STUDY ON NEW TECHNOLOGY OF EARTHQUAKE EARLY WARNING

Shan-you LI* Jian-qi LU Jin-dong SONG Qiang MA Zhen ZHAO

Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

* Corresponding author, E-mail: lishanyou@vip.126.com; Tel.: +86-451-86652743.

The earthquake early warning (EEW) system of China is in the stage of testing. It is still facing the common scientific and technological problems such as the problem of magnitude estimation with large uncertainty, the difficulty in quickly identifying rupture parameters and the irrational estimation of the shakemap especially for large events. Moreover, another big challenge for the EEW system of China is the special technical problem of sending tens-millions-level alarm message in sub-second. In order to solve these problems, a project named "Advanced technical development and field demonstration for earthquake early warning" has launched by the Science and Technology Ministry of China. This paper provides an overview of the current situation of EEW system construction and summarizes the key strategies proposed by this project for solving these problems.

Keywords: Earthquake Early Warning; Artificial intelligence; Source parameters; Magnitude estimation

1. INTRODUCTION

As a major natural disaster, earthquake disasters can cause serious damage to social infrastructure and thus cause serious impact on social and economic development. As an effective means of disaster mitigation, earthquake warning has been widely used and developed in earthquake-prone countries, such as Japan, the United States, and Mexico, etc[11,15]. After the 2008 Wenchuan Ms8.0 earthquake, China began to build its own EEW system[11]. In October 2010, China initiated the establishment of the National Earthquake Early Warning System Construction Project with an investment of about 1.9 billion RMB Yuan. The project plans to build 15,000 earthquake early warning stations, 31 provincial early warning centers and a national early warning center in five years, and plans to form earthquake early warning capabilities in five key areas. At present, the EEW demonstration systems in the four metropolitan areas of the Capital Region, Lanzhou, Fujian and Chuandian were completed. In terms of magnitude estimation, various magnitude determination methods were tested. For example, the methods of Pd, Pv and Pa were tested in Fujian system, the methods of τ_p and τ_c were tested in Chuandian system. In terms of earthquake location, the single station positioning method with respect to B-△ has been used when only one station is triggered, and not yet triggered stations have been used as limitation[11]. After more than three stations were triggered, the double-difference positioning method is used to determine the source location[6,11]. In terms of shakemap estimation, the ground motion of target site is estimated by ground motion prediction equation. In addition, several new techniques, with respect to P-wave automatic picking and noise elimination method, continuous magnitude estimation method, and strong ground motion prediction method, were tested in demonstration EEW systems of China, and these new techniques are as below.

（1）P-wave onset automatic picking and interference eliminating method

Identifying earthquakes from background noise and obtaining reliable P-wave first arrival is a key technology in earthquake early warning. Currently, the commonly used P-wave onset picking method is the Short Term Average to Long Term Average ratio method (STA-LTA)[2,10]. The P-wave onset obtained from STA-LTA is always lag behind the real one. In order to obtain a more accurate P-wave onset, Akaike Information Criterion (AIC) is used to determine the exact P-wave onset in a short time window (the commonly used time window length is 2 seconds) before the cursory onset determined by STA-LTA. This method can largely improve the accuracy of P-wave onset

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picking[10]. Eliminating interference from real seismic P-wave is also an important technique in EEW systems, considering the triggered time of each station correspond to the same earthquake have a good correlation between the epicenter of the earthquake and location of the triggered station, using Delaunay triangulation can well reflect the location relation of each triggered station and their corresponding time relation. Using this technique, the interference's erroneous trigger can be eliminated from being considered as real P-wave first arrival. This method was tested on real continuous data at Fujian demonstration EEW system[10].

