



# Application of the Modified PLUM Method to a Dense Seismic Intensity Network of a Local Government in Japan: A Case Study on Tottori Prefecture

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An application of the PLUM (Propagation of Local Undamped Motion) method to real-time seismic intensity distribution from a dense seismic intensity network maintained by a local government in Japan is demonstrated. The JMA (Japan Meteorological Agency) has employed the PLUM method from March 2018 as a supplement to the traditional EEW (Earthquake Early Warning) which requires hypocenter determination. A dense observation network is desirable for upgrading accuracy and immediateness of EEW including the PLUM method. Seismic intensity meters in Tottori Prefecture, Japan, are suitable for the purpose because they have been improved to broadcast packets with peak ground acceleration and JMA seismic intensity at every 1 s. Also, 34 seismic intensity meters are installed in the target area while only six observation sites are used for the EEW by the JMA. The packet data are received at Tottori University, and the modified PLUM method considers wave propagation with damping from not only the observation points but also all evaluating grid points at a 1 km mesh. Additionally, P-wave amplitudes in preliminary tremors are also introduced to estimate seismic intensities from an empirical relationship. Applying the methodology to past earthquake data, more detailed and rapid evaluations of seismic intensity distribution are achieved. We expect the system will be utilized for earthquake disaster mitigation measures of local governments.

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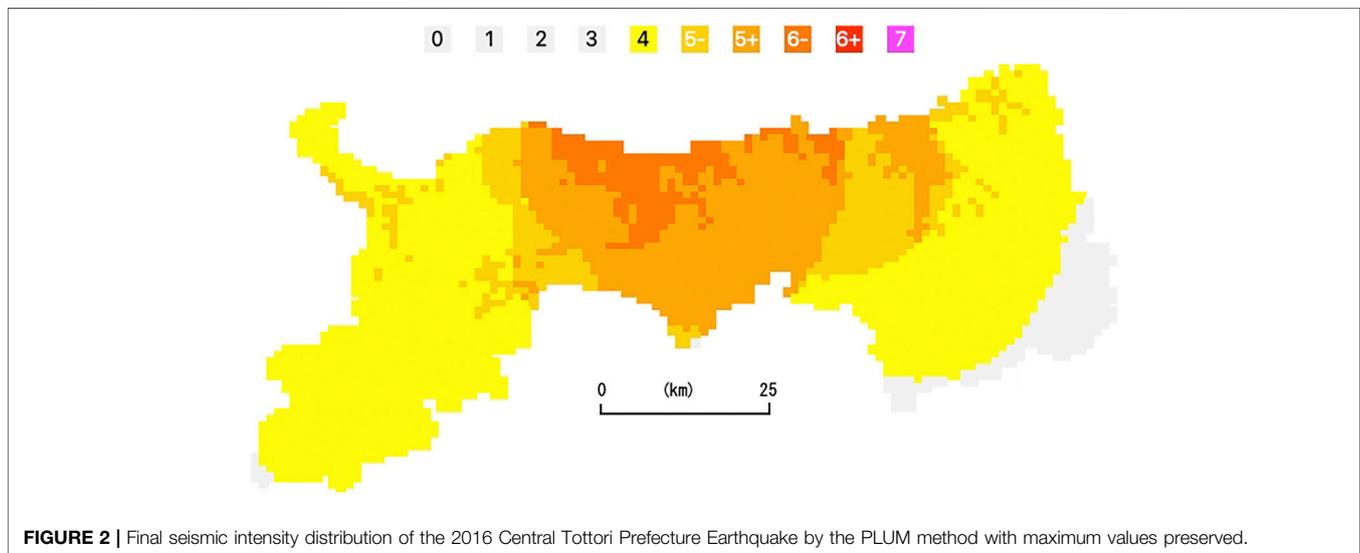
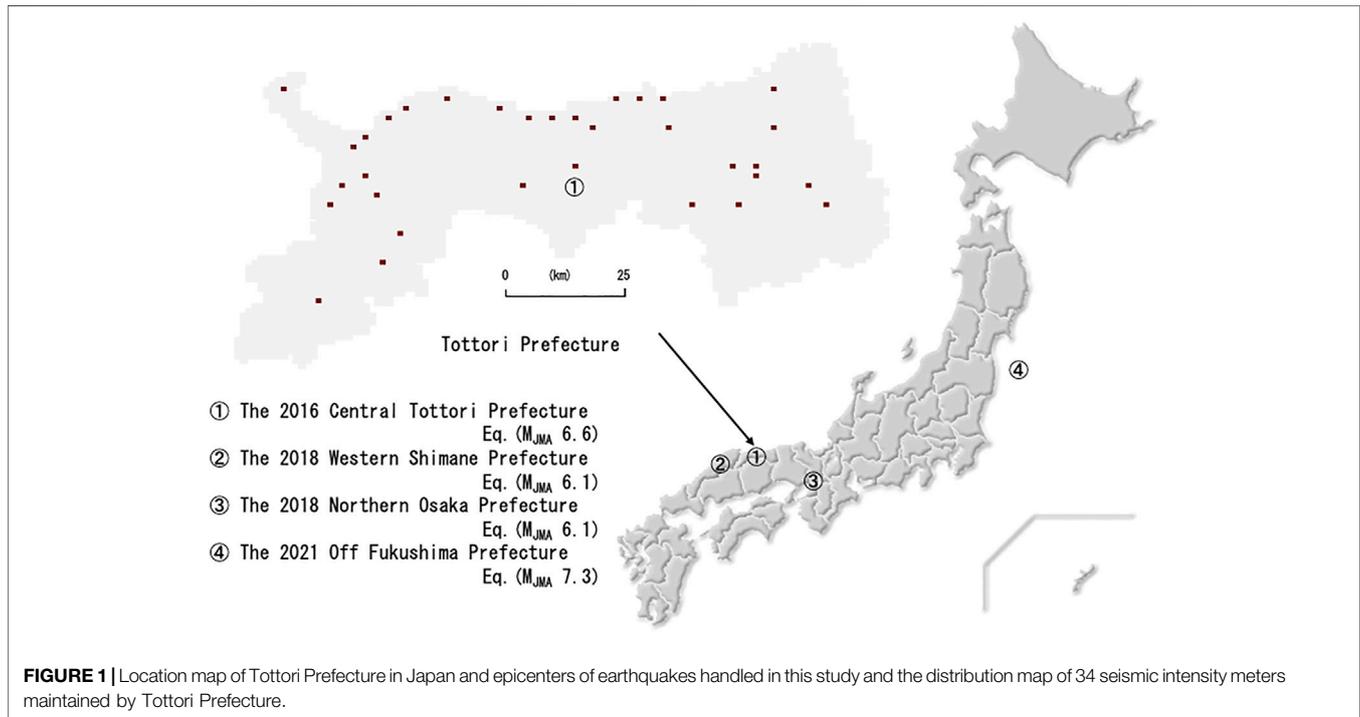
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## INTRODUCTION

