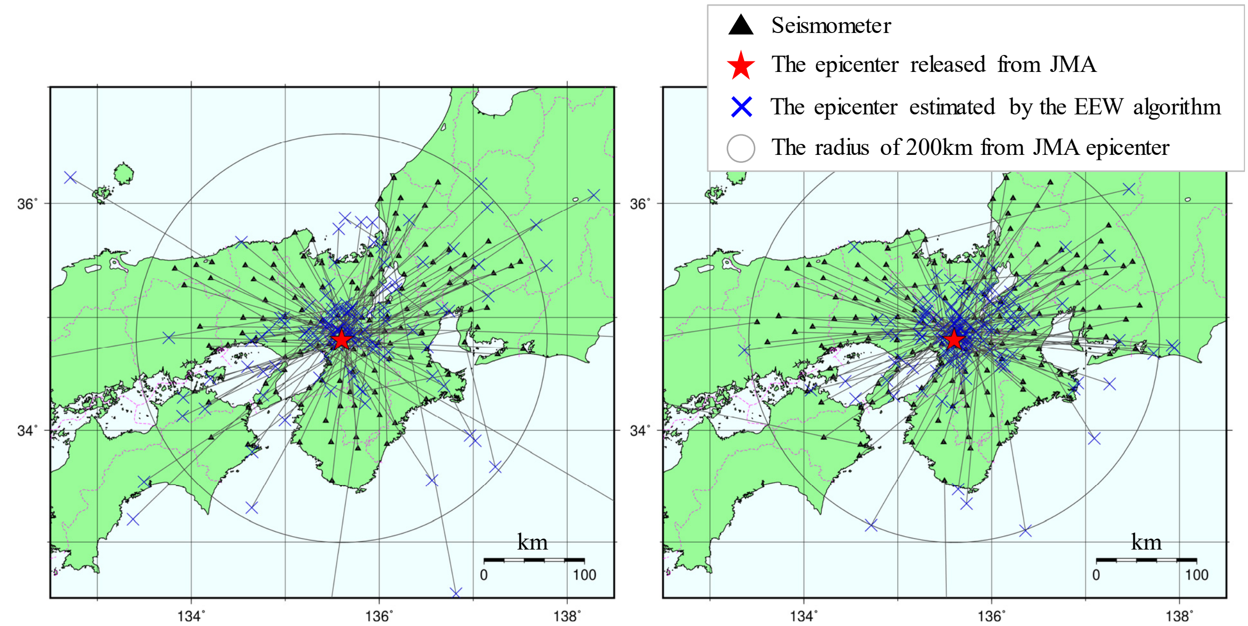

(a) The conventional algorithm (N=127)　　(b) The improved algorithm (N=142)

Fig. 4 –Estimated epicenter locations in case of the Northern Osaka Prefecture Earthquake

4. Method to determine a range of an alarm issuance

In this section, we describe the method to determine the range of the alarm issuance by the EEW system of Shinkansen. With relation to the EEW system, a method to determine the range of the alarm issuance based on the relation between the magnitude (M) and the epicentral distance (Δ) of the location where a railway facility was damaged in the past earthquake (M-Δ method) is widely used. The relation between the magnitude and the epicentral distance in which a railway facility was damaged (Fig. 5) is represented by the Eq. (1) [10].

$$\log_{10}\Delta=0.51M-1.5 \quad (1)$$

Where, Δ is the epicentral distance (km) of the farthest point where a railway facilities were damaged and M