（2） Multi-parameter early warning magnitude continuous determination method

The magnitude estimation results obtained by the single-parameter-based magnitude estimation method have large discreteness. In contrast, the magnitude estimation results obtained by using the multi-parameter-based magnitude estimation method have less discreteness. In China's demonstration EEW systems, a multi-parameter-based magnitude continuous estimation method is used. This method has trained multi-parameter with respect to PGA, PGV and PGD corresponding to the time length 1 s, 3 s, 5 s, 10 s and the epicentral distance using the back-propagation neural network. The results show that the standard deviation of the obtained magnitude is ±0.344[11].

（3）Ground motion prediction method based on artificial neural network

The ground motion of a target site is the main indicator for sending EEW alarm. Generally, the ground motion of the target site is estimated through the ground motion prediction equation, which is the simplest way, because the estimation is under the assumption of point source model. When the real source model is not symmetric, the ground motion of some areas will be estimated erroneously. Onsite ground motion prediction as a good alternative can offer more reliable but inefficient ground motion prediction. The coefficients of onsite ground motion prediction are obtained through artificial neural network[11,14].

2. KEY SCIENTIFIC AND TECHNOLOGICAL PROBLEMS OF EEW

The final goal of EEW is to provide the most reliable warning information (accuracy) for EEW users in the shortest time (rapidity). Therefore, the issue of accuracy and rapidity are common problems faced by all EEW systems. These common problems can be broken down into below:

（1）Magnitude estimation

Accurate estimation of earthquake magnitude in real-time is a bottleneck scientific problem in EEW research. A variety of parameters[5,7,17,23] such as peak amplitude (peak displacement, peak velocity, and peak acceleration, etc.), dominant period (τ_p τ_c) are used to estimate earthquake magnitude in real-time, but it might result in large uncertainty especially for small and large earthquakes. Therefore, how to accurately estimate an ongoing earthquake's magnitude with limited information is still a pending issue.

（2）Seismogenic fault parameters estimation

In the first stage of EEW research, seismologists are focusing on estimating an ongoing earthquake's magnitude. The ground motion of a target site is generally estimated using ground motion prediction equation in which the source model is approximating with symmetric bilateral rupture model, and the rupture length is predicted by the statistical relationship between the earthquake magnitude and the length of rupture. However, things is not always the case, some large earthquakes that have already occurred have shown great discrepancy between the approximated source model and the real source model, such as 2008 Wenchuan Ms 8.0 earthquake and 2011 Tohoku-oki Mw 9.0 earthquake. This great discrepancy will lead to the erroneous estimation on the ground motion of the target site which in turn leads to false alarm. Seismologists began to realize the importance of real-time rupture parameters estimation. Some real-time rupture parameters estimation methods have already been proposed and tested in EEW systems[3,16], but the accuracy and efficiency of these methods still need to be improved.

（3）Ground motion prediction in case of multi-events

At present, the commonly used ground motion prediction method is that using ground motion prediction equation to obtain the ground motion of a target site. This method is suitable for a single event. Most EEW systems are designing with algorithms based on single event. When multi-events occur, it will lead to system confusion[1]. For example, after 2011 Tohoku-oki Mw 9.0 earthquake, simultaneously occurred two small aftershocks have been misjudged by Japan EEW system as a large earthquake[21,22]. Therefore, how to reasonably estimate the ground motion in case of multi-events is a key technical issue.

(4) **Massive alarm message sending in sub-second**

Besides the common problems all EEW systems are facing, China's EEW system is also faced with another technological challenge of sending alarm message to 10-million-level users in sub-secondDue to the large population density of China, the population of most capital cities is beyond 10 million. This will lead to great burden to EEW alarm message sending.