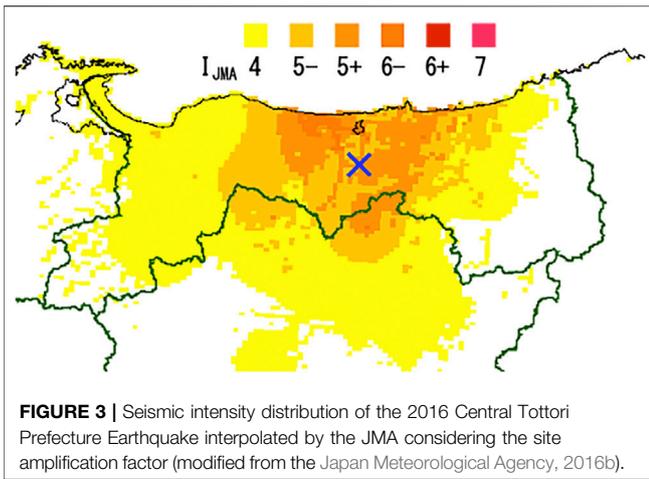
Real-time shake map estimation using seismic intensity meters maintained by local governments in Japan has been enhanced. To improving the accuracy and rapidness of the EEW (Earthquake Early Warning), a dense observation network is desirable. Seismic intensity meters installed in all Japanese municipalities are the most suitable equipment for this purpose, since the station installation interval is less than 5 km in some areas. The seismic intensity meters in Tottori Prefecture have been upgraded to broadcast UDP (User Datagram Protocol) packets with peak ground acceleration and JMA (Japan Meteorological Agency) seismic intensity every second. At present, the system maintained by the prefecture is the only one that broadcasts such a packet. **Figure 1** shows the location of Tottori Prefecture in Japan and the layout of the 34 seismic intensity meters maintained by the prefecture. The data are received at Tottori University, Japan,



and the PLUM (Propagation of Local Undamped Motion) method (Hoshiya, 2013) is applied to the data for estimating JMA seismic intensity distribution at 1 km grid points. However, in case of the 2016 Central Tottori Prefecture Earthquake, Japan, with  $M_{JMA}$  6.6, the seismic intensities around the observation sites were overestimated to use as a reference for initial response to the disaster, since the seismic intensities are assumed to propagate without attenuation with emphasis on issuing earlier warning at the expense of accuracy.

In this study, three additional methodologies are introduced into the system to obtain more realistic seismic intensity distribution.

One is the introduction of attenuation in seismic intensity propagation from observed sites, and the other is the assumption of every 1 km grid point for seismic intensity estimation as a secondary source point (Kagawa, 2019). The third is the usage of vertical P-wave amplitudes for seismic intensity estimation (Ueda et al., 2009). Using the methodologies, seismic intensity distributions with improved accuracy and rapidness are demonstrated. Although there are some issues such as underestimation due to the bias of the observation point arrangement, it is possible to provide generally good seismic intensity distribution in real time.



34 sites (**Figure 1**) are received at Tottori University *via* the Tottori Prefecture Information Highway, main line 10 Gbps and access point 1 Gbps, and when the vertical acceleration exceeds  $1 \text{ cm/s}^2$ , and output files with timestamp and site number are generated. There are far more seismographs available in Tottori Prefecture than the six points of JMA observation points for EEW purpose, so it is expected that the accuracy and rapidness will be improved.

In this study, the dataset due to the 2016 Central Tottori Prefecture Earthquake is used as a sample data. The epicenter location is indicated in **Figure 1**. All local seismic intensity meters have operated without problems while delivering 1 s packets mentioned above, have saved waveform records, and have stably transmitted many aftershock data. However, the system to receive the packets and to visualize the results was not completed at the time of the event, so 1 s packets used in this study were reproduced from the observed waveforms.

### IMPROVEMENT OF SEISMIC INTENSITY METERS MAINTAINED BY TOTTORI PREFECTURE

We have improved the local seismic intensity meters in Tottori Prefecture so that they could send 1 s packets of peak ground acceleration and JMA seismic intensity. Since seismographs operated by local governments are used for disaster prevention purposes such as breaking news of seismic intensities immediately after an earthquake, improvements should not bother their operations. For this reason, we decided to transmit only real-time seismic intensity calculated on site and the maximum horizontal and vertical accelerations on the UDP. The seismic intensity is evaluated from 2 s data that start 1 s earlier. Data from