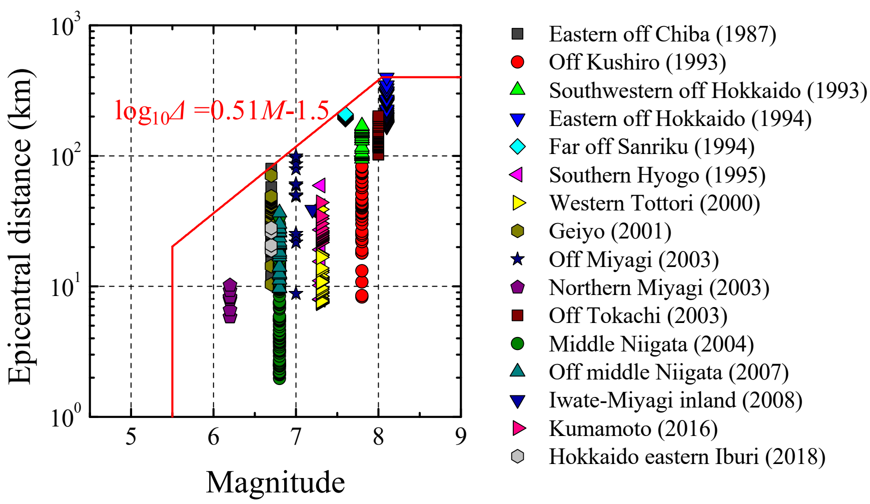

Fig. 5 – Relationship between epicentral distances of the locations where a railway facilitie were damaged [14, 15] and magnitude in various earthquakes (M-Δ diagram)

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is the magnitude released from JMA. The EEW system of Shinkansen uses two types of methods to determine the range of the alarm issuance applying the M-Δ method. The first method, which suspends trains within a predefined range, issues the alarm when the seismometer is contained in the range defined by the Eq. (1). This is a basic control method used for seismometers of railway systems. It plays an important role in the system because it allows the concerned seismometer alone to issue the alarm even if the communication with the other seismometer and the server is disrupted. The second method, which suspends trains in a range within which damage is expected to occur changes the range of the alarm issuance according to the estimated epicenter location and the magnitude. The seismometers issue the alarm for the whole range defined by the Eq. (1). The method is able to issue an appropriate alarm according to the estimated seismic source parameters.

5. Comprehensive performance evaluation of algorithms

To introduce the improved EEW algorithm, we conducted comprehensive performance evaluation for the algorithm to compare it with the conventional algorithm to verify the effect of the introduction. We have already inspected the accuracy for the methods listed in Table 1 to evaluate the performance of the EEW algorithm and confirmed that the accuracy of the improved algorithm matches or is superior to that of the conventional algorithm [8, 9]. On the other hand, to verify the effectiveness of introduction of the improved EEW algorithm, it is required to comprehensively evaluate the performance of the system when each estimation methods are combined with the method for determining whether to issue the alarm described in Section 2. For this purpose, as a comprehensive performance evaluation, we evaluated the range and the timing of the alarm issuance.

5.1 Correct and false alarm ratios for the range of the alarm issuance

To evaluate how well the range for which the EEW algorithm determines to issue the alarm matches with the correct range of the alarm issuance, we calculated the correct and false alarm ratios of the alarm issuance and compared them between the conventional and improved algorithm. Fig. 6 shows a schematic illustration of the correct and false alarm ratios for the range of the alarm issuance. The range of the alarm issuance is defined as the range using the Eq. (1). The range defined in this paper is described below.

- Alarm range by JMA information (Range A): The alarm range determined by using the earthquake source parameters released from Japan Meteorological Agency (JMA)
- Correct alarm range by estimation (Range B): The range where Range A and the alarm range estimated by the EEW algorithm overlap
- False alarm range by estimation (Range C): The range where Range A is removed from the alarm range estimated by the EEW algorithm
- Correct alarm ratio: The ratio of Range B divided by Range A
- False alarm ratio: The ratio of Range C divided by Range A

For the case in which more than one seismometer issued the alarm for each earthquake, the estimated range of the alarm issuance is defined by lapping over the ranges that those seismometers respectively estimated. For the safety of railway systems during earthquakes, it is preferable that the correct alarm ratio approaches to 1. For the stability of railway transportations, it is preferable that the false alarm ratio is decreased as much as possible. For this evaluation, we used the seismic data for 195 earthquakes of M_j4.5 or larger that occurred in the period from 1996 to 2011 and recorded by the earthquake observation networks which are K-NET and KiK-net operated by NIED [13]. In this evaluation, the seismometers of the K-NET and KiK-net are assumed as those for the EEW seismometers of railway system.