3. CORE THEORY AND SOLUTIONS FOR KEY TECHNICAL ISSUES

In order to solve these scientific and technical problems faced by China's EEW system, a project named "Advanced technical development and field demonstration for earthquake early warning" was launched by the Science and Technology Ministry of China. The project is led by the Institute of Engineering Mechanics, China Earthquake Administration (CEA), combined with the Institute of Geophysics of CEA, the Seismological Network Center of CEA, the University of Science and Technology, the Wuhan University, the Zhejiang University, the Fujian Seismological Bureau, etc. The total investment of the project is 21.42 million RMB Yuan, and the project execution period is from December 2018 to December 2021. The project starting with new observation methods, new early warning algorithms, new data collection and processing technology and new alarm message sending technology, aims at solving those common and special scientific and technological problems faced by the EEW system of China. The research results of this project will be applied in Xichang city, Sichuan province. These studies will provide technical support for the construction of China's EEW system. The key scientific and technical strategies and methods proposed by this project are as follows:

3.1 Magnitude continuous estimation strategy based on artificial intelligence

Under the condition that the fault rupture has not yet ended, it is still very difficult to estimate the magnitude by relying on a small amount of information. Whether it is possible to estimate the magnitude based on limited information with high resolution is still inconclusive. From the existing research results, we can get some clues, that is, as the estimation parameters increase, the accuracy of the estimation will also increase. It may either be because our understanding to the data is not deep enough, or the information contained in the data are not fully utilized, the magnitude estimation result is still under our expectation. Recently, artificial intelligence has shown its advantage in big data information mining, which might be an effective way to improve the resolution of real-time magnitude estimation in EEW system. Therefore, extracting the parameters that can reflect the rupture process and earthquake nucleation process at the early stage of the earthquake occurrence, analyzing the variation trend of these parameters and studying the correlation between the magnitude and these parameters using artificial intelligence technology, the resolution of magnitude estimation will be improved. This is the strategy proposed by this project to solve the problem of accurately estimating an ongoing earthquake's magnitude. The flow chart of the strategy is shown in Fig. 1.

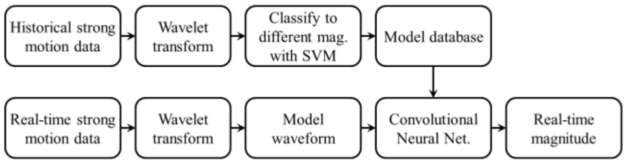

Fig. 1. Flow chart of magnitude estimation strategy

3.2 Real-time determination of rupture parameters by compressive sensing and pattern recognition

Studies have shown that the amplitude of the near-source ground motion is distinguishable from the amplitude of the far-source ground motion[3,18]. This can help one to monitor the space distribution of seismogenic fault in real-time. This technology will be further developed in this project. The flow chart of the strategy is shown in Fig. 2.

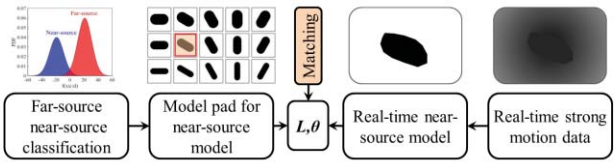

Fig. 2 Flow chart of rupture parameters real-time determination with pattern recognition

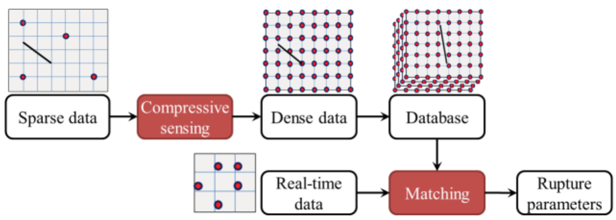

Fig. 3 Flow chart of rupture parameters real-time determination with compressive sensing

The method of identifying fault rupture parameters by using near to far source parameters is limited by the small amount of near-source data of large earthquakes. It is difficult to ensure the reliability of this method. Moreover, this method identifying the spatial spread of fault rupture only after the fault rupture has occurred, so, the efficiency of this method is limited. The technology of compressed sensing has been widely used in the fields of image restoration and reconstruction, data recovery and so on. This technology can recover the missed information through a recursive transformation using only a small amount of observed data. Thus, if missed ground motion of any location can be recovered from observed data by using this technology, we can get the ground motion of any location that we need. By restoring the historical ground motion, the template corresponding to different source mechanics can be established. In the process of earthquake occurrence, the rupture parameters of an ongoing earthquake can be identified in real-time by using fast matching algorithm. The flow chart of the strategy is shown in Fig. 3.

