Earthquake Research in China

Volume 28, Number 3, 2014

Recent Developments of Earthquake Early Warning in California, USA[1]

Wang Honglei[1)] and Walter D. Mooney[2)]

1) Earthquake Administration of Hebei Province, Shijiazhuang 050021, China
2) Earthquake Science Center, USGS, 345 Middlefield Rd., Menlo Park, California, USA

In this paper we outline the science, engineering, and societal considerations of the prototype Earthquake Early Warning System (EEWS) in California and detail the development and testing of methodologies in the last 10 years in America. Also, we give a brief introduction of Earthquake Early Warning (EEW) in China, and based on the summary of EEW in California we make an analysis of the perspectives, misconceptions, and challenges that China may have.

Key words: Earthquake Early Warning; Prototype; ShakeAlert; California

INTRODUCTION

An earthquake early warning system can provide a few seconds to tens of seconds warning prior to ground shaking during an earthquake. Currently, public warning systems exist in Japan and Mexico and the development of other EEWS is ongoing in many other regions of the world including the US West Coast (Allen et al., 2009) (Fig. 1).

Scientists and engineers at the California Institute of Technology (Caltech), University of California, Berkeley (UC Berkeley), the Swiss Federal Institute of Technology (ETH), and the University of Southern California (USC) started in 2007 to develop and implement a prototype earthquake early warning system for California, called the California Integrated Seismic Network (CISN) ShakeAlert (Böse et al., 2012). In the first phase of the project, three algorithms were tested in the CISN real-time environment: Onsite, the Virtual Seismologist (VS), and Earthquake Alarm Systems (ElarmS). Now in its second phase, the implementation and evaluation of an end-to-end real-time system that is under testing, and updates earthquake alerts after an earthquake has started. This project is a step on the path to full implementation of

[1] Received on May 9, 2014.

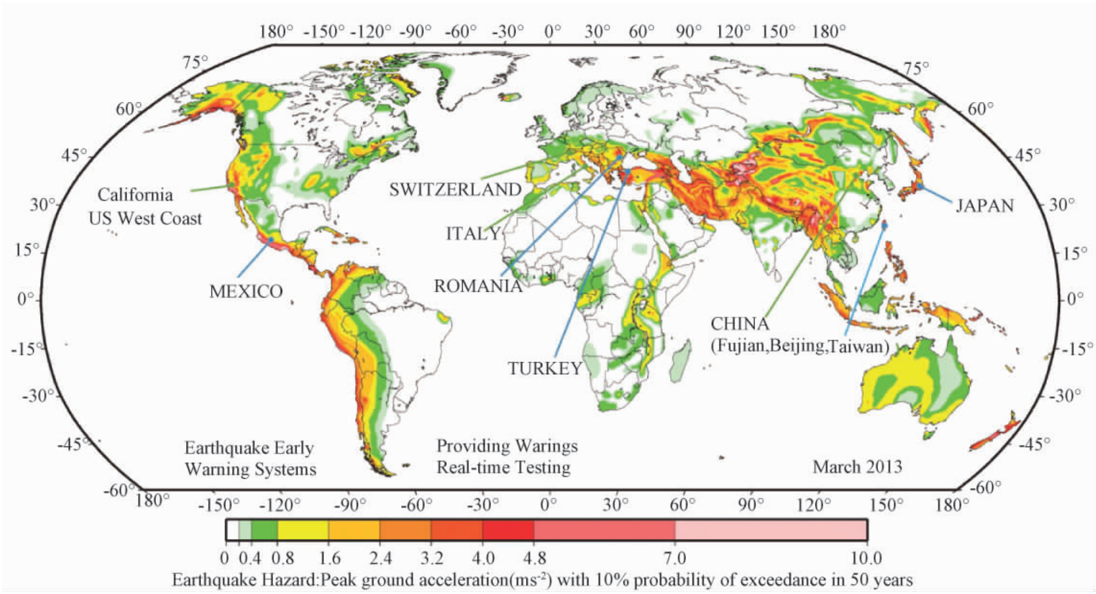

Fig. 1

Earthquake Early Warning System in the World

earthquake early warning.

China has a high level of seismic activity. Strong earthquakes have caused great losses of people's lives and property. Since 1900, there have been 416 earthquakes in the Chinese mainland ($6.0 \leqslant M \leqslant 6.9$), 70 earthquakes ($7.0 \leqslant M \leqslant 7.9$) and 7 earthquakes ($M \geqslant 8.0$). The earthquakes affected 28 provinces, causing 660,000 fatalities, ranking highest all over the world. Since the 21st century, the Chinese mainland and its surrounding areas has entered a relatively seismically active period, where earthquake frequency, distribution area and occurrence rate have obviously increased. There have been two earthquakes above magnitude 8.0 in the last decade, which caused huge casualties and unprecedented economic losses.

Developing an earthquake early warning system in China is therefore of great importance and necessity. This necessity is dramatically highlighted by the disastrous Wenchuan earthquake in 2008. Accordingly, the China Earthquake Administration (CEA) was motivated to configure a nationwide EEWS (Peng et al., 2011).

