Applicability of Magnitude Determination Method Considering Time Dependence of P-Wave Growth to Railway Earthquake Early Warning System

Shunta NODA
Seismic Data Analysis Laboratory, Center for Railway Earthquake Engineering Research

This article examines an earthquake magnitude (M) determination method to test its applicability for the railway earthquake early warning system. Although the effectiveness of the M determination method has been shown so far when multiple station approach is used, the railway system employs a single station algorithm considering immediacy of the warning. This study investigates if the M determination method can improve the performance of the system analyzing seismic records observed in Japan. As a result, the test demonstrated that the method speeds up the final M estimation without loss of accuracy, suggesting that the risks of running trains during an earthquake can be reduced by applying the new technique to the railway system.

Keywords: earthquake early warning, magnitude, P wave

1. Introduction

Earthquake early warning (EEW) systems can provide a lead time to halt running trains during an earthquake event [e.g., 1]. The Japanese high-speed railway (Shinkansen) is equipped with its own EEW systems which consist of hundreds of seismometers deployed across the country. One of the essential functions in the Shinkansen system is that earthquake parameters, such as epicenter location and earthquake magnitude (M), are estimated at every single station (hereafter, single station algorithm) in order to issue a stop signal at the earliest opportunity [1]. To locate an epicenter, the system employs the C-Δ method that uses a correlation relationship between the initial slope of the P-wave acceleration data (C) and epicentral distance (Δ) [2, 3]. The method has important advantages: the initial slope parameter C can be determined within 1 second of P-wave onset; and the correlation is found independently of M. This suggests that M can be estimated and even updated after locating the epicenter examining P-wave growth. If M increases, the earthquake warning is issued to trains running in the larger area looking at the M-Δ diagram [4], demonstrating that the fast M determination is a key to ensure the safety of running trains when an earthquake occurs.

To estimate M in the single station algorithm of the Shinkansen system, the ground motion prediction equation (GMPE) approach is utilized [e.g., 2, 5, 6], for example:

\[ \log \text{Disp}_p = \log \text{Disp}_s + \alpha \times \Delta + \beta \times M + \gamma, \]  

(1)

where Disp is displacement amplitude, Disp_s is displacement amplitude corrected by distance, Δ is epicentral distance and α, β, and γ are coefficients determined for the relation (note that (1) is the simplest form for GMPE). Equation (1) shows that M is proportional to the common logarithm of displacement observed at a given distance. In other words, the bigger M grows, the stronger recorded displacement becomes, while the earthquake rupture is in progress. This suggests that, as a technical limitation of the GMPE approach, the final M is obtained at the time when the peak amplitude is detected as long as the coefficients are constant. [7] and [8] reported that about 1.5 s, 3 – 4 s, and 10 s after the P onset were commonly required to observe the peak amplitude arrivals of M 5, M 6, and M 7 earthquakes, respectively, which are consistent with the typical rupture durations [e.g., 9].

To overcome this technical limitation, [10] found new characteristics in initial P-wave growth, which will be briefly introduced in Chapter 2. Examining the characteristic, [11] proposed updating the conventional GMPE approach to improve the speed of the M estimation. This will be described in Chapter 3. The approach proposed by [11], however, has not yet been tested to determine if it can be applied to the single station algorithm used in the Shinkansen EEW system.

This study thus demonstrates this applicability in Chapter 4. It can be concluded that the proposed approach is effective to reduce the risks of running trains while an earthquake is underway.

2. Findings in the time dependence of P-wave growth

[10] analyzed a dataset of Kyoshin net (K-NET) seismograms recorded by the National Research Institute for Earth Science and Disaster Resilience (NIED) [12] in terms of how the initial P-wave data started and grew. The dataset contained 7,514 accelerograms observed from 150 events with 4.5 ≤ M_w ≤ 9.0 (M_w: moment magnitude) and source depth ≤ 60 km (see [10] for the hypocenter distribution). They selected the records with hypocentral distances of less than 200 km and analyzed the averages of absolute displacement binned by distance and M_w.

Consequently, [10] found some characteristics in the initial P waves as shown in Fig. 1 (see [10] and [13] for the detail). Although the P waves were initially similar (i.e. no dependence on the final M could be found at the P onset), similarity in growth ended earlier for smaller earthquakes (i.e. the departure from similar growth occurs depending on the final M). Most importantly, the departure time, \( T_{\text{dp}} \),
was significantly shorter than the peak amplitude arrival (= typical source duration). That is to say, for $M_5$, $M_6$, and $M_7$ events, the peak amplitudes were measured at about 1.5 s, 3 – 4 s and 10 s after P-wave onset as indicated above, while $T_{dp}$ was 0.4 s, 1.1 s and 2.9 s, respectively. As shown in Fig. 2, the scaling relationship between $M_w$ and $T_{dp}$ was:

$$M_w = 2.29 \times \log T_{dp} + 5.95.$$  \hspace{1cm} (2)

Note that this relation was established up to $M_7$ class earthquakes.