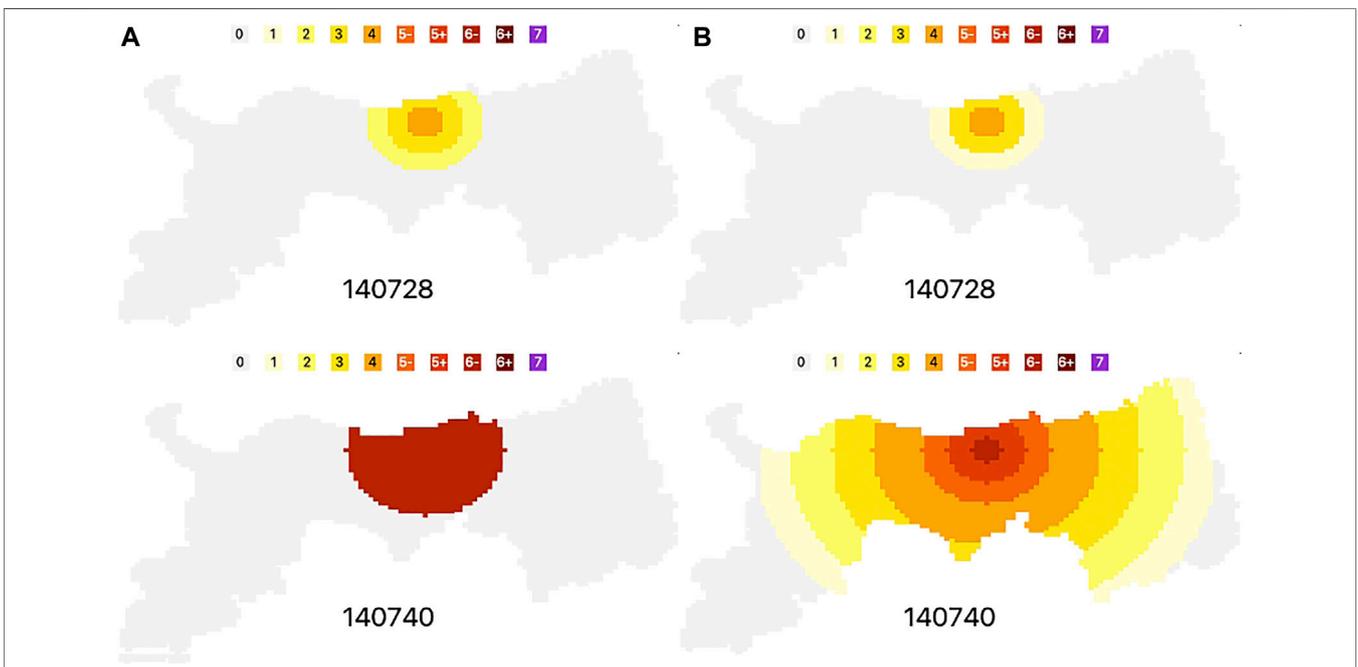
### ESTIMATION OF REAL-TIME SEISMIC INTENSITIES

#### Application of the PLUM Method

First, we tried to apply the PLUM (Propagation of Local Undamped Motion) method (Hoshiya, 2013), which is employed in EEW operation by the JMA. Seismic intensity estimation by the PLUM method is shown in the following equation:

$$I(\mathbf{r}, t) \approx \max_i \left( F_{oi} + I \left( \mathbf{r}_i, t - \frac{|\mathbf{r} - \mathbf{r}_i|}{V_0} \right) \right), \text{ where } |\mathbf{r} - \mathbf{r}_i| \leq V_0 T.$$

Here,  $I(\mathbf{r}, t)$  is the estimated seismic intensity at time  $t$  and point  $\mathbf{r}$ ,  $\mathbf{r}_i$  is the location of the  $i$ th seismic intensity meter, and  $F_{oi}$  is the site



**FIGURE 4 |** Demonstration of seismic intensity propagation from a single observation site without site amplification: (A) PLUM method; (B) proposed method.

amplification estimated from AVS30 at the point (Midorikawa et al., 1994). Amplification at each estimating point in a 1 km grid is given from a dataset that was used for the earthquake damage estimation project of Tottori Prefecture (Tottori Prefecture, 2018), but the data are based on the national AVS30 distribution database provided by the J-SHIS map by the NIED (National Research Institute for Earth Science and Disaster Resilience, 2019). Assuming  $V_0$  as the S-wave velocity and  $T$  as the lead time for estimation, i.e., how much the future is predicted from the present time, the maximum seismic intensity that can be propagated from the observation site within the distance range of  $V_0T$  is estimated considering time delay and site amplification. In this study,  $V_0 = 4.0$  km/s is used as a standard upper crustal S-wave velocity in the area, and lead time  $T = 4$  s is assumed to cover the delay due to data transmission and data analyses. As a result, the maximum applicable distance for seismic intensity propagation is 16 km that corresponds to an averaged spacing of seismic intensity meters.

**Figure 2** shows a final seismic intensity distribution of the 2016 Central Tottori Prefecture Earthquake ( $M_{JMA}$  6.6) with maximum values preserved. The maximum JMA seismic intensity observed was six lower, and the damage was spot limited. **Figure 3** shows the seismic intensity distribution interpolated by the JMA considering the site amplification factor at each estimating point. The points with JMA seismic intensity six lower are limited, and seismic intensity four does not cover almost the whole prefecture area. The distribution by the PLUM method is overestimated; however it is unavoidable since it treats wave propagation as undamped.

The PLUM method employs undamped propagation since it prioritizes quickness to broadcast EEW at the expense of some accuracy of seismic intensity distribution. Our purpose is to monitor the seismic intensity distribution more accurately and utilize it for the disaster mitigation response immediately after the earthquake, which is a little different from the concept of the PLUM method.

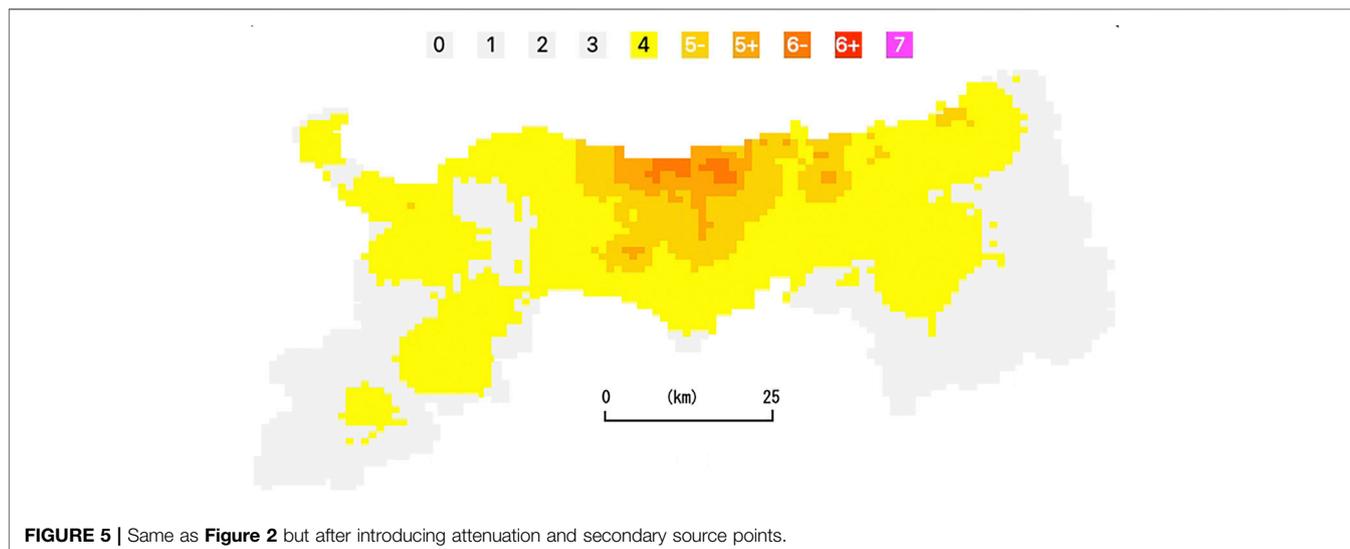
## Introduction of Damping and Secondary Source Points