1 ALGORITHM RESEARCH IN AMERICA FOR EEW

When we talk about the approach to the EEWS, there are mainly two, regional and single-sensor.

Earthquake early warning techniques have improved significantly over the last decade, including both technological advances in real-time seismology and the development of algorithms for the rapid detection of possibly damaging earthquakes a few seconds to some tens of seconds before strong shaking occurs (Allen et al., 2009). These algorithms require the seismic waveforms either from a single seismic sensor (the so-called Onsite warning systems (Wu and Kanamori, 2005; Kanamori, 2005; Zollo et al., 2006; Böse et al., 2007)) or from a seismic network or subnetwork (the so-called regional warning systems (Wu and Teng, 2002; Allen and Kanamori, 2003; Cua and Heaton, 2007)).

Three EEW algorithms are currently tested within the CISN: ElarmS (Wurman et al., 2007;

Allen, 2007; Allen and Kanamori, 2003), the Virtual Seismologist (Cua and Heaton, 2007), and the $\tau_c - P_d$ Onsite algorithm (Kanamori, 2005; Wu et al., 2007). The two first algorithms are regional (network based) warning approaches, while the $\tau_c - P_d$ algorithm belongs to the group of onsite (single sensor based) warning methods (Kanamori, 2005).

1.1 Onsite

The $\tau_c - P_d$ Onsite algorithm has been researched and tested in California by Caltech over the past ten years. It uses the period τ_c and amplitude P_d of initial shaking to estimate the size and forthcoming shaking in an earthquake (Kanamori, 2005). Real-time tests of the $\tau_c - P_d$ Onsite algorithm in California over the past six years (2007 ~ 2013) have shown that some modifications are necessary to increase the robustness of the algorithm (Böse et al., 2012; Böse et al., 2009b). The main modifications that have been developed are in two aspects, the $\tau_c - P_d$ Trigger-Criterion and the Two-Station-Method (Böse et al., 2009a). In addition, a simple associator and localization procedure for Onsite was developed. Since 2010, Onsite is also providing uncertainty estimates and likelihood parameters (Fig. 2). For the current telemetry and processing, delays from $\tau_c - P_d$ Onsite usually become available 5 seconds after the event origin or later, depending on the distance between the earthquake and the reporting station, as well as station equipment.

1.2 ElarmS

ElarmS is a network based EEW system. Over the last 10 years, the ElarmS algorithms have been completely reassessed and re-coded to solve technological and methodological challenges (Fig. 2).

The second generation (ElarmS-2 or E2) is designed specifically to maximize the current network, hardware, and software performance capabilities by improving both the speed and accuracy of early warning processing. The E2 is divided into a waveform processing (WP) module and an event monitoring module (EM). From Fig. 3 we can see an overview of the data processing flow: Station waveform feeds are processed at the three CISN network hubs, UC Berkeley, Caltech and Menlo Park. P-wave triggers, peak amplitudes, signal-to-noise ratio (SNR), peak ground acceleration and velocity (PGA and PGV), and other parameters (Brown et al., 2011) are generated at the three processing centers and forwarded to a single, state-wide trigger pool and event monitor running at UC Berkeley. After a quality check of new triggers, association is first attempted with existing events based on the trigger time falling within a defined space-time window. If new triggers cannot be associated with existing events, the associator then attempts to create a new event based on the space-time proximity of unassociated triggers. If three or more triggers are close in space and time, a new event is created. New or modified events are then located using the arrival times and a simple grid search algorithm, and magnitude is estimated. A split event filter checks that the triggers from a single event have not been split into two events i. e. two or more events within a small space-time window, in which case one is deleted and the triggers are returned to the trigger pool. Finally, an alert filter continuously checks the event pool to identify any events that pass another set of criteria and can be published to the Decision Module.

E2 is designed as a modular code. This means it is easy to upgrade individual elements of the algorithm (location, magnitude, etc.) at any time, without disrupting the processing stream (Fig. 3).

1.3 Virtual Seismologist (VS)

The Virtual Seismologist (VS) early warning approach was originally formulated by Cua and

