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SHAKE MAP ESTIMATION USING P WAVE AMPLITUDES AND REAL-TIME SEISMIC INTENSITIES FROM DENSE SEISMOMETER NETWORK

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Abstract

Real-time estimations of shake maps using seismic intensity meters network maintained by a local government, Japan is demonstrated. Dense observation network is desirable for upgrading quickness, accuracy and quality of Earthquake Early Warning. Seismic intensity meters installed in all municipalities in Japan are one of the most suitable equipment for the purpose. The seismic intensity meters in Tottori prefecture, Japan are improved to broadcast packets with two component (horizontal and vertical) peak ground acceleration and JMA (Japan Meteorological Agency) seismic intensity at every one second. The data are received at Tottori University and PLUM (Propagation of Local Undamped Motion) method is applied to the data for estimating JMA seismic intensity distribution at 1km grid points in Tottori prefecture. The methodology was applied to the data observed through the 2016 central Tottori prefecture earthquake (M_{JMA}6.6). However, seismic intensities were rather overestimated and were not well estimated in some area where seismic intensity meters are not installed nearby, because the PLUM method assumes undamped propagation only from the observation points up to a certain distance. Additional functions have been introduced on the system to overcome the disadvantages. One is propagation of seismic intensity from observed sites with attenuation to avoid overestimation. Attenuated propagation from every target grid point are also introduced to cover the area without enough seismic intensity meter. The other is an introduction of P wave amplitudes for estimating seismic intensities. An empirical relationship between amplitudes of vertical P waves and final seismic intensities are employed for the purpose. Using the upgraded methodology, more rapid and detailed seismic intensity distribution are provided than before. Some examples applied to the recent earthquakes are demonstrated.

Keywords: real-time estimation, shake map, local government, PLUM method, P wave

1. Introduction

The Earthquake Early Warning, hereafter EEW, in Japan has been generally available since October 2007, and similar systems are operated in other parts of the world. EEW generally predicts seismic intensity distribution by estimating source location and magnitude of the earthquake from observation of P wave. At the same time, PLUM (Propagation of Local Undamped Motion) method [1], which does not require a source information but predicts shake map from observed ground motion data, is also installed in Japan. In either case, the denser the observation points, the faster and more effectively ground motions can be predicted. However, observation points of the Japan Meteorological Agency, hereafter JMA, are not dense enough, and EEW through the source information do not catch up the strong ground motions near the epicenter. Therefore, studies have been conducted using municipal seismic intensity meters installed at higher densities than those of JMA sites [2].

In this paper, as a case of EEW using seismic intensity meters maintained by a local government, a case study of Tottori prefecture, Japan [2] is introduced and a newly developed technique using P wave amplitude is explained. The results are demonstrated by using the observed data due to the 2016 central Tottori prefecture earthquake (M_{JMA}6.6).

2. Additional function of Tottori seismic intensity network

Japanese municipal seismic intensity meters have a function to report the measured seismic intensities locally evaluated immediately after an earthquake occurs. To prevent this important function from being disturbed, a new function was added to 34 seismic intensity meters that are maintained by Tottori prefecture. It is an option to send internet packets of real-time seismic intensity and peak ground accelerations, hereafter PGA, at every one second by User Datagram Protocol (UDP) transmission. The PGA data includes horizontal and vertical components, and the real-time seismic intensities are calculated from two second duration data at one second before. The UDP packets from the local stations are retransmitted once, if there is no response from the client. And the past data up to 11 seconds ago can be retransmitted if requested.

Data from 34 sites are received every one second at Tottori university via the Tottori prefectural information highway (main line 10 Gbps, to access point 1 Gbps), and when the received real-time seismic intensity exceeds 0, a file with time stamp and observation point number is generated. The client system is built on Linux (Xubuntu), and stable reception has continued for a long time. The data from the 2016 central Tottori prefecture earthquake (M_{JMA}6.6) are used for demonstration after here, however, the client system was not operating at the time. The demonstrations are conducted using the dataset generated from observed waveforms. On the other hand, the new function has installed to on-site seismic intensity meters before the earthquake and operate well without any problem while delivering one second packets, saves waveform records and transmits data even under the main shock and aftershock sequence.