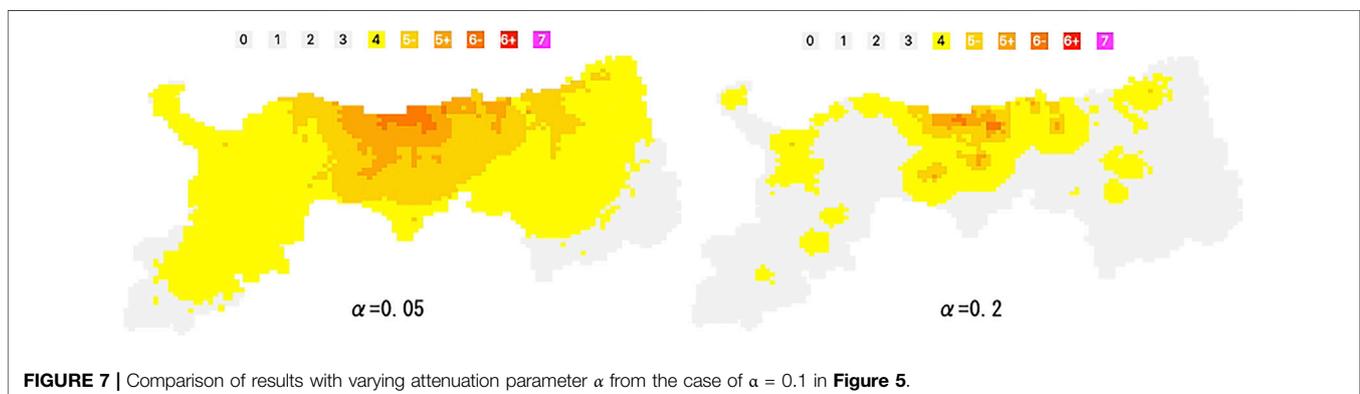
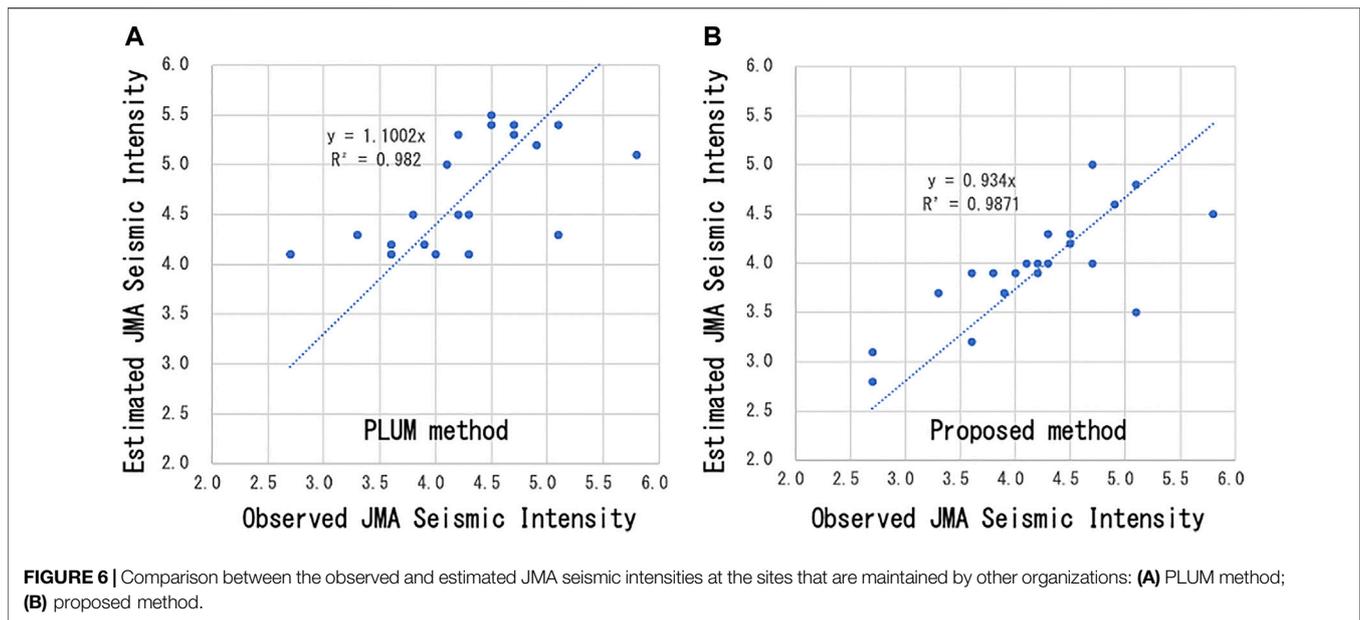
Attenuation (damping) is introduced into wave propagation to estimate more accurate seismic intensity distribution. In addition, all estimation points are considered as secondary sources that generate attenuating waves with the maximum value at the observation point. The following equation explains the methodology:

$$I(\mathbf{r}, t) \approx \max_k \left( F_{ok} + I \left( \mathbf{r}_k, t - \frac{|\mathbf{r} - \mathbf{r}_k|}{V_0} \right) - \alpha |\mathbf{r} - \mathbf{r}_k| \right), \text{ where } |\mathbf{r} - \mathbf{r}_k| \leq V_0 T.$$

Here,  $\mathbf{r}_k$  is the location of the  $k$ th estimating point in 1 km grids and  $F_{ok}$  is the site amplification there. In the previous equation of the PLUM method, the maximum seismic intensity is selected from observation points  $\mathbf{r}_i$  that satisfy the distance condition within  $V_0T$ . On the contrary, the proposed method searches the maximum value from all 1 km grid points  $\mathbf{r}_k$  around the target point  $\mathbf{r}$ . If the  $k$ th grid point is the same as an observation point, estimation is updated with observed data like data assimilation of several-hour weather forecasting. The third term of the equation including a parameter  $\alpha$  indicates attenuation. The damping parameter  $\alpha$  is adjusted as 0.1 through trial and error. It means that JMA seismic intensity decreases 1.0 with distance 10 km. The result might be almost the same as the ground-motion-based EEW (i.e., Hoshiba and Aoki, 2015), but the methodology is simpler and values at the observation sites are assimilated every 1 s.