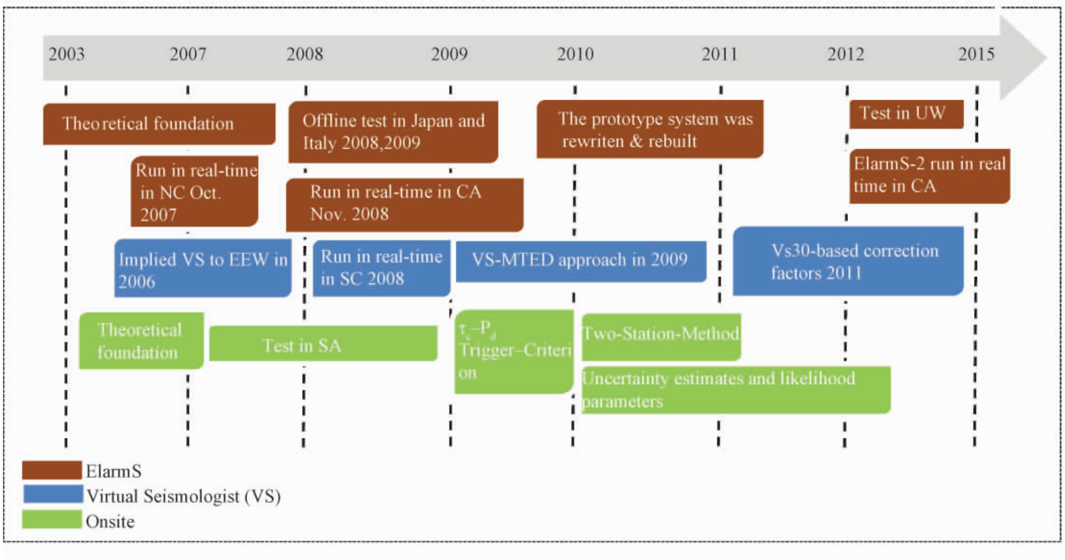

Fig. 2
The development of the 3 EEW algorithms from foundation to 2015 in America

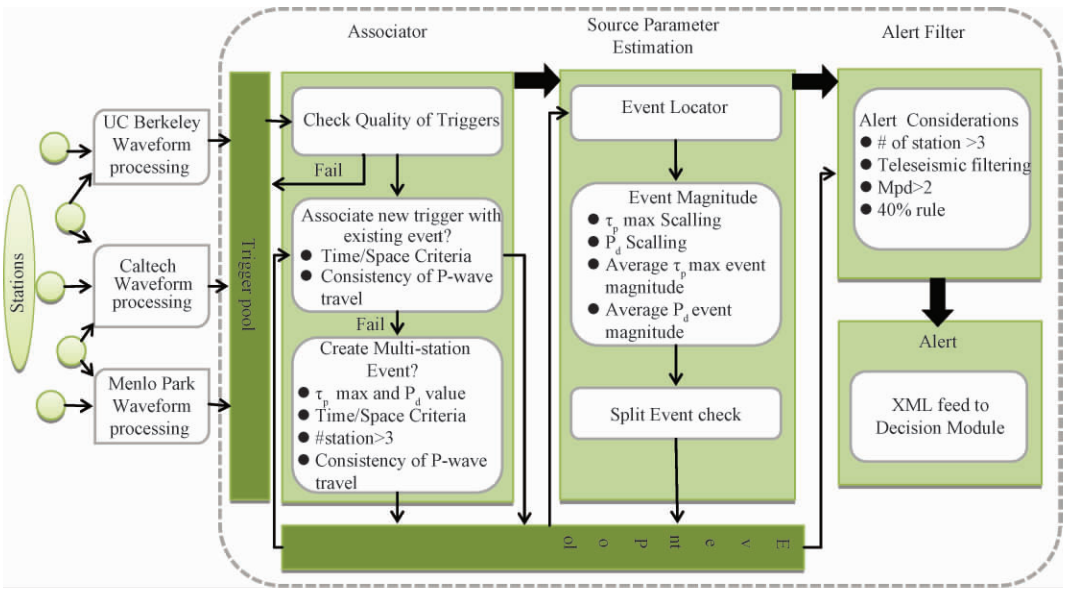

Fig. 3
Processing flow for E2 (CISN Report, 2012)

Heaton (Cua and Heaton, 2007) as a Bayesian approach that combines various types of potential prior information (network topology, fault maps, previously observed seismicity), along with the processing and interpretation of real-time information (envelope amplitudes, picks) to provide the most probable earthquake point-source characterization at a given time.

Hauksson et al. (Hauksson et al., 2006) developed a real-time processing environment that provides an interface between the real-time network data streams and the EEW algorithms participating in the CISN project. The VS codes are the three subsystems (or collections of

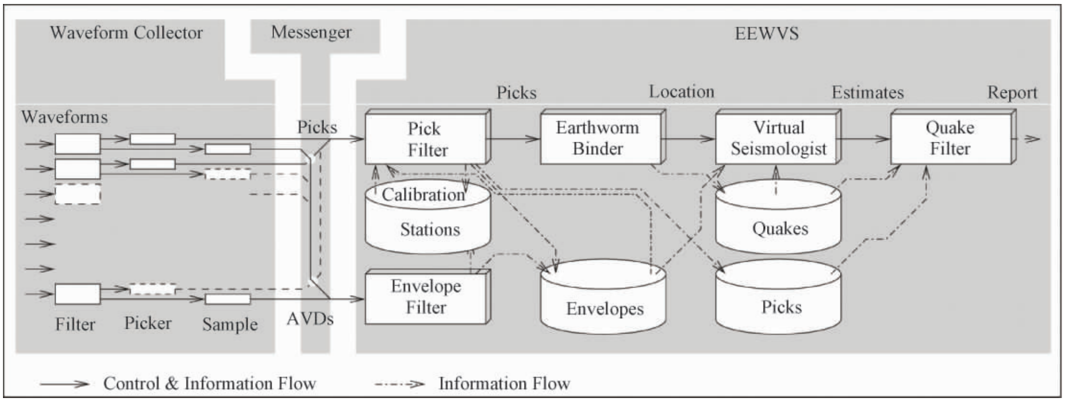

Fig. 4

System architecture of the VS early warning algorithm. Rectangles represent processing modules, drums represent dynamic data areas (Cua et al., 2009)