3. Prediction of real-time seismic intensity distribution

Now on the system, a program that reads the file generated by the process above and estimates the seismic intensity distribution and plots it, is running independently from the packet reading program. The PLUM method which is introduced to EEW by JMA [1] is employed to predict seismic intensity distribution. Equations (1) and (2) show the seismic intensity estimation by the PLUM method. Here $I(\mathbf{r},t)$ is the estimated seismic intensity at time t at point $\mathbf{r}$, $\mathbf{r}_i$ is the location of the i-th seismic intensity, and F_{oi} indicates amplification factor at the site. Assuming that the seismic wave propagation velocity is V_0 and the estimated lead time (how much the future is predicted from the present time) is T, the propagation within the V_0T distance range takes into account as time shift from the seismic intensity observation point. The maximum seismic intensity expected at the seismic intensity prediction point is applied in consideration of site amplification. Here, $V_0 = 4.0$ km/s and lead time $T = 3$ seconds are used, so the maximum applicable distance for seismic intensity propagation is 12 km. Even if a seismic intensity packet is received with a delay of one second and the processing takes a little time, by setting the lead time to three seconds, it is possible to predict the seismic intensity distribution almost in real time or one second earlier.

$$I(\mathbf{r},t) \approx \max_i \left(F_{oi} + I\left(\mathbf{r}_i, t - \frac{|\mathbf{r}-\mathbf{r}_i|}{V_0}\right)\right) \tag{1}$$

$$|\mathbf{r}-\mathbf{r}_i| \le V_0 T \tag{2}$$

The prediction target is a 1km mesh in Tottori prefecture, and site amplification [3, 4] (incremental seismic intensity) is corrected using the national land information [5] including the observation site location. Fig.1 and 2 show a seismic intensity distribution estimated from the data of the 2016 central Tottori prefecture earthquake. The earthquake occurred on October 21, 2016 at 14: 07: 22.5, and the EEW was issued at 14: 07: 28.1 with the first report (forecast), and at 14: 07: 36.4 the third report as an alert for general public was issued. Fig. 1 is a snapshot taken at the later time. JMA uses six seismic intensity meters in Tottori prefecture for EEW, however, it is suggested that the situation of earthquake occurrence and seismic intensity distribution can be grasped earlier than the current emergency earthquake report, if the seismic intensity network by Tottori prefecture which has more stations in the area is utilized.

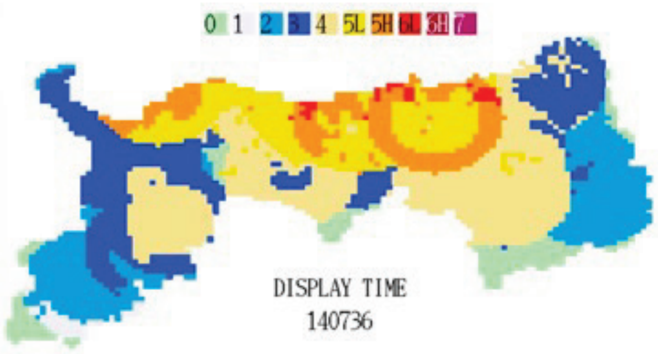

Fig. 1 – Application example of PLUM method to Tottori seismic intensity network [2]
(the 2016 central Tottori prefecture earthquake, 14:07:36)

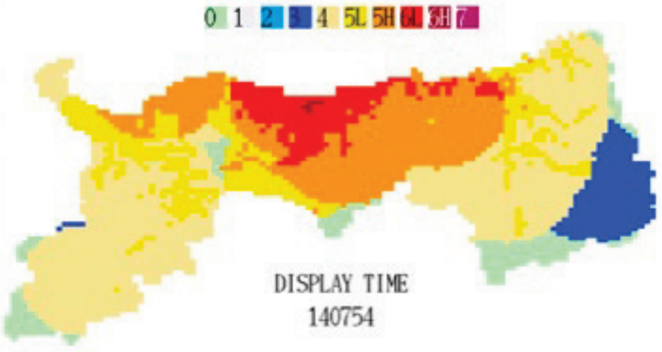

Fig. 2 – Final estimation of maximum seismic intensity distribution after Fig. 1 [2]

Fig. 2 shows final estimation of maximum seismic intensity distribution due to the 2016 central Tottori prefecture earthquake by PLUM method. The maximum observed seismic intensity was 6 low (red in the figures) at only three sites, however, the estimation seems to be overestimated. It might be because the PLUM method does not take attenuation into the account. In addition, there is an area where the seismic intensity cannot be evaluated at the area of Daisen mountain or in other mountainous areas at the prefectural borders due to the bias in the observation point density as shown in Fig. 3. Moreover, there are areas that might be underestimated due to sparse observation points. When monitoring the situation in Fig. 1 over time, due to the existence of areas with sparse observation points, phenomena in which large seismic intensity areas move so as to jump over these areas are scattered.