Fig.7 (a) and (b) show the example of the range of the alarm issuance in case of the earthquake of M_j5.8 on April 20, 2005. It shows that the epicenter estimated by the improved algorithm is located near the correct epicenter by JMA and the false alarm ratio significantly decreases. Table 2 lists the correct and false alarm ratios for the range of the alarm issuance due to all the data used for the evaluation. In this table, the average of the correct alarm ratio for each earthquake is represented as that for the whole evaluation. For the false

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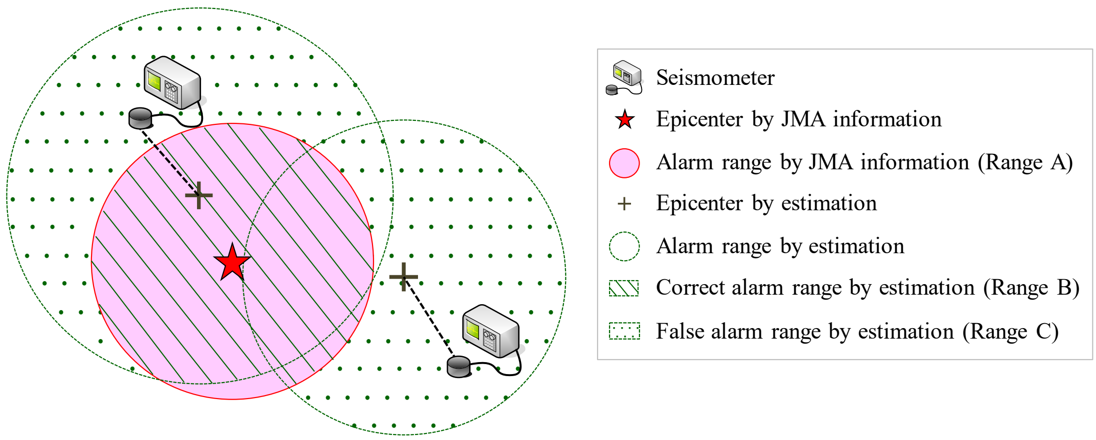
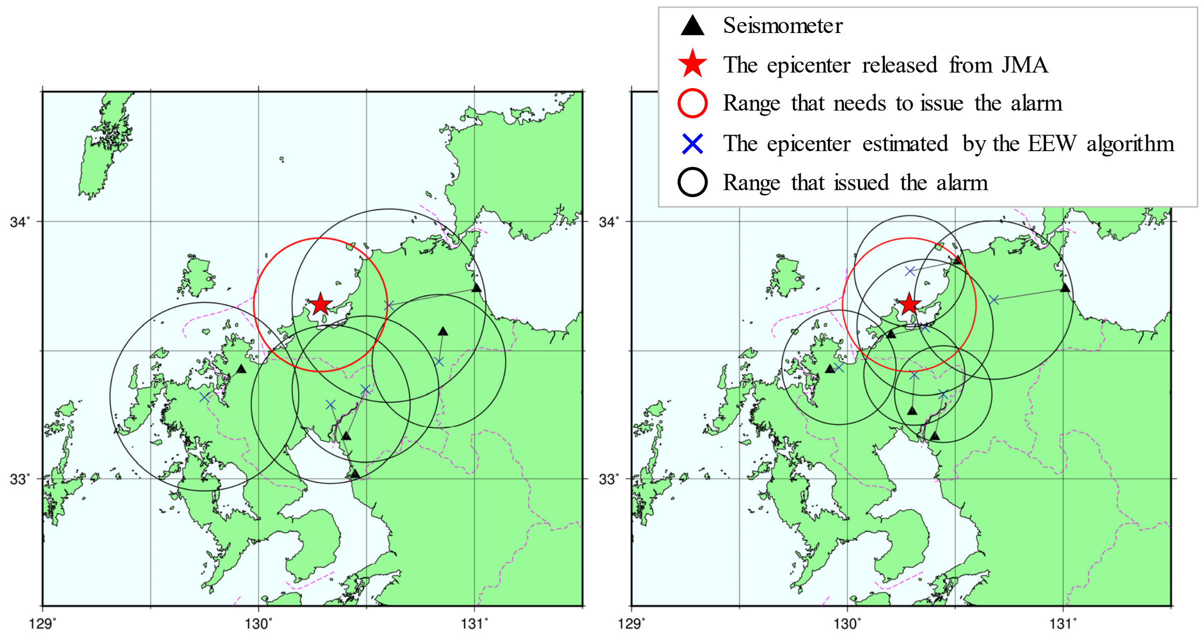