modules) shown in Fig. 4. Each subsystem has a particular task. The Waveform Collector subsystem performs basic waveform processing such as picking, gain correction, baseline removal, filtering, and down-sampling. The ground motion envelope amplitudes of acceleration, velocity, and filtered displacement (AVDs in Fig. 4) required as inputs to the VS likelihood function are calculated here. The Messenger subsystem sends information from the Waveform Collector subsystem to the EEWVS (which stands for Earthquake Early Warning Virtual Seismologist) subsystem. The EEWVS subsystem: (1) filters and weighs incoming picks, (2) estimates location and origin time based on acceptable picks using the Earthworm Binder phase associator, (3) estimates magnitude given the Binder location estimate and the available envelope amplitudes using the VS likelihood function relationships, (4) evaluates the reliability of the magnitude and location estimate, and (5) logs the estimated magnitude, location, and predicted peak ground shaking to an event summary file. All event summary files are stored locally for subsequent performance analysis. Event summary files within initial magnitude estimates are automatically sent to the Decision Module.

The real-time VS codes are currently configured to require a minimum of 4 stations to initiate event declarations. In southern California, on average, the initial VS estimates are available approximately 20 seconds after the earthquake origin time, corresponding to a blind zone of approximately 75km. (The time to the initial estimate is strongly driven by the station density in a particular region.) Producing faster estimates and hence increasing the available warning time is a high priority of on-going VS research (Caprio et al., 2011).

1.4 Under Development and New Methodology for EEW

1.4.1 Finite Fault Detection

Seismic ground motions can be seriously underestimated for large earthquakes ($M > 6.5$) when predicted from hypocentral rather than rupture-to-site distances in empirical ground-motion prediction equations. However using rupture-to-site distances requires real-time information on finite fault rupture extent.

To provide rapid estimates of fault rupture extent during large earthquakes, Caltech has developed the Finite Fault Rupture Detector algorithm (FinDer) that is based on strong-motion data (Allen et al., 2012). The approach is based on a rapid high-frequency near/far-source classification of ground motion amplitudes in a dense seismic network (station spacing < 50 km), and comparison with a set of pre-calculated templates using Matching by Correlation.

Since September 2012, Caltech has been running FinDer in real-time mode for earthquakes in Southern California, FinDer has successfully detected and processed a number of small earthquakes (using lower thresholds for testing).

1.4.2 Real-time GPS

As part of the ongoing methodological development, real-time GPS displacement data streams are used for rapid detection and source parameter estimation for the EEW (Bock et al., 2011; Crowell et al., 2009; Crowell et al., 2012). The GPS based magnitude estimate showed its robustness and independence of existing seismic methods from the test of April 4, 2010, M_W7.2 El Mayor-Cucapah earthquake. A hardened and transparent real-time GPS system is being developed in order to improve earthquake early warning – in particular magnitude information – for large earthquakes to increase the accuracy of ground shaking predictions (Grapenthin et al., 2013). The most effective use of the GPS data would be to integrate the GPS information with seismically derived information. Also, the availability of high-rate, low-latency GPS data presents the opportunity to use static offsets from GPS to provide information on the fault plane orientation and total slip in a finite slip inversion, which is used to produce the ShakeMap (Johanson et al., 2012).

1.4.3 PreSEIS

PreSEIS is an algorithm for EEW developed by Böse (Böse et al., 2008; Böse, 2006) that is based on artificial neural networks (ANNs). It has several important features to implement on EEW. A nonlinear mapping is allowed between the seismic waveforms recorded at one or more seismic sensors and the predicted source and ground-motion parameters at a user site. Examples and experience oriented self-learning way are similar to the human brain, so it does not require explicit formulations of relationships and exhibits a high tolerance against noisy data, which is a common problem in real-time seismology; it is computationally efficient, that is, very fast, which makes them applicable to real-time procedures such as EEW (Böse et al., 2008).

PreSEIS was tested in several seismic-active regions around the world (Köhler et al., 2009; Köhler, 2010; Hilbring et al., 2010). These studies revealed two major shortcomings of the PreSEIS algorithm. First, ANNs require large datasets for training. Second, the PreSEIS algorithm is network-dependent, that is, once the ANNs have been trained for a particular seismic network or subnetwork, single sensors cannot be easily added or removed (Böse et al., 2012).