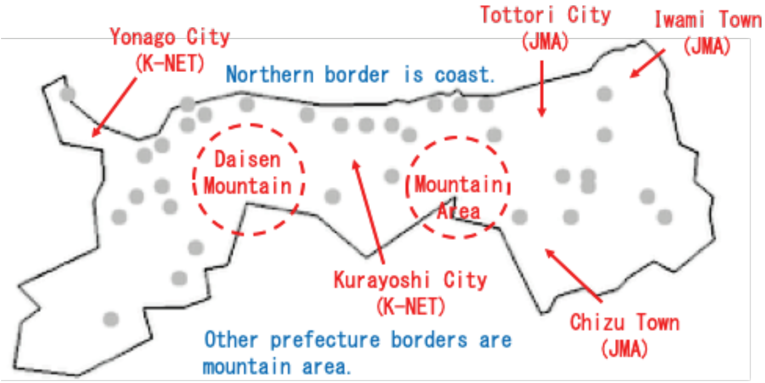

Fig. 3 – Location and issues of seismic intensity meters maintained by Tottori prefecture [2]

To avoid the problems above, propagation and attenuation of seismic intensities are introduced [2]. Equations (3) and (4) shows the procedure. The basic skeleton of the formulae is the same as equations (1) and (2), but α indicates attenuation factor. Furthermore, $\mathbf{r}_k$ is every target point in spite that $\mathbf{r}_i$ indicates observation point in equation (1). In other words, the seismic intensities at all target points are used as the secondary source of seismic intensity propagation in the next step, and real-time seismic intensities from observation sites are used for data assimilation. For α, 0.1 is used from the result of trial and error. It corresponds that the measured seismic intensity decreases by 1.2 at the maximum applicable distance of 12 km. The evaluation above is operated for the earthquakes that occurred in and around the network. The value is applicable also for the 2018 northern Osaka prefecture earthquake (M_{JMA}6.1) that occurred far outside of the network.

$$I(\mathbf{r},t) \approx \max_k \left(F_{ok} + I\left(\mathbf{r}_k, t - \frac{|\mathbf{r}-\mathbf{r}_k|}{V_0} \right) - \alpha |\mathbf{r}-\mathbf{r}_k| \right) \tag{3}$$

$$|\mathbf{r}-\mathbf{r}_k| \le V_0 T \tag{4}$$

Fig. 4 shows the result of final seismic intensity distribution of the 2016 central Tottori prefecture earthquake. It can be seen that the overestimation is improved as compared to Fig. 2. And the estimated seismic intensity distribution matches well with the interpolated seismic intensity map by JMA [7]. Since seismic intensity propagates to the area where observation points are sparse, all target points are evaluated and the area of underestimation is improved. In addition, the propagation with attenuation is smooth enough.

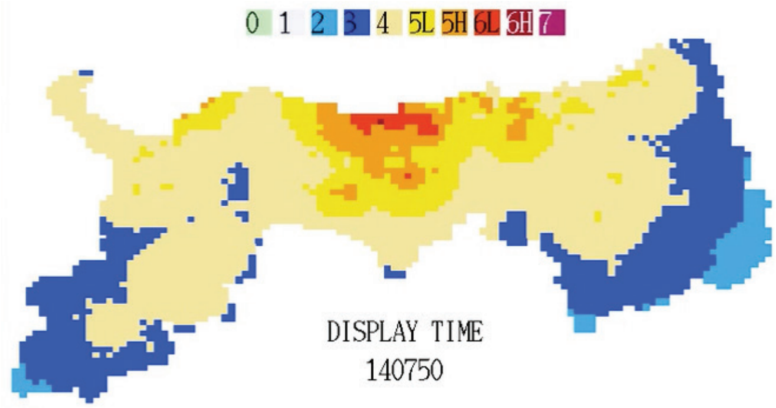

Fig. 4 – Final estimation of maximum seismic intensity distribution using the methodology explained by equation (3) and (4) [2]

4. Introduction of seismic intensity prediction using P wave amplitude

In the methods described so far, the prediction is performed using the observed seismic intensity, so the margin time for large shaking is not long enough. To overcome the problem, estimation from P wave amplitudes is introduced. Here empirical formula (5) derived from Fig. 5 [9] is used for estimation. Assuming the vertical PGAs in the packets from observation sites as those of P wave, the formula (5) is applied up to seismic intensity 5.0. The upper limit is introduced because the data over seismic intensity 5.0 are few in Fig. 5 and overestimation due to misidentification of S wave as P wave is afraid.

