

The PLUM Method Considering the Attenuation Law of Ground Motion

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Abstract. The Propagation of Local Undamped Motion (PLUM) method is a seismic early warning approach that directly predicts ground motion based on observed ground shaking. It can achieve good early warning effects in simultaneous multiple earthquakes and earthquakes with severe rupture zone expansion. The traditional PLUM method provides a relatively short effective early warning time. To further increase the early warning duration of PLUM, this paper proposes a PLUM method that considers the attenuation law of ground motion. Unlike the traditional PLUM method, which can only predict ground shaking for sites within a fixed radius, the new method can predict real-time ground motion for sites at greater distances based on the attenuation law of seismic intensity and issue early warning information to users. Finally, a retrospective simulation of the January 1, 2024, earthquake in the Noto Peninsula, Japan, is conducted.

Keywords: PLUM, Attenuation relation.

1. Introduction

The conventional earthquake early warning method first uses the automatic identification method of P-wave arrival to identify seismic P-waves and extract the P-wave arrival time [1-4]. The time difference between the first arrival and arrival of four or more P-waves is used for seismic location [5-10]. The 3-second peak displacement of P-wave front is used to estimate the magnitude of the earthquake [11-14]. Earthquake influence field (intensity field, peak field of ground motion) is estimated by using the attenuation relation of ground motion [15, 16]. The location and magnitude of earthquake epicenter are the basic parameters of earthquake. However, the regional influence field estimation method based on seismic basic parameters combined with ground motion attenuation relationship has several problems: (1) When there is a large deviation in location or magnitude estimation, even though some stations have observed destructive ground motion and reached the early warning conditions, due to the small estimation of focal parameters, the early warning method does not consider using the peak information of ground motion observed by a single station for early warning, resulting in the small estimation of the impact field and resulting in missed reporting; (2) Under the main shock condition of foreshock, the P-wave peak value of foreshock is very small, and the magnitude estimated by foreshock is also very small, while the information of subsequent large earthquakes cannot enter the early warning algorithm, and the observed peak value is still difficult to use, resulting in missing reporting; (3) In the case of double earthquakes, underreporting caused by small magnitude estimation will also occur, which often occurs in both China's earthquake early warning system and Japan's earthquake early warning system; (4) The earthquake needs three or more P-waves to arrive before it can be carried out, which will take a few seconds, and the destructive ground motion of the near source station may have arrived before the completion of positioning, but because the method does not respond to the early warning measures, the warning blind area will increase.

To solve these problems, Kodera, a Japanese, proposed the PLUM method [17, 18]. Based on the assumption that "when an earthquake occurs, the observed seismic waves will not attenuate during the propagation within a distance of R", Plum method uses the station information in the area with

the target prediction site as the center of the circle and the radius of R to predict the real-time ground motion of the target site and release the early warning information to the earthquake early warning users. But this creates new problems. The warning time of PLUM method is determined by the size of the fixed prediction radius. Too large a forecast radius will lead to excessive alerts, while reducing the forecast radius will shorten the warning time and may lead to missed alerts. For ground tremors and large earthquakes close to the source, this fixed prediction radius also limits the warning time available at locations farther from the source [19].

In order to solve the above problems, the PLUM method considering the attenuation law of ground motion is proposed in this paper. In the region within R, the original hypothesis remains unchanged, and in the region outside R, the predicted intensity is calculated according to the attenuation law of seismic intensity to expand the prediction radius and prediction time of the PLUM method.