To overcome the limitations, PreSEIS Onsite was developed, it uses the acceleration, velocity and displacement waveforms from a single three-component broadband or strong-motion sensor to perform real-time earthquake/noise discrimination and near/far source classification (Fig. 5). When a local earthquake is detected, the algorithm estimates the moment magnitude, epicentral distance Δ, and peak ground velocity (PGV) at the site of observation. First estimates become available 0.25 seconds after the P-pick and are regularly updated with progressing time. The algorithm was developed and tested using 2,431 records of 161 crustal earthquakes in California, Japan and Taiwan with $3.1 \leqslant M \leqslant 7.6$ at $\Delta \leqslant 115$km. The prediction errors of this new approach are around 60% smaller compared to the $\tau_c - P_d$ Onsite algorithm (Böse et al., 2012).

2 CISN SHAKEALERT (CISN EARTHQUAKE ALERT SYSTEM)

The project, christened ShakeAlert, implements, tests, and integrates three distinct EEW systems (Onsite, Elarms, VS) into a single, end-to-end production-grade system to provide warnings to test users from industrial, governmental, and corporate groups, with a view to

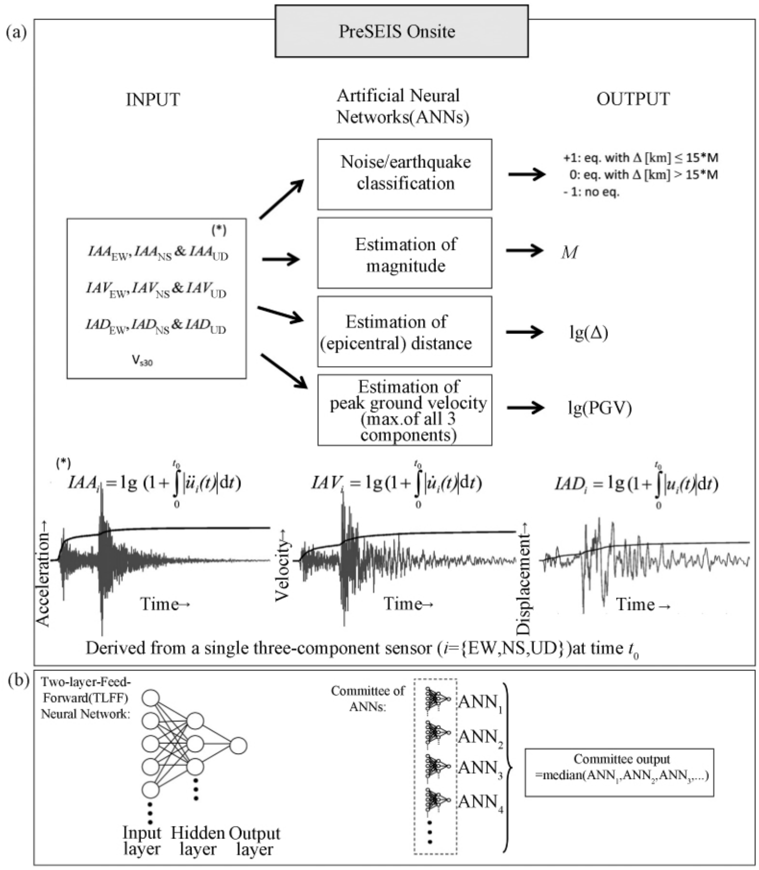

Fig. 5

Principal approach of PreSEIS Onsite (Böse et al., 2012)

eventually provide warnings to the general public. The system uses seismic data from about 400 seismic stations from the seismic networks across the state that contribute to the CISN (Fig. 6). CISN ShakeAlert provides a continuum of earthquake alert information, including the predictions of source (origin time, magnitude, location) and ground-motion parameters (peak shaking, MMI intensity, warning times) and their uncertainties.

The project partners are the California Institute of Technology, the University of California Berkeley, ETH Zürich (Swiss Federal Institute of Technology Zürich). The Southern California Earthquake Center, and the U. S. Geological Survey. The project is funded by the U. S. Geological Survey.

ShakeAlert consists of five modules: (a) Waveform Processing Library. (b) Event Detection. (c) Decision Module. (d) User Display. (e) Testing Center. (Fig. 7)

3 DISCUSSION

3.1 Challenges for America

With more than 20 years of development, earthquake early warning is today becoming an effective answer to the problem of seismic risk mitigation at short time-scales. The research of CISN ShakeAlert in California also proved that there are no strong objections to the possibility of

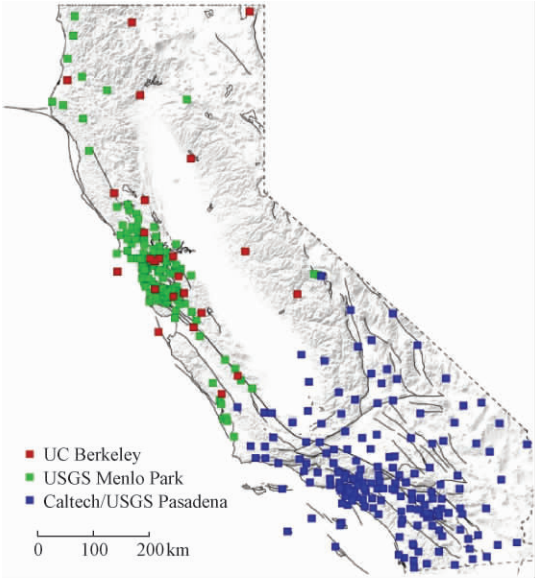

Fig. 6
Map of CISN seismic stations that contribute to ShakeAlert processing (Useful images, 2013)