**Figure 4** shows demonstrations of seismic intensity propagation from a single observation site without considering site amplification. The left column indicates the result by the PLUM method. At 14:07:28, three different observed values are propagated without attenuation, and it draws three circles with radius of 4, 8, and 12 km and is saturated with a seismic intensity of six lower as the maximum observed seismic intensity at the site





in the bottom panel with a radius of 16 km ( $V_0T$ ). The timestamp in the bottom panel indicates 40 s, but it was saturated at 14:07:33 in reality. The right column shows the result by the proposed method. The seismic intensity distribution at 14:07:28 is slightly attenuated, and it propagates with attenuation farther than that of the PLUM method. It is because every grid point works as a secondary source point. Different color scales comparing the previous figures are used here to see the distribution of small seismic intensity.

**Figure 5** shows an application to the 2016 Central Tottori Prefecture Earthquake. The final distribution of JMA seismic intensity agrees well with the interpolated distribution by the JMA in **Figure 3**. The intensity six lower appears as spot limited in the coastal area, and the border of intensity four is almost the same as the JMA interpolation. However, intensity five lower is smaller than the JMA interpolation, especially in the southern and western part from the source area. It is because there are few observation points maintained by Tottori Prefecture (**Figure 1**). The seismic intensity meters are installed mainly at town halls in populated areas. They are not installed in mountain regions

around prefecture borders. Moreover, JMA and NIED seismographs are used as substitutes for urban areas with large population to complement the seismic intensity distribution in Tottori Prefecture, but they are not included in the 34 sites used for this study.

In order to quantitatively evaluate the results of the PLUM method and the proposed method, we compared the estimated results at observation points other than the 34 points used in this study. They are six JMA, nine K-NET, and six KiK-net sites maintained by the NIED. The left and right panels in **Figure 6** show the results of the PLUM method and the proposed method, respectively. The horizontal axis indicates the observed JMA seismic intensities, and the vertical axis shows the estimated values. In the panels, approximate linear lines of intercept zero are shown with their inclination and correlation coefficients. It is clear that the PLUM method is overestimated but the proposed method is almost valid.

**Figure 7** shows the examples of trial and error to obtain proper attenuation parameter  $\alpha = 0.1$ . Comparing the results with the

case in **Figure 5**, it is found that smaller attenuation case ( $\alpha = 0.05$ ) results in slight overestimation, and larger attenuation ( $\alpha = 0.2$ ) shows underestimation. The operational parameter  $\alpha = 0.1$  was determined through these checks, although it has not been sufficiently quantitatively examined.

## Introduction of P-Wave Amplitude

For the next approach, P-wave amplitudes are introduced for seismic intensity estimation. The 1 s packets from seismic intensity meters include maximum accelerations of horizontal and vertical

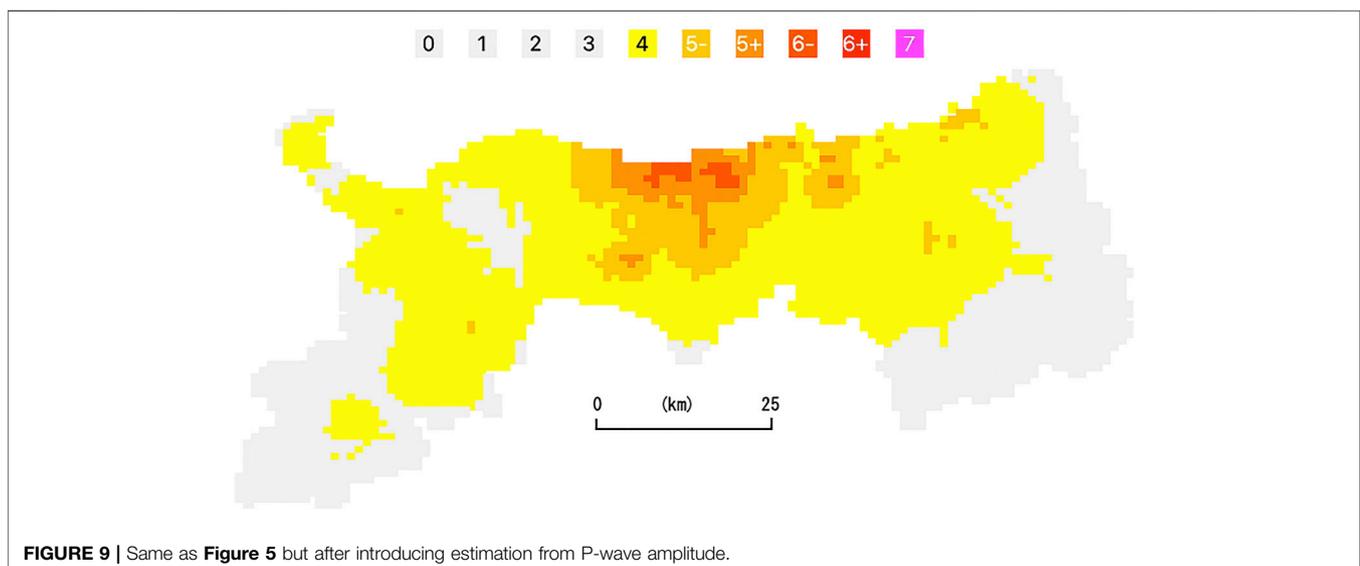
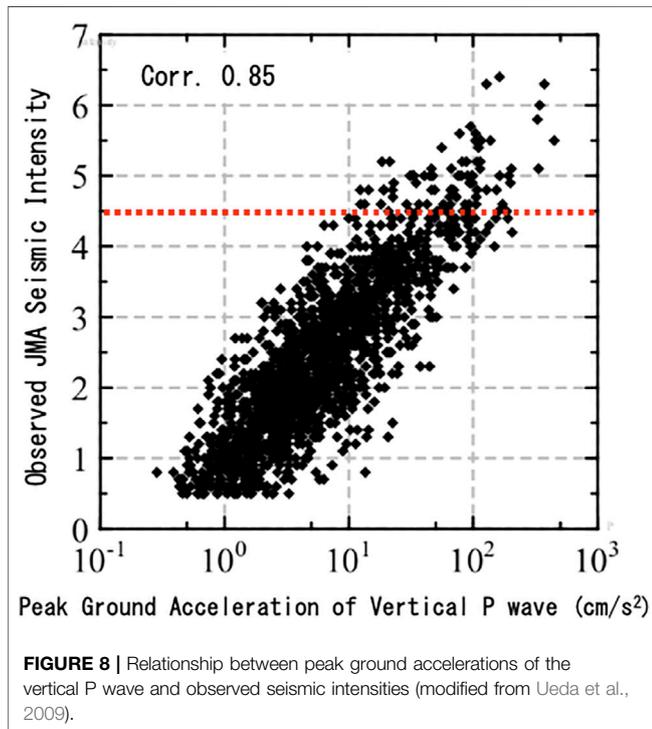
components. In case that vertical acceleration is larger than the horizontal one, empirical estimation of JMA seismic intensity from P-wave amplitude (Ueda et al., 2009) is calculated, and the value is employed if it is larger than real-time seismic intensity observed at the time. The relationship is shown in **Figure 8** and the following equation (Ueda et al., 2009). They used 1,570 data at 124 sites due to 55 events including the main and aftershocks of the Mid Niigata Prefecture Earthquake in 2004 ( $M_{JMA}$  6.8) and the Iwate-Miyagi Nairiku Earthquake in 2008 ( $M_{JMA}$  7.2). The following equation is derived from least-squares approximation:

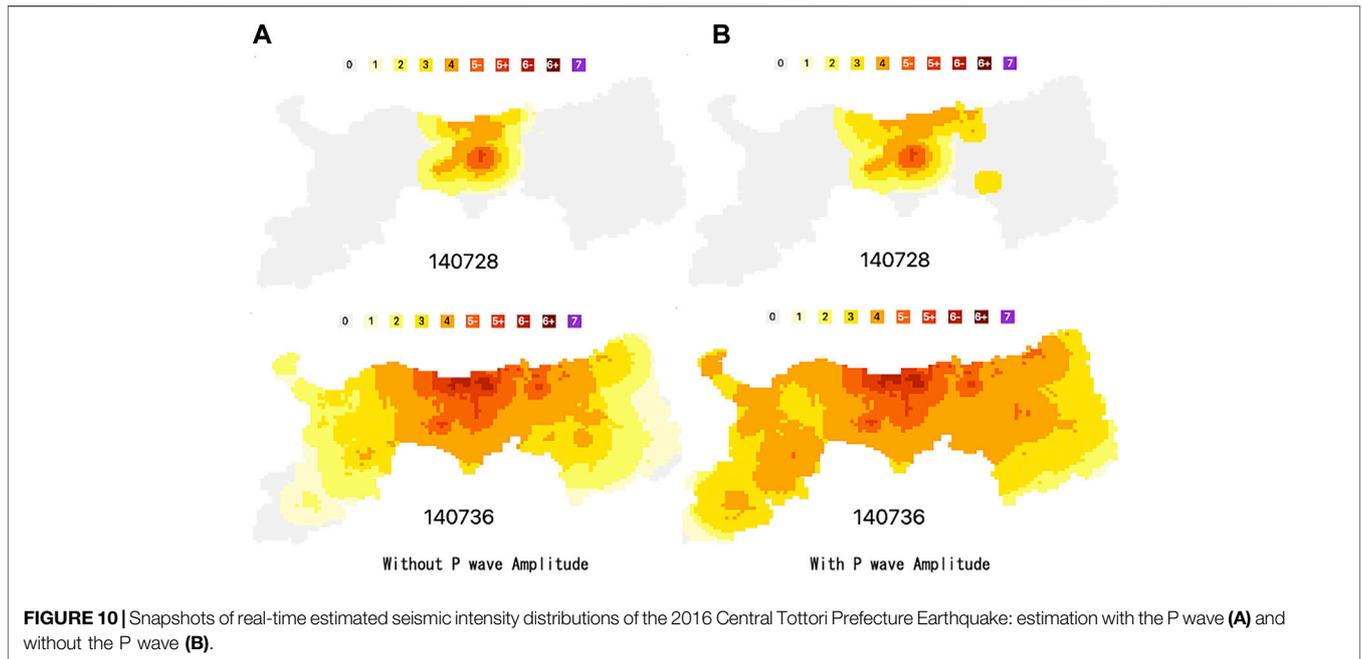
$$I_{JMA} = 2.18 \log(PGA_P) + 0.77$$

where  $I_{JMA}$  is the JMA seismic intensity and  $PGA_P$  is the peak ground acceleration of the vertical P wave. Both show a good correlation, but the number of data are not enough in large amplitude range. In this study, the maximum seismic intensity estimated from P-wave amplitude is set for 4.5 as shown in **Figure 8**.

The methodology mentioned above is applied for the 2016 Central Tottori Prefecture Earthquake. **Figure 9** shows the result under the same condition as in **Figures 2, 5**. The results are almost same in their final seismic intensity distributions. The most expecting advantage for using P-wave amplitude is its rapidness of estimation. **Figure 10** shows the comparison of snapshots between estimation with the P wave in the right column and without the P wave in the left column. Time 14:07:28 of the upper line panels is the timing when the first forecast-type EEW by the JMA (Japan Meteorological Agency, 2016a) was broadcasted, and warning-type EEW on the third forecast was broadcasted for general public at time 14:07:36 of the lower line panels. Both columns show the possibility that we can grasp realistic seismic intensity distribution as the same or faster than current EEW in case we use the data from a denser network.

Estimation with the P wave shows faster propagation of large seismic intensity area than that without the P wave. However, the final estimated distribution with P wave amplitude is almost the