$$I_{JMA} = 2.18\log(PGA_P) + 0.77 \tag{5}$$

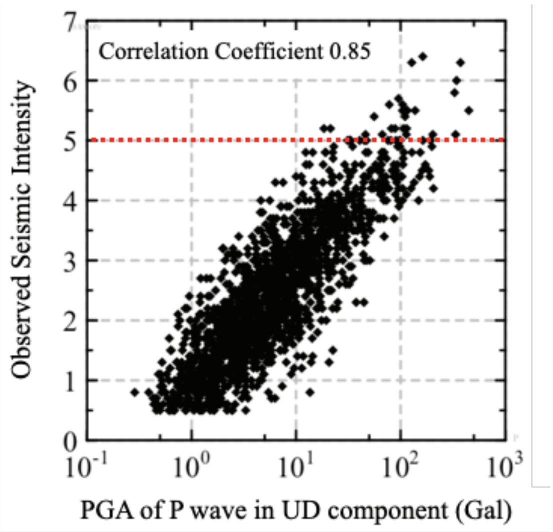

Fig. 5 – Relationship between PGA of P waves in UD component and observed seismic intensities (Added to the figure by Ueda et al. [9])

Fig. 6 shows the snap shot of seismic intensity distribution using P wave amplitude. The time estimated is 14:07:28 when the first report (forecast) of EEW was issued for professional users. In areas with large seismic intensity, the distribution can be almost reproduced by data assimilation and estimation from P wave amplitude. This is due to the use of denser observation points than JMA. Fig. 7 shows the result by the methodology without P wave amplitude that corresponds to the snap shot of Fig. 4 at 14:07:28. Comparing the two figures, introduction of P wave amplitude realized predictions to distant places.

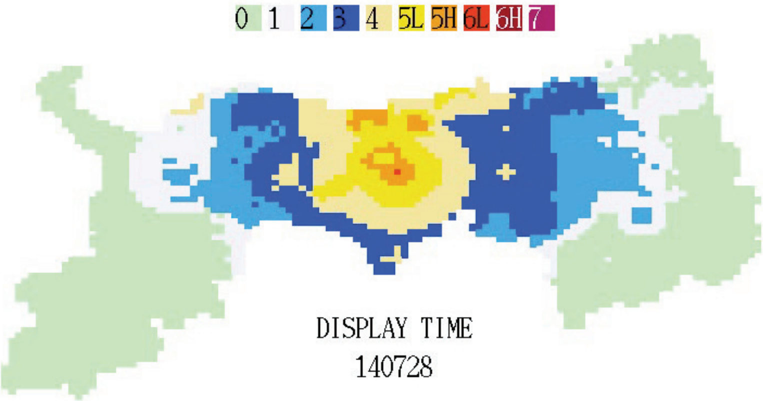

Fig. 6 – Final estimation of maximum seismic intensity distribution with P wave amplitude at 14:07:28

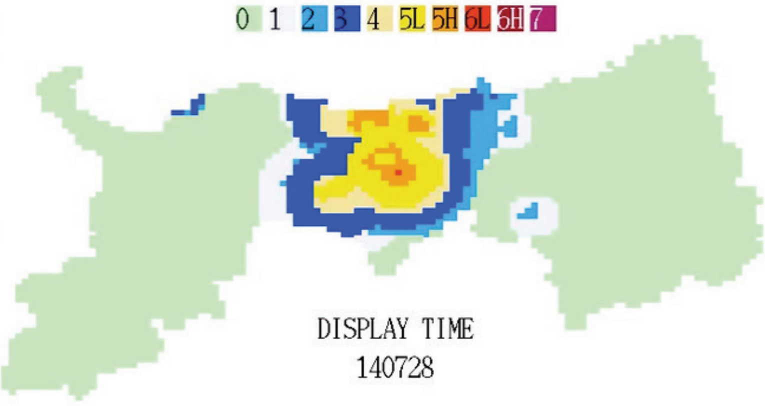

Fig. 7 – Same as Fig. 6 but without P wave amplitude (Snap shot of Fig. 4 at 14:07:28)

5. Discussions

Fig. 8 is the output at 14:07:26, two second earlier than Fig. 6. Looking at these two figures suggests the possibility of earlier EEW alert than current one, since seismic intensity 5 low which is criteria to broadcast alert is estimated even at 14:07:26 in Fig. 7. Again, this is due to the use of denser observation points than JMA. Dense observation network is desirable for upgrading quickness, accuracy and quality of EEW.