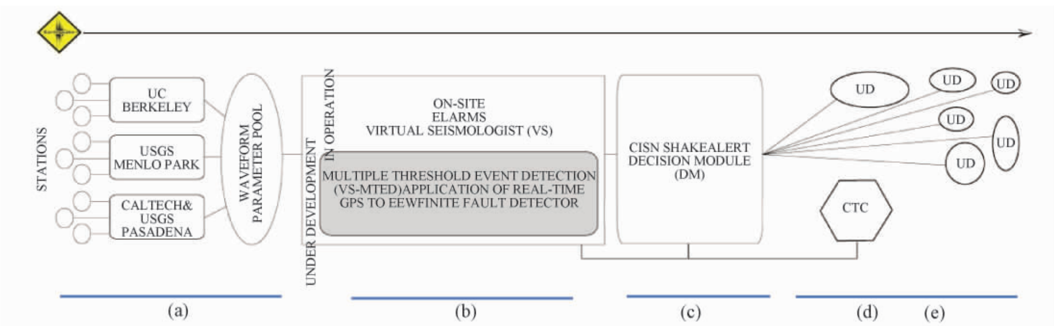

Fig. 7
CISN ShakeAlert process chart (CISN, 2013)

developing and implementing EEW systems. However, there are still questions and concerns for the California scientists.

The scientific challenges are focused on: (1) Arguments about the warning time and false alarms. As we know that the duration between the issued earthquake warning and the subsequent ground shaking at a given location is the "warning time". This is dictated by many factors, of which the most important are the proximity of stations to the earthquake epicenter, data telemetry speed, data processing time, and the time needed to disseminate the warning (Kuyuk et al., 2014). Due to the complex factors, the optimal alert criteria in an earthquake early warning system are much more important. If the criteria are too strict, an alert message is then delayed or not sent at all. If criteria are not strict enough it may result in a false alarm. The public will not tolerate false alarms. That is a huge topic between reliability and science. (2) How to face a real big earthquake? Each of the active EEW system has been implemented in response to a significant damaging earthquake. The challenge for earthquake-prone regions without EEW is to implement a system before the next big earthquake rather than following it. The missing scientific piece is a real earthquake and real-time mapping of finite-fault sources. Do we really need to know the actual parameters, if $M \geqslant 6.5$ before issuing an alert (Satriano et al., 2011)?

CISN ShakeAlert demonstrates that building an earthquake early warning system in California with CISN as a backbone is feasible. The real challenge here is not seismology but how to start making use the information.

3.2 Opportunities for China

China is planning to build a national earthquake monitoring and warning system in the near future. The improvement of national comprehensive strength of the Chinese government laid a material foundation to implement a major action plan, such as earthquake disaster mitigation for seismic safety requirements. On the other hand, the development of the Earthquake Early Warning System was launched in 2009 and scientists in China have primarily made progress with the algorithms and other related technologies (Ma, 2008; Jin et al., 2012; Zhao and Zhang et al., 2009; Jin et al., 2012).

As previously mentioned, the CISN ShakeAlert system is under testing and partly implemented in California, and different methodologies and procedures have been studied and developed. The leading experience of California will offer China tremendous experimental value in developing both the conceptual and technical basis for EEW. However China should choose a suitable methodology instead of simply copying one of the other countries.

The station distribution in China is not uniform. Not surprisingly, the performance including the warning time and the blind zone radius of a network-based system is directly related to the density of the network (Brown et al., 2011; Kuyuk et al., 2014). Accuracy improves when more stations contribute to an event estimate, but potential warning time is lost while waiting for those stations to trigger, especially when the stations are far apart. Thus, a denser seismic network should be adopted.

Reliability and real time of data transmission is very limited. First, the packetization of data by station data loggers is the primary source of telemetry latencies. Usually many station loggers are currently set for packet sizes equivalent to 1 second of data. Decreasing data packet size to less than 0.5 seconds would provide an additional second. Secondly, stations transmit data to the processing centers by DDN, microwaves, CDMA/GPRS, or radio (Kang et al., 2010), depending on the station, and communication latency is different. Using the most advanced telecommunication technologies can potentially decrease the current telemetry delay by 1 ~ 2 seconds (Kuyuk et al., 2014).

The geology of China is highly diverse. The choice of the most appropriate approach to EEW (regional, Onsite, or mixed) has to be based on the knowledge of the target area: the distribution of seismogenic zones, the type of seismicity (depth, mechanism, magnitude range) and the site characteristics (Satriano et al., 2011). Therefore, there is no one-fits-all methodology for the whole of China, and the algorithm applied in different regions is very heterogeneous. Therefore, designing efficient code, improving event detection and alert filtering algorithms should be regional-oriented in the following research.