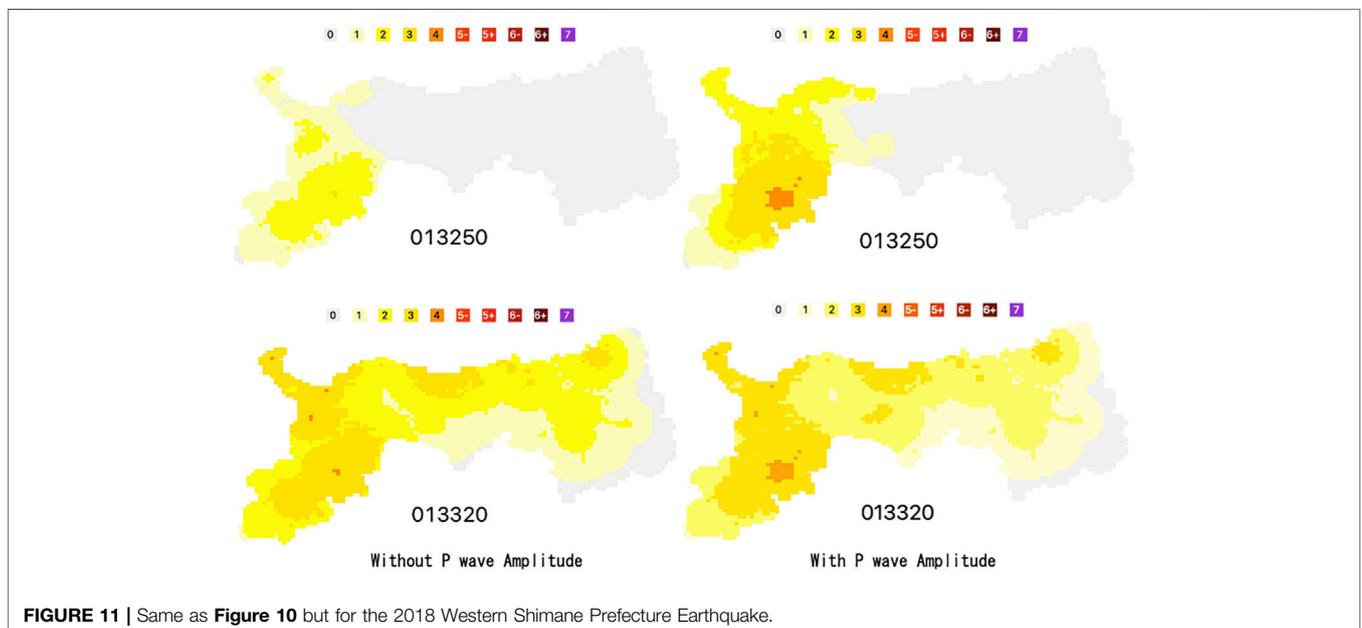
same as that without the P wave, as compared between **Figures 5, 9**. The right bottom panel of **Figure 10** corresponds to **Figure 9**. Note that the color scale is changed from the previous figures to grasp the situation of small seismic intensity. The scale is applied for the following figures.

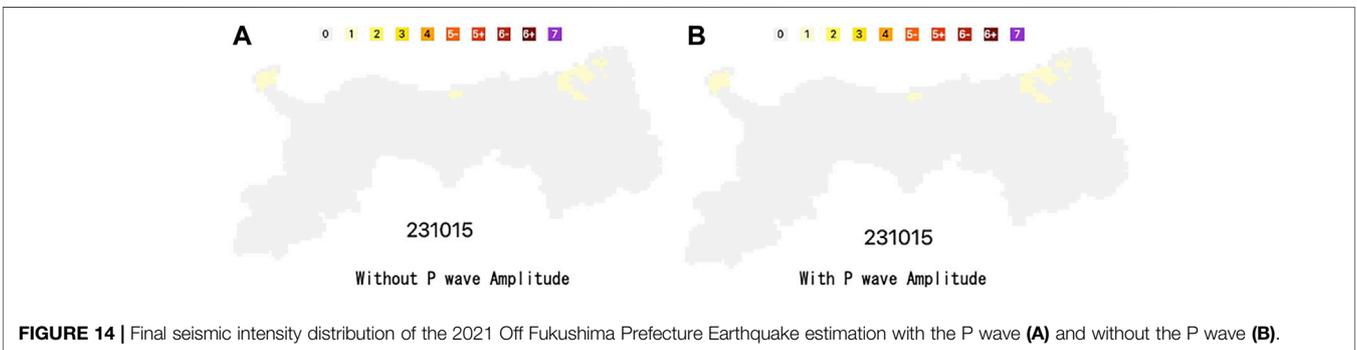
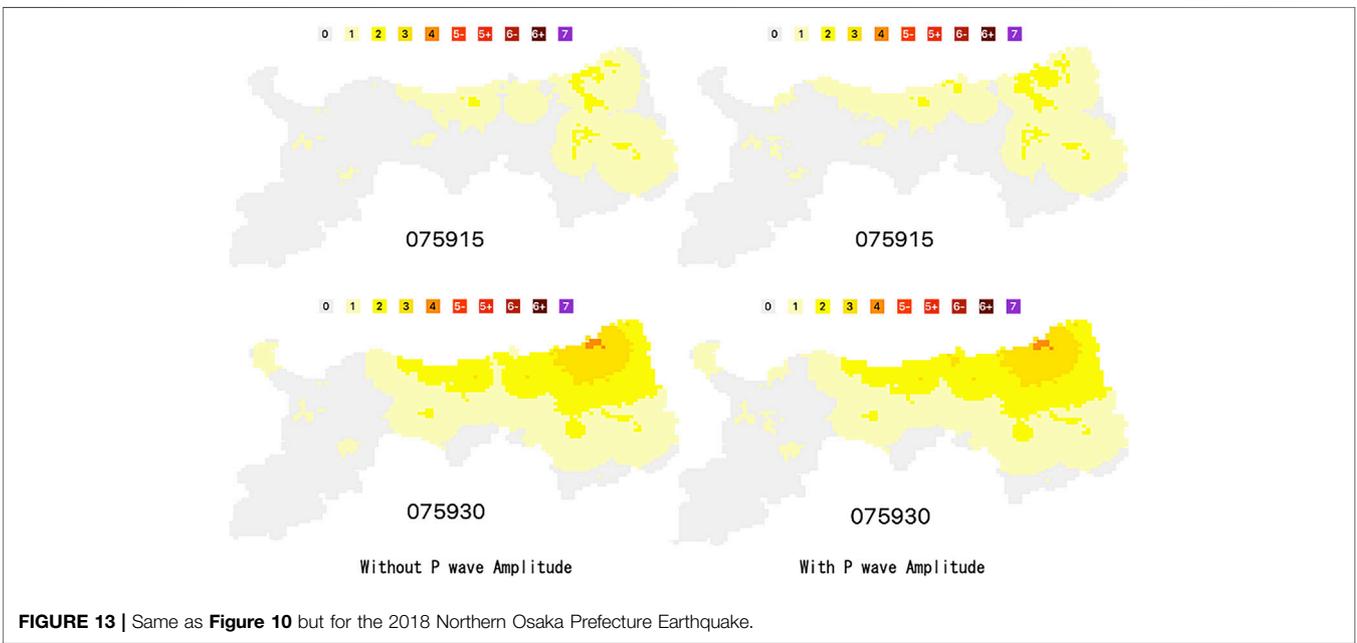
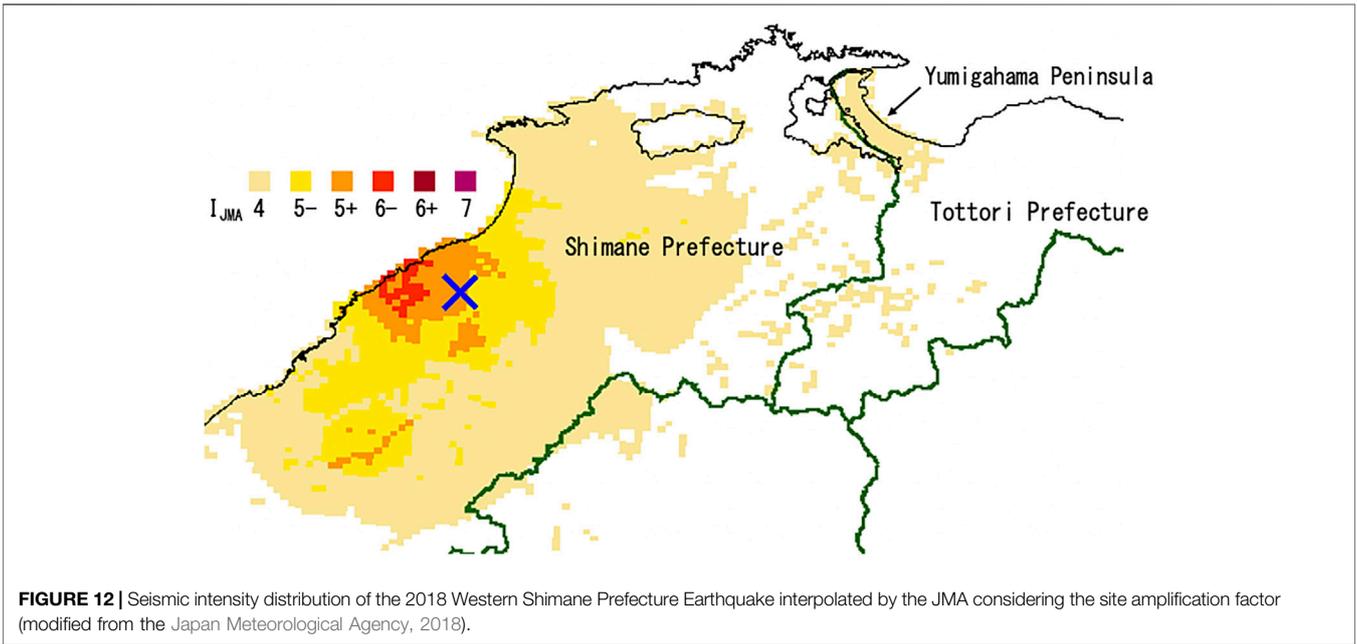
## DISCUSSION