2. Dataset Creation

According to the determination of the China Earthquake Networks Center: January 1, 2024 at 16:10 minutes 10 seconds (Japan standard time), the MW7.4 earthquake occurred in the west coast of Honshu, Japan, the epicenter of 37.50 degrees north latitude, 137.20 degrees east longitude, focal depth of 30 kilometers. Taking the earthquake as an example, the traditional plum and improved PLUM were used for retrospective simulation. Japan's K-NET strong earthquake observation network has been in operation since 1996, and more than 1,000 strong earthquake accelerometers have been deployed at an average station spacing of 20 kilometers on the free surface, which is close to the station layout of China's "National Intensity Quick Reporting and early Warning Project". In this paper, K-NET seismic record data was selected for processing. A total of 584 stations acquired seismic records, and the selected data were processed as follows:

(1) The EDP-Picker method proposed by Lu Jianqi et al in 2020 is used to automatically pick up the seismic P-wave time and manually check the automatically identified seismic P-wave time.

(2) The velocity record obtained by one integration and the displacement record obtained by two integrations are performed on the acceleration record, and the low-frequency drift phenomenon after integration is eliminated by the fourth-order 0.075Hz high-pass filtering.

(3) According to the "China Seismic Intensity Scale" (GB/T 17742-2020), the three-direction velocity records are respectively filtered by 0.1~10Hz bandpass.

3. Method

In order to form a practical method for earthquake early warning in China, this paper uses the calculation method of China Instrument Intensity II published by "China Earthquake Intensity Scale" (GB/T 17742-2020). The specific calculation formula is as follows:

$$I_A = 3.17\log_{10}(\text{PGA}) + 6.59 \quad (1)$$

$$I_V = 3.00\log_{10}(\text{PGV}) + 9.77 \quad (2)$$

$$I_I = \begin{cases} I_V, & I_A \geq 6.0 \\ (I_A + I_V)/2, & I_A < 6.0 \end{cases} \quad (3)$$

Where PGA and PGV are the peak acceleration and peak velocity of ground motion, respectively.

In this paper, Ma Yunyi et al. 's 2020 attenuation rule of instrument seismic intensity in China based on line source model [20] is adopted. The attenuation model is as follows:

$$I = 6.1 + 1.072M + 0.0346M^2 - 4.566\lg(R_d + 15) - 0.0055R_d \pm 0.93 \quad (4)$$

Where I is the instrument intensity of China; M is the magnitude; Rd is a line source in kilometers.

Due to the large area of China, different from Japan, which uses prefectures in administrative divisions as grids, this paper adopts a simple rectangular grid division, the size of each grid is $0.2^\circ \times 0.2^\circ$

(each grid spans 0.2 longitude and 0.2 latitude), and 4 prediction points are evenly distributed in each grid.

The "China Earthquake Intensity Scale" (GBT17742-2020) shows that when the intensity of the instrument is $2.5 \leq II < 3.5$, a small earthquake is felt in the earthquake area. An earthquake occurs when an instrument intensity of at least 2.5 degrees is observed at an adjacent station within 15 seconds. After an earthquake occurs, the maximum observed intensity of the trigger station is assigned to the predicted intensity of the predicted points within R. Earthquake intensity prediction is based on the following formula:

$$I_{\text{pred}}^{(k)} = \max_{i \in C_R} \{I_{\text{obs}}^{(i)} - F_0^{(i)}\} + F_0^{(k)} \quad (5)$$

Where i and k are spatial positions; $I_{\text{pred}}^{(k)}$ is the predicted intensity of the target site k; $I_{\text{obs}}^{(i)}$ is the observed intensity at i; $F_0^{(i)}$ and $F_0^{(k)}$ are the field amplification coefficients of i, k; C_R is a circular region with radius R centered on the predicted site.

The predicted intensity of the predicted point whose distance exceeds R is given according to the attenuation law of seismic intensity. We assume that the trigger station is directly above the source, Rd is the distance between the prediction point and the trigger station, and the M of the same earthquake does not change. According to equation (4), we can obtain the predicted intensity of observation points at any distance between a single earthquake and the trigger station, and calculate the predicted intensity of all predicted points 200 kilometers away from the trigger station with this method. There may be multiple stations triggered at the same time, which will cause some prediction points to calculate multiple prediction intensification, the maximum of which is the prediction intensity of the prediction point at the same time. We take the maximum prediction intensity of all prediction points in the early warning grid as the prediction intensity of the grid. As the earthquake spreads, more stations are triggered, and more warning grids issue earthquake warnings. An earthquake is considered to have ended when no more stations observe an intensity greater than 2.5 degrees for 10 seconds.

4. PLUM early warning results

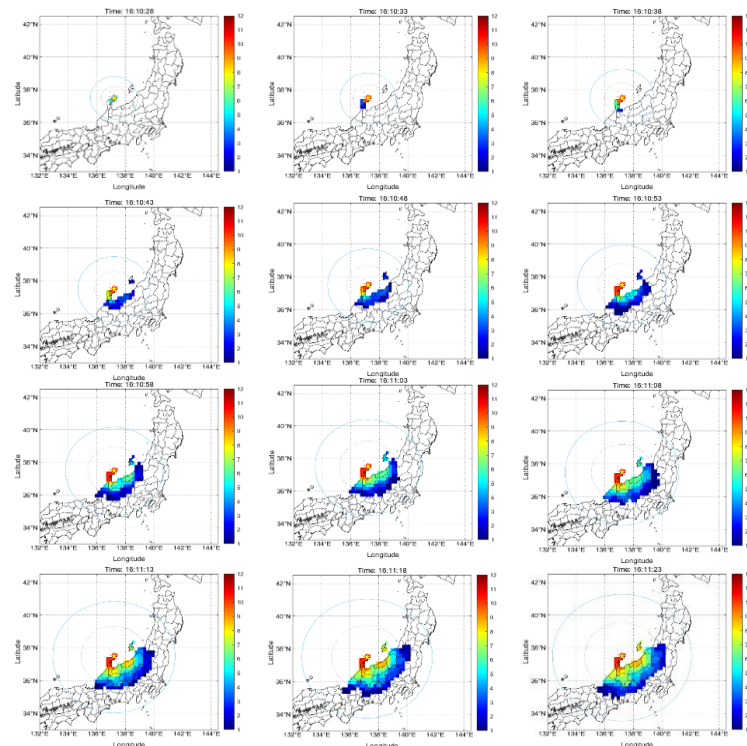


Figure 1. Intensity prediction map based on PLUM

According to the data of Japan's K-NET strong earthquake observation network, 15 seconds after the earthquake (Japan standard Time 16:10:25 seconds) the first station (ISK001) p wave triggered, 3 seconds after the P-wave triggered, ISK001 and ISK002 observation China instrument intensity 5.1 and 4.5, respectively, at this time announced the earthquake. Assuming that the seismic waves observed within 30 kilometers are unattenuated plane waves in the bedrock, the intensity of the target site is predicted based on the seismic intensity observed by stations around the target site and warning information is issued. Figure 1 is drawn. In the figure, the five-pointed star represents the epicenter, the dashed line circle represents the P-wave front, and the solid line circle represents the S-wave front (the same below):

5. Early warning results and evaluation of PLUM considering attenuation law of ground motion

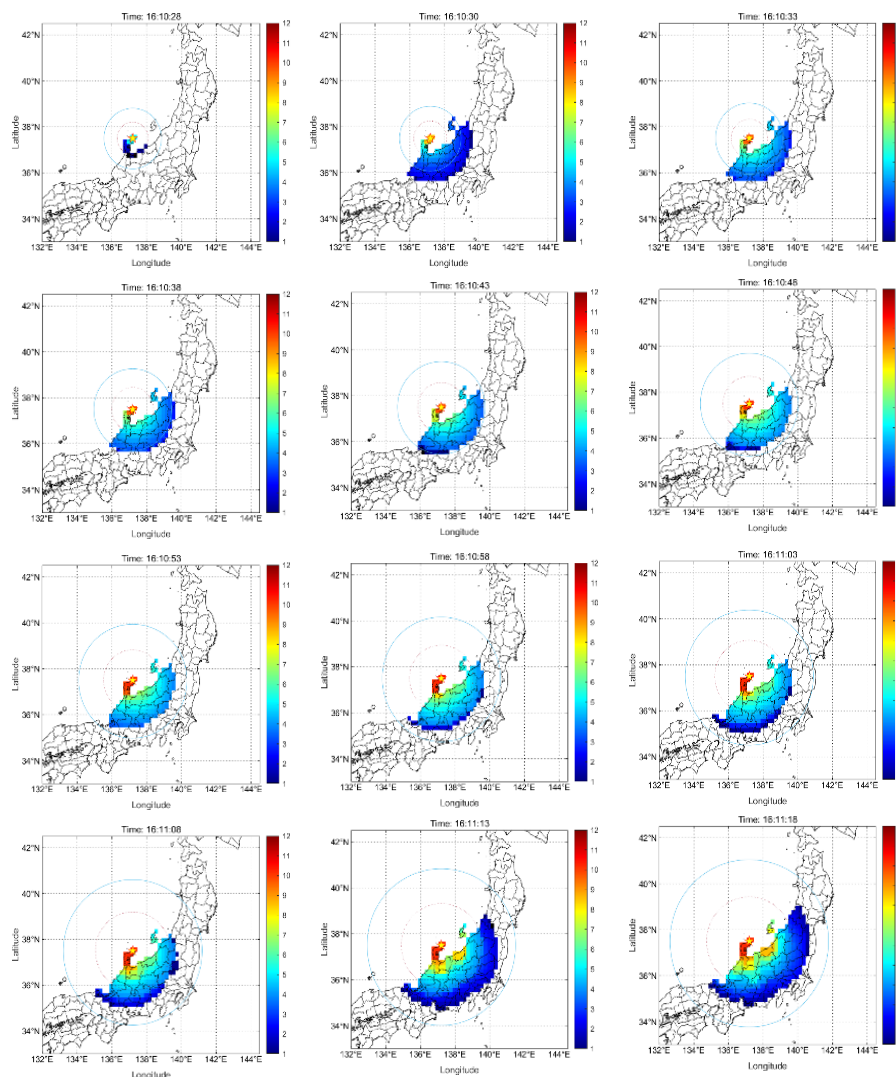


Figure 2. Intensity prediction map based on PLUM considering attenuation law of ground motion

According to the data of Japan's K-NET strong earthquake observation network, the P-wave of the first station (ISK001) was triggered 15 seconds after the earthquake (16:10:25 JST), and the observed intensity of ISK001 and ISK002 was 5.1 and 4.5 respectively 3 seconds after the P-wave was triggered. The plum method considering the attenuation law of ground motion will announce the occurrence of earthquake at this time. In the calculation of predicted intensity, equation (5) takes 30km without considering the influence of site amplification factor. For forecast points over 30 km and less than 200 km, the forecast intensity is calculated using equation (4). In addition, time delay is not considered in this seismic simulation. The predicted intensity diagram of the 2024 Noto earthquake

in Japan, which takes the maximum intensity from the beginning time to the mapping time as the PLUM method considering the attenuation law of ground motion, is shown in Figure 2.

The simulation results show that, compared with the traditional plum method, the early warning range is significantly expanded and the early warning time is greatly improved.

6. Conclusion

China is one of the countries that suffered the most from the earthquake disaster, and China began to carry out research on earthquake early warning in the 1990s. The Plum method considering the attenuation relationship does not need to estimate the source information, but directly uses the observed ground motion to predict. This method can effectively overcome the problems of missing and underestimating existing in the traditional point-source model earthquake early warning method. However, since the prediction of ground motion in this method uses S-wave information, the determination of seismic events and the issuing of the first earthquake early warning are not timely enough, and the early warning time is not long enough. If the point-source model is combined with this method, the data processing and alarm issuing may be more timely and the earthquake warning time can be extended.

Acknowledgements

This research was supported by the Key Science and Technology Project of the Ministry of Emergency Management of the People's Republic of China (2024EMST040409). Special thanks to K-NET for providing the seismic data.

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