ACKNOWLEDGEMENTS

This paper was supported by the China Scholarship Council (CSC), China Earthquake Administration (CEA) and Earthquake Administration of Hebei Province, this work was partially funded by the U.S. Geological Survey (USGS). We thank Tom Heaton, Richard Allen, Peggy Hellweg, Ingrid Johanson, and David Oppenheimer for useful discussion and helpful comments on the Earthquake Early Warning System in California.

REFERENCES

Allen R. M., Brown H., Hellweg M., Neuhauser D., Henson I., Kuyuk H. S. *CISN Earthquake Early Warning* [C]. The 2012 Northern California Earthquake Hazards Workshop, 2013.

Allen R. M., Gasparini P., Kamigaichi O, et al. Böse, M. The status of earthquake early warning around the world: an introductory overview [J]. *Seismol Res Lett*, 2009, 80 (5): 682 ~ 93, doi: 10. 1785/gssrl. 80. 5. 682.

Allen R. M., Kanamori H. The potential for earthquake early warning in southern California [J]. *Science*, 2003, 300: 786 ~ 789.

Allen R. M. *The ElarmS Earthquake Early Warning Methodology and Its Application across California* [M]. In: (edited by Gasparini P, Manfredi G, Zschau J.) *Earthquake Early Warning Systems*. Berlin: Springer; 2007. 21 ~ 43, doi: 10. 1007/978-3-540-72241-0_3.

Bock Y., Melgar D., Crowell B. W. Real-time strong-motion broadband displacements from collocated GPS and accelerometers [J]. *Bull. Seismol. Soc. Am.*, 2011, 101 (5), doi: 10. 1785/0120110007.

Böse M., Allen R., Brown H., et al. *CISN Shake Alert—An Earthquake Early Warning Demonstration System for California* [G]. In: (edited by Wenzel F. & Zschau J.) *"Early Warning for Geological Disasters – Scientific Concepts and Current Practice"* [M]. Springer, 2012.

Böse M., Hauksson E., Solanki K., et al. A new trigger criterion for improved real-time performance of on-site earthquake early warning in southern California [J]. *Bull. Seism. Soc. Am.*, 2009a, 99 (2A): 897 ~ 905, doi: 10. 1785/0120080034.

Böse M., Hauksson E., Solanki K., et al. Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29 2008 M_W 5. 4 Chino Hills earthquake [J]. *Geophys. Res. Lett.*, 2009b, 36: L00B03, doi: 10. 1029/2008GL036366.

Böse M., Ionescu C., Wenzel F. Earthquake early warning for Bucharest, Romania: Novel and revisited scaling relations [J]. *Geophysical Research Letters*, 2007, 34: L07302.

Böse M., Wenzel F., Erdik M. PreSEIS: A neural network based approach to earthquake early warning for finite faults [J]. *Bull. Seismol. Soc. Am.*, 2008, 98 (1): 366 ~ 382, doi 10. 1785/0120070002.

Böse M. *Earthquake Early Warning for Istanbul Using Artificial Neural Networks* [D]. Ph. D. Thesis, 2006. 181 pp., Karlsruhe University, Germany, http:// www. ubka. uni-karlsruhe. de/cgi-bin/psview? document = 2006/physik/6, last accessed October 2011.

Brown H. M., Allen R. M., Hellweg M., et al. Development of the ElarmS methodology for earthquake early warning: Real-time application in California and offline testing in Japan [J]. *Soil Dyn. Earthquake Eng.*, 2011, 31: 188 ~ 200, doi: 10. 1016/j. soildyn. 2010. 03. 008.

Böse M., Heaton T. H., Hauksson E.: Rapid estimation of earthquake source and ground-motion parameters for earthquake early warning using data from a single three component broadband or strong-motion sensor [J]. *Bull. Seism. Soc. Am.*, 2012, 102 (2): 738 ~ 750, April 2012, doi: 10. 1785/0120110152.

Caprio M., Cua G. B., Fischer M., et al. *CISN ShakeAlert: Accounting for Site Amplification and Quantifying Time and Spatial Dependence of Uncertainty Estimates in the Virtual Seismologist Earthquake Early Warning Algorithm* [G]. American Geophysical Union Fall Meeting, San Francisco, 2011, S53A – 2251.

CISN Earthquake Early Warning Team. *CISN ShakeAlert Final Report* [R]: August 2009 ~ July 2012.

CISN: EEW Project, http://www. cisn. org/eew/EEWProject. html, last visit April 2013.

Crowell B. W., Bock Y., Squibb M. B. Demonstration of earthquake early warning using total displacement waveforms from real time GPS networks [J]. *Seismol. Res. Lett.*, 2009, 80: 772 ~ 782, doi 10. 1785/gssrl. 80. 5. 772.

Crowell B. W., Bock Y., Melgar D. Melgar. Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment [J], *Geophys. Res. Lett.*, 2012, 39: L09305, doi: 10. 1029/2012GL051318.

Cua G., Fischer M., Heaton T., et al. Real-time performance of the Virtual Seismologist method in southern California [J]. *Seismol Res Lett*, 2009, 80: 740 ~ 748, doi: 710. 1785/gssrl. 1780. 1785. 1740.