Applications for other earthquakes are shown in this section, since the proposed methodology was found to be effective but

only for a single near-field earthquake. The location of the additionally handled earthquakes is shown in **Figure 1**.

**Figure 11** shows the estimated snapshot of JMA seismic intensity distribution due to the 2018 Western Shimane Prefecture Earthquake ( $M_{\text{JMA}} 6.1$ ) on April 9 01:32. The shortest epicentral distance was about 50 km from the western prefecture border. Estimation with the P wave shows faster propagation of large seismic intensity area the same as the 2016 Central Tottori Prefecture case in **Figure 10**. **Figure 12** shows the seismic intensity distribution interpolated by the JMA,





but the color scale is slightly different from that of the previous figures. The largest JMA seismic intensity observed in the western part of the prefecture was 4 as estimated. Although a little overestimation is seen in large intensity area at southwest of the prefecture, the seismic intensity distribution is generally practical. A little underestimation is also noticed along the Yumigahama Peninsula indicated in **Figure 12**. The reason is considered to be the lack of observation points in the area, see **Figure 1**.

**Figure 13** is the result of the 2018 Northern Osaka Prefecture Earthquake ( $M_{JMA}$  6.1) on June 18 07:58. The shortest epicentral distance at the southeast prefecture border was about 150 km, and the largest JMA seismic intensity observed in the eastern part of the prefecture was 3, but 4 is estimated at the coastal area in eastern part in both cases. It is caused by large amplification around the site where intensity 3 was observed. The effects of P-wave amplitudes are noticed in limited areas along the coast in central part. It is because high-frequency amplitude in P-wave acceleration is not large for slightly long-distance earthquake. Unfortunately, the area is out of the range of seismic intensity distribution map published by the JMA because the target of the map is the range of JMA seismic intensity four or higher.

Finally, a case of long-distance earthquake is shown in **Figure 14**, but only for the final distributions. The source is the 2021 Off Fukushima Prefecture Earthquake ( $M_{JMA}$  7.3) on February 13 23:07. The epicentral distance is about 750 km east, and the maximum observed JMA seismic intensity was 1. They were observed at a soft ground area in the eastern, central, and western part of the prefecture, as estimated in **Figure 14**. Estimation from P-wave amplitude does not work on this case, and the two panels are the same. It is also because of small acceleration due to the long-distance earthquake. The area is also out of the range of the seismic intensity distribution map by the JMA.

Four different types of earthquakes are treated in this study. The first is a near-field event that caused a disaster in Tottori Prefecture, the second is a disaster earthquake occurred in the neighboring prefecture, the third is a slightly long-distance event in the range of 150 km, and the fourth is a long-distance large earthquake with an epicentral distance of 750 km. Although they are limited cases, the proposed method seems to work well through the examinations so far.

It is being planned to install the methodology in a web-based display system, and its results will be provided for municipal crisis management for immediate response to earthquake disaster. We would like to make improvements any time as a problem arises.

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## CONCLUSION

Real-time seismic intensity estimation is established using seismic intensity meters maintained by local governments in Japan. The 34 seismic intensity meters of Tottori Prefecture were improved to broadcast 1 s packets with real-time peak ground acceleration and JMA seismic intensity. The modified PLUM method introduces wave attenuation from all estimation points in a 1 km grid as secondary sources. Vertical P-wave amplitude is also considered for intensity estimation. The methodologies were applied for four different types of earthquakes with epicentral distance 0–750 km and JMA magnitude range 6.1–7.3. The results were practical enough to estimate almost the same intensity distribution provided by the JMA after the earthquakes. Also, the estimations are expected to be faster than those of EEW by the JMA since denser seismograph network is employed for the proposed system. We hope that such real-time seismic intensity estimations would be widely constructed using next-generation seismic intensity meters.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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