Correct alarm ratio = Range B / Range A   False alarm ratio = Range C / Range A

Fig. 6 – Schematic illustration of the correct and false alarm ranges



(a) The conventional algorithm   (b) The improved algorithm

Fig. 7 –Range of the alarm issuance in case of the earthquake of M_J5.8 on April 20, 2005

Table 2 – Evaluation result of the correct and false alarm ratios

	Conventional algorithm	Improved algorithm
Correct alarm ratio	0.87	0.93
False alarm ratio	1.42	0.19

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alarm ratio, the median for all the earthquakes is represented as that for the whole evaluation because the values of the false alarm ratio determined for the earthquakes do not conform to a Gaussian distribution. As indicated in Table 2, both the conventional and improved algorithms achieve the correct alarm ratio of nearly 90%. The improved algorithm increases the correct alarm ratio by approximately 6% and decreases the false alarm ratio by approximately 87% in comparison with the conventional algorithm. The result indicates that the improved algorithm more correctly determines the range of the alarm issuance and is expected to contribute for the improvement of the safety and stability during earthquakes.

5.2 Timing of the alarm issuance

We also examined the timing of the alarm issuance for each earthquake to evaluate how earlier the alarm is issued by the improved algorithm. To evaluate the estimation result and the action based on the determination of the alarm issuance due to each seismometer, the timing when the seismometer is contained in the range for which the concerned seismometer itself based on the Eq. (1) was adopted as the timing of alarm issuance illustrated in Fig. 8. Fig. 9 shows the result of the examination for the timing of alarm issuance in case of the Middle Niigata Prefecture Earthquake of M_j6.8 on October 23, 2004. We examined the data of the seismometers of which the epicentral distance is 50 km or less among the recorded data by K-NET [13] for the Middle Niigata Prefecture Earthquake. The horizontal and vertical axes in Fig. 9 respectively represents the time has elapsed after the earthquake occurred and the rate of seismometers that