Cua G., Heaton T. *The Virtual Seismologist (VS) Method: A Bayesian Approach to Earthquake Early Warning* [C]. (Edited by P. Gasparini, G. Manfredi, J. Zschau) In: *Earthquake Early Warning Systems* [M]. Berlin and New York: Springer, 2007. 97 ~ 132.

Grapenthin R., Johanson I., Allen R. *Integrating Real-time GPS into Earthquake Early Warning for Northern California* [C]. SSA Annual Meeting, Salt Lake City, April 2013.

Hauksson E., Solanki K., Friberg P., Given D., Maechling P., Neuhauser D., Helweg M. *Implementation of*

Real-Time Testing of Earthquake Early Warning Algorithms Using the California Integrated Seismic Network Infrastructure as a Test Bed [C]. Abstract, Seismological Society of America Annual Meeting, April 2006, San Francisco, California.

Hilbring D., Titzschkau T., Buchmann A., et al. Earthquake early warning for transport lines [J]. *Nat. Hazards*, 2010, doi 10.1007/s11069-010-9609-3.

Jin X., Zhang H. C., Li J., Wei Y. X., Ma Q. Research on earthquake early warning magnitude estimate [J]. *Acta Seismologica Sinica*, 2012, 34(5): 593~610 (in Chinese with English abstract).

Jin X., Zhang H. C., Li J., et al. Research on continuous location method used in earthquake early warning system [J]. *Chinese J. Geophys.*, 2012, 55(3): 925~936, doi: 10.6038/j.issn.0001-5733.2012.03.022 (in Chinese).

Johanson I., Dreger D. S., Grapenthin R. *Rapid Finite-Fault Earthquakes and Afterslip Information from Seismic and Real-time GPS Observations* [C]. The 2012 Northern California Earthquake Hazards Workshop, 2013

Kanamori H. Real-time seismology and earthquake damage mitigation [J]. *Annual Review of Earth and Planetary Sciences*, 2005, 33: 195~214.

Kang H., Wang Y. W., Wu T. Consideration about tele-transmission of seismic data post the Wenchuan *M*8.0 earthquake [J]. *Seismological and Geomagnetic Observation and Research*, 2010, 31(4): 32~38 (in Chinese), doi: 10.3969/j.issn.1003-3246.2010.04.006.

Köhler N., Cua G., Wenzel F., et al. Rapid source parameter estimations of Southern California earthquakes using PreSEIS [J]. *Seismol. Res. Lett*, 2009, 80(5): 748~754, doi 10.1785/gssrl.80.5.748.

Köhler N. *Real-time Information from Seismic Networks* [D]. Ph. D. Thesis, 150 pp., Karlsruhe Institute of Technology, Germany, 2010, http://digbib.ubka.uni-karlsruhe.de/volltexte/1000015555, last accessed October 2011.

Kuyuk H. S., Brown H., Henson I., Allen R. M., Hellweg M., Neuhauser D. ElarmS-2: Designing a Network-based Earthquake Early Warning System for California (in prep).

Ma Q. *Study on Application of Earthquake Early Warning* [D]. Ph. D. Thesis. Harbin: Institute of Engineering Mechanics, China Earthquake Administration, 2008 (in Chinese).

Peng H., Wu Z., Wu Y. M., et al. Developing a prototype Earthquake Early Warning System in the Beijing Capital Region [J]. *Seismol Res Lett*, 2011, 82(3), doi: 10.1785/gssrl.82.3.394.

Satriano C., Wu Y. M., Zollo A., et al. Earthquake early warning: Concepts, methods and physical grounds [J]. *Soil Dynamics and Earthquake Engineering*, 2011, 31: 106~118, doi: 10.1016/j.soildyn.2010.07.007.

Useful Images, Videos and Presentations [OL], http://seismo.berkeley.edu/~rallen/images/, last visit April 2013.

Wu Y. M., Kanamori H. Experiment on an onsite early warning method for the Taiwan early warning system [J]. *Bulletin of the Seismological Society of America*, 2005, 95: 347~353.

Wu Y. M., Teng T. A virtual subnetwork approach to earthquake early warning [J]. *Bulletin of the Seismological Society of America*, 2002, 92: 2,008~2,018.

Wurman G., Allen R. M., Lombard P. Toward earthquake early warning in northern California [J]. *Journal of Geophysical Research*, 2007, 112: B08311, doi: 10.1029/2006JB004830.

Yih-Min W., Kanamori H., Allen R. M., Hauksson, et al. Determination of earthquake early warning parameters, t_c and P_d, for southern California [J]. *Geophysical Journal International*, 2007, 170: 711~717.

Zhao J. D., Zhang Z. Q. Development, application and suggestions on earthquake early warning system [J]. *Geological Bulletin of China*, 2009, 28(4): 456~462 (in Chinese with English abstract).

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

About the Author

Wang Honglei, born in 1981, is an engineer at the Earthquake Administration of Hebei Province. She received the funding from the China Earthquake Administration and China Scholar Council, as a visiting scholar in USGS in the year 