The reasons why $T_{dp}$ occurs earlier than the peak arrival and why the relation cannot scale with huge earthquakes ($M_8$ class and larger) were discussed in [13], although these are still controversial. As described in the next chapter, however, the scaling relationship can be useful to improve the rapidity of $M$ estimation for EEW [11].

3. $M$ determination considering the scaling relationship between $M_w$ and $T_{dp}$

To improve the performance of the GMPE approach, [11] proposed a new technique using (1) (note that [11] analyzed the same dataset with [10]). First, the coefficient $\alpha$, which is associated with the geometrical spreading, was determined considering the attenuation of displacement amplitude. This resulted in a constant $\alpha$ value because the geometrical-spreading effect was not time-dependent.

Second, the coefficients $\beta$ and $\gamma$ were obtained, which control the relationship between $M$ and displacement corrected by distance. The $\beta$ value corresponds with the slope of the relationship so that it adjusts the correlation between them, and the $\gamma$ value represents the intercept of the relationship. In the new technique, $\beta$ was determined as a constant value examining the displacement measurements after $T_{dp}$ which had a significant correlation with $M_w$. This was because the scaling relation, (2), demonstrated that the correlation was not significant before $T_{dp}$ occurs, while it was found to be so after $T_{dp}$. On the other hand, $\gamma$ increased with time when fixing $\beta$ (i.e., $\gamma$ is set as a function of time, $\gamma[T]$; see [11] for more detail). Table 1 shows the coefficients determined in [11]. Note that the units of displacement ($Disp$ and $Disp_c$) and epicentral distance ($\Delta$) are centimeter and kilometer, respectively.

[11] tested the proposed technique using the five closest station data for each event epicenter, that is, multiple station data were analyzed, whereas the Shinkansen EEW system employs the single station algorithm as mentioned above. In the next chapter, verifications were made to check if the time-dependent GMPE approach is applicable to the railway system.
4. Applicability of the \( M \) determination method to the single station algorithm

This study looks at the performance of the \( M \) estimation approach proposed by [11] for the single station algorithm utilized in the Shinkansen EEW system. The same dataset was used as in [11]. The accelerograms were twice integrated to convert them to displacement, and they were then filtered with the band-pass frequency of 0.075 – 3 Hz. The running maximum of the absolute displacement was taken and the initial 4-second data after the P arrival was analyzed. The \( M \) estimates (\( M_{\text{est}} \)) were computed for every single station using the GMPE approach in which the coefficients are shown in Table 1.

![Figure 2](image)

**Figure 2** Relationship between \( \log T_{dp} \) and \( M_w \) presented by [10]. Black solid and dashed lines show the regression relationship and its standard deviation (SD), respectively.

**Table 1** Coefficients of (1) determined by [11]

| \( T \) (s): Time from the P onset | \( \alpha \) | \( \beta \) | \( \gamma \) |
|-----------------------------------|----------|----------|----------|
| 1.00                              |          |          | -3.30    |
| 1.25                              |          |          | -3.25    |
| 1.50                              |          |          | -3.22    |
| 1.75                              |          |          | -3.17    |
| 2.00                              |          |          | -3.15    |
| 2.50                              |          |          | -3.09    |
| 3.00                              |          |          | -3.02    |
| 4.00                              | 1.33     | 0.68     | -2.95    |

Even though single station data was used, this result demonstrates that firstly, the deviations from the proposed approach are equivalent with the ones from the conventional method suggesting that the new technique can infer \( M \) without losing estimation accuracy, and secondly, that the final \( M \) can be determined more rapidly using the proposed method than the conventional technique because the means of \( M_{\text{est}} - M_w \) from the proposed one (red triangles) are closer to zero than from the conventional one (blue squares) even at early time \( T \). It can be concluded that these are consistent with [11] in which multiple station data was tested for each event, i.e. the proposed approach is useful to improve the speed of \( M \) estimation even for the single station algorithms used in the Shinkansen EEW system.

5. Discussion and conclusions

The new technique proposed in [11] has two important advantages: firstly, the technique uses a time-dependent intercept \( \gamma[T] \) up to 4 s as shown in Table 1. This is because the scaling relationship between \( M \) and \( T_{dp} \), (2), can be established up to \( M \) 7 class earthquakes (note that \( T_{dp} \) for \( M \) 7 is about 2.9 s), i.e. the time-dependent intercept should not be applied to the data after 4 s at this point. However, the constant intercept (that is, \( \gamma[T = 4 s] \)) can be applied to the data after 4 s, i.e. the approach after 4 s is consequently same as the conventional method. As a result, for earthquakes exceeding \( M \) 7 class, the performance of the proposed approach is not compromised compared with the conventional method.