It works well in the sampled earthquake, the 2016 central Tottori prefecture earthquake, and can predict seismic intensity distribution more quickly. However, in case of the earthquakes occurred outside the network, i.e. the 2018 western Shimane prefecture earthquake (M_{JMA}6.1) and the 2018 northern Osaka prefecture earthquake (M_{JMA}6.1), overestimations were found in that S wave was misidentified as P wave in analysis. Fig. 9 shows the case of the 2018 northern Osaka prefecture earthquake. The maximum observed seismic intensity was 3 but seismic intensity 4 is predicted in limited area. It needs some additional procedure to avoid the misidentification, however, it is expected to be applicable for disaster earthquakes that bring large ground motion in the target area since large seismic intensity over 5.0 is estimated only from data assimilation of real-time seismic intensities.

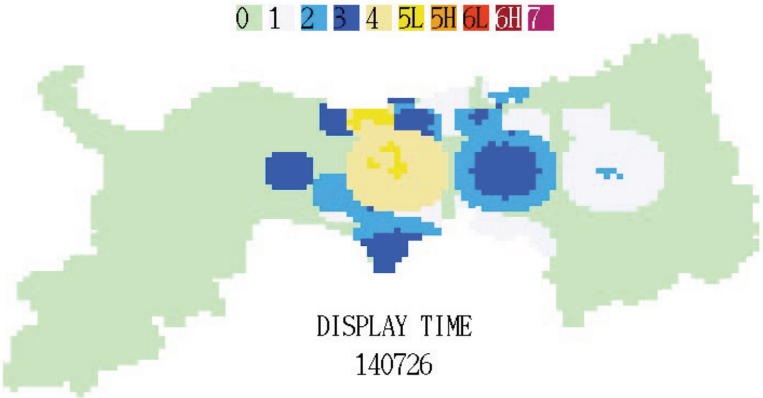

Fig. 8 – Same as Fig. 6 but at 14:07:26

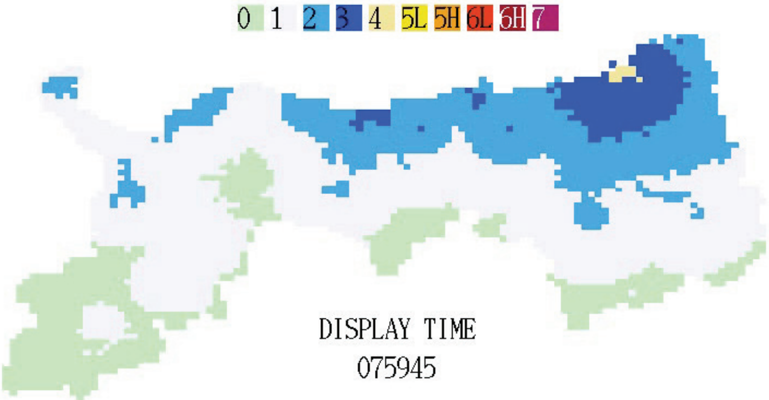

Fig. 9 – Final estimation of maximum seismic intensity distribution with P wave amplitude due to the 2018 northern Osaka prefecture earthquake

6. Conclusions

In order to improve prediction of the real-time seismic intensity distribution from the seismic intensity network maintained by local government, seismic intensity meters of Tottori prefecture have updated to broadcast UDP packets with PGAs and real-time seismic intensities at every second. The only municipal seismometers with such a function are currently operated by Tottori prefecture in Japan. More rapid and detailed EEW is expected, if standardization is carried out by examining specifications at the time of seismic intensity meter update in the future and the municipal seismic intensity meter can be used for alert issues.

A procedure based on the PLUM method, which is used in EEW by JMA, is applied to the received packets, and a system to monitor and display the real-time seismic intensity distribution in Tottori prefecture is constructed. In addition to data assimilation by observed seismic intensity at the sites, three additional improvements were made. One is to use all prediction points of 1 km mesh as secondary sources, second is to consider attenuation in seismic intensity propagation, and the third is to introduce seismic intensity prediction from PGA of vertical P wave motion.

Appling the methodology to the data due to the 2016 central Tottori prefecture earthquake, it was confirmed that a realistic seismic intensity distribution could be grasped almost in real-time. Development and implementation should be continued in order to put the system into practical use in risk management of the local government.

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6. References

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