3.3 Shakemap determination

Reasonable prediction on the shakemap of large earthquakes is the key issue of earthquake early warning. The commonly used shakemap prediction method is the strong motion prediction equation in the case of a given magnitude and rupture space distribution. In this project, we are intended to use the stochastic finite fault method to predict the shakemap. This method can well approximate the directional effect of the earthquake with large rupture length, especially for the unilateral rupture. Besides the shakemap prediction method of stochastic finite fault, a complement method of numerical shaking prediction[4] is also used in case of multi-events concurrency.

3.4 Massive alarm message sending in sub-second

The massive alarm message sending in sub-second is a special problem faced by China's EEW system. For some large and medium-sized cities, the number of user is generally more than 10 million. It takes a lot of technical difficulty to send all of these messages to tens of millions of users in one second. Therefore, the project will use information compression, hierarchical cascading, high-frequency high-concurrency and other technologies to solve this problem. The flow chart of the strategy is shown in Fig. 4.

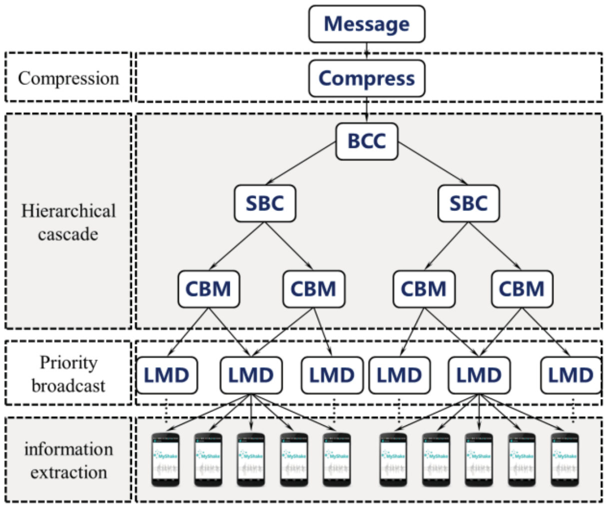

Fig. 4 Flow chart of message sending strategy

There are totally six steps in this strategy.

Step1: Compress the EEW message into the smallest format, and then deliver it to broadcast center (BCC).

Step2: The broadcast center delivers the message to the sub-broadcast center (SBC).

Step3: The sub-broadcast center delivers the message to cascading broadcast module (CBM).

Step4: The cascading broadcast module delivers the message to link module (LMD).

Step5: The link module using GPS positioning tool searches for the related users for priority broadcast.

Step6: Extract the compressed message with a mobile phone App into readable message.

4. CONCLUSION

This paper provides an overview of the current construction situation and some key scientific and technical problems in China's EEW system. Meanwhile, the strategies and methods proposed by the project named "Advanced technical development and field demonstration for earthquake early warning" for solving these problems are summarized.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Annie L, Masumi Y. Bayesian Approach for Identification of Multiple Events in an Early Warning

System. *Bull. Seismol. Soc. Am.*, **104**(3):1111-1121, 2014.

[2] Allen R M. Automatic earthquake recognition and timing for single traces. *Bull. Seismol. Soc. Am.*, **68**(5):1521-1532, 1978.

[3] Böse M, C Felizardo, T H Heaton. Finite-Fault Rupture Detector (FinDer): Going Real-Time in Californian ShakeAlert Warning System. *Seismological Research Letters*, **86**(6): 1692-1704. 2015.

[4] Hoshiba M, S Aoki. Numerical shake prediction for earthquake early warning: Data assimilation, real-time shake mapping, and simulation of wave propagation. *Bull. Seismol. Soc. Am.*, **105**:1324-1338, 2005.

[5] Huseyin S K, Richard M. Allen. A global approach to provide magnitude estimates for earthquake early warning alerts. *Geophysical research letters,* **40**: 6329-6333, 2013.