The other advantage is that the proposed approach can be easily installed with the Shinkansen EEW system because the algorithm holds the coefficients of GMPE for the \( M \) estimation as parameters that can be updated without changing the source program. This can help the railway companies to introduce the new technique into the system. It is therefore concluded that the proposed technique is useful to improve the safety of running trains when an earthquake happens.
Fig. 3  Distribution at each $T$ between $M_w$ (horizontal axis) and $M_{est}$ ($M$ estimates determined at each single station) – $M_w$ (vertical axis). Black solid line indicates the reference of $M_{est} - M_w = 0$. Black and gray points show the results from the time-dependent intercept $\gamma[T]$ and the constant $\gamma[T = 4 \text{ s}]$, respectively. The averages of $M_{est} - M_w$ by $M_w$ 0.5 magnitude units are shown by the red triangles (for the black points: the proposed method) and by the blue squares (for the gray points: the conventional method), and the error bars indicate their standard deviations.

Acknowledgement

The author would thank the National Research Institute for Earth Science and Disaster Resilience for providing access to waveform data for this paper [12].

References

[1] Yamamoto, S., and Tomori, M., “EARTHQUAKE EARLY WARNING SYSTEM FOR RAILWAYS AND ITS PERFORMANCE,” Journal of Japan Society of Civil Engineers, Vol. 1, pp. 322–328, 2013.

[2] Iwata, N., Yamamoto, S., Korenaga, M., and Noda, S., “Improved Algorithms of Seismic Parameters Estima-
tion and Noise Discrimination in Earthquake Early Warning,” *Quarterly Report of RTRI*, Vol. 56, No. 4, pp. 291–298, 2015.

[3] Steele, H., Noda, S., Yamamoto, S., and Korenaga, M., “Improved Epicentral Distance Estimations for Railway Earthquake Early Warning,” *Quarterly Report of RTRI*, Vol. 61, No. 3, pp. 222–227, 2020.

[4] Nakamura, H., Iwata, N., Ashiya, K., “Statistical Relationships between Earthquake Disaster and Seismic Parameters Used for Train Operation Control after Earthquake,” *RTRI Report*, Vol. 19, No. 10, pp. 11–16, 2005 (in Japanese).

[5] Odaka, T., Ashiya, K., Tsukada, S., Sato, S., Ohtake, K., and Nozaka, D., “A New Method of Quickly Estimating Epicentral Distance and Magnitude from a Single Seismic Record,” *Bulletin of the Seismological Society of America*, Vol. 93, No. 1, pp. 526–532, 2003.

[6] Kuyuk, H. S., and Allen, R. M., “A global approach to provide magnitude estimates for earthquake early warning alerts,” *Geophysical Research Letters*, Vol. 40, pp. 6329–6333, doi:10.1002/2013GL058580, 2013.

[7] Colombelli, S., and Zollo, A., “Fast determination of earthquake magnitude and fault extent from real-time P-wave recordings,” *Geophysical Journal International*, Vol. 202, pp. 1158–1163, 2015.

[8] Noda, S., Yamamoto, S., and Ellsworth, W. L., “Rapid Estimation of Earthquake Magnitude from the Arrival Time of the Peak High-Frequency Amplitude,” *Bulletin of the Seismological Society of America*, Vol. 106, No. 1, pp. 232–241, 2016.

[9] Kanamori, H., and Brodsky, E., “The physics of earthquakes,” *Reports on Progress in Physics*, Vol. 67, pp. 1429–1496, 2004.

[10] Noda, S., and Ellsworth, W. L., “Scaling relation between earthquake magnitude and the departure time from P wave similar growth,” *Geophysical Research Letters*, Vol. 43, doi:10.1002/2016GL070069, 2016.

[11] Noda, S., and Ellsworth, W. L., “Determination of Earthquake Magnitude for Early Warning from the Time Dependence of P-Wave Amplitudes,” *Bulletin of the Seismological Society of America*, Vol. 107, No. 4, pp. 1860–1867, 2017.

[12] National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net, doi:10.17598/NIED.0004, 2019.

[13] Noda, S., “Statistical characterization of P-wave growth for earthquake early warning,” *Quarterly Report of RTRI*, Vol. 59, No. 2, pp. 128–134, 2018.

Author

*Shunta NODA*
Assistant Senior Researcher, Seismic Data Analysis Laboratory, Center for Railway Earthquake Engineering Research
Research Areas: Earthquake Engineering, Seismology