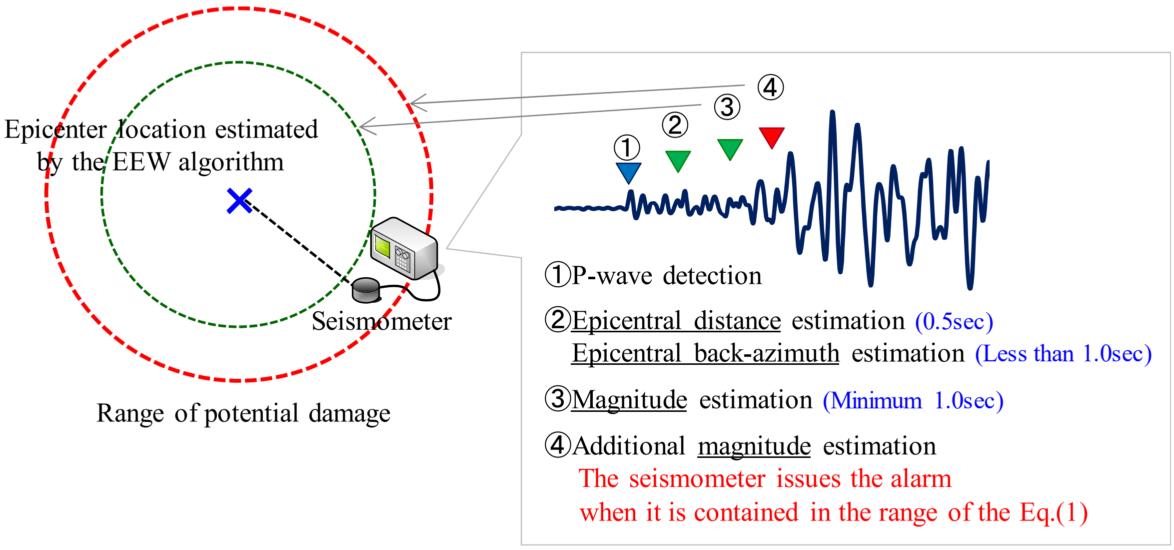

Fig. 8 – Overview of the timing of the alarm issuance

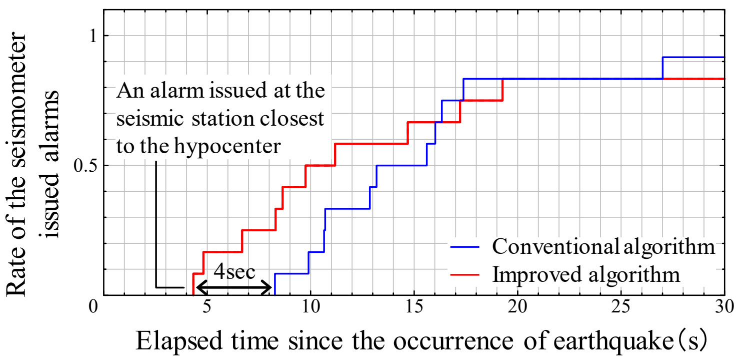

Fig. 9 – Timing of the alarm issuance in case of the Middle Niigata Prefecture Earthquake

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issued the alarm. As shown in Fig. 9, the improved algorithm issued the first alarm earlier and the difference in the timing of the alarm issuance was approximately 4 seconds. Also, for the second and following alarms, the improved algorithm issues the alarm earlier than the conventional algorithm for almost all seismometers. The result of evaluation on the near-source data for other damaging earthquakes indicates the same tendency, therefore it is proved that it is able to issue the alarm earlier by introducing the improved algorithm.

6. Conclusions

RTRI have improved the EEW algorithm for the Japanese high-speed railways of Shinkasen. In this paper we showed the flow of the alarm issuance by the EEW algorithm. Then we described the improved methods to estimate seismic parameters and to determine the range of the alarm issuance. To evaluate the effect of the improved EEW algorithm, we conducted comprehensive performance evaluation of the range of the alarm issuance and time required for the alarm issuance to compare the results with those of the conventional algorithm. By comparing the correct and false alarm ratios for the range of the alarm issuance, we confirmed that the correct alarm ratio was increased by approximately 6% and the false alarm ratio decreased by approximately 87% compared with the conventional algorithm. Also, we confirmed that the timing of the alarm issuance became earlier by 4 seconds at the maximum at the nearest observation point compared with the conventional algorithm in case of the Middle Niigata Prefecture earthquake. These results indicate that the accuracy of the alarm issuance is improved and it is able to issue the alarm earlier by introducing the improved EEW algorithm. The improved EEW algorithm described in this paper is being introduced for the EEW system of Shinkansen since 2018 and is expected to contribute to further improvement of safety and stability of railway transportation during earthquakes.

7. Acknowledgments

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