[6] Jin X, Zhang HC, Li J, et al. Research on continuous location method used in earthquake early warning system. *Chinese J. Geiphys.*, **55**(3):925-936, 2012. (in Chinese)

[7] Li SY, Jin X, Ma Q, et al. Study on earthquake early warning system and intelligent emergency controlling system. *World Earthquake Engineering*, **20**(4): 21-26, 2004. (in Chinese)

[8] Li SY, Wu DP, Jin X, et al. The real-time calculation method of instantaneous parameters of seismic signal. *Earthquake Engineering and Engineering vibration*. **24**(5): 13-16, 2004. (in Chinese)

[9] Li SY, Zhu HY, Wu Dongpo, et al. Automatic recognition of seismic phase based on amplitude and instantaneous frequency. *World Earthquake Engineering*, **22**(4):1-4, 2006. (in Chinese)

[10] Ma Q, Jin X, Li SY, et al. Automatic P-Arrival Detection for Earthquake Early Warning. *Chinese J. Geiphys.*, **56**(7):2313-2321, 2013. (in Chinese)

[11] Ma Q. *Study and Application on Earthquake Early Warning*. Doctor's Dissertation of Institute of Engineering Mechanics, CEA. 2008. (in Chinese)

[12] Satriano C, Lomax A, Zollo A. Real-time evolutionary earthquake location for seismic early warning. *Bull. Seismol. Soc. Am.,* **98**(3):1482-1494, 2008.

[13] Shigeki H, Hiroaki N, Kana A, et al. An Automatic Processing System for Broadcasting Earthquake Alarms. *Bull. Seismol. Soc. Am.*, **95**(2): 708-718, 2005.

[14] Song JD. *Research on Seismic Ground Motion Indices for Operation Control and Single Station Earthquake Early Warning Applied for High-speed Railway*. Institute of Engineering Mechanics, Doctor's Dissertation of Institute of Engineering Mechanics, CEA. 2013. (in Chinese)

[15] Song JD, Jiao CC, Li SY, et al. Prediction Method of First-Level Earthquake Warning for High Speed Railway Based on Two-Parameter Threshold of Seismic P-Wave. *China Railway Science*, **39**(1): 138-144, 2018.

[16] Vincenzo C, Mauro C, Raffaella D M, et al. Fault extent estimation for near-real-time ground-shaking map computation purposes. *Bull. Seismol. Soc. Am.*, **102**(2):661-679, 2012.

[17] Wu YM, Kanamori H, Allen R M, et al. Determination of earthquake early warning parameters, τc and Pd, for southern California. *Geophysical Journal International*, **170**(2):711-717, 2007.

[18] Yamada M, T Heaton, J Beck. Real-time estimation of fault rupture extent using near-source versus far-source classification. *Bull. Seismol. Soc. Am.*, **97**: 1890-1910, 2007.

[19] Yuki K. Real-time detection of rupture development: earthquake early warning using P waves from growing ruptures. *Geophysical Research Letters*, **45**:156-165, 2018.

[20] Yuki K, Yasuyuki Y, Kazuyuki H, et al. The propagation of local undamped motion (PLUM) method: A simple and robust seismic wavefield estimation approach for earthquake early warning. *Bull. Seismol. Soc. Am.*, **108**(2):983-1003, 2018.

[21] Yuki K, Jun S, Naoki H, et al. Earthquake early warning for the 2016 Kumamoto earthquake: performance evaluation of the current system and the next-generation methods of the Japan Meteorological Agency. *Earth, Planets and Space*, **68**:202,2016.

[22] Yukio F, Yoichi N. Japan's Earthquake Early Warning System on 11 March 2011: Performance, Shortcomings, and Changes. *Earthquake Spectra*, **29**(S1): S341-S368, 2013.

[23] Zollo A, Lancieri M, Nielsen S. Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records. *Geophysical Research Letters*, 33, L23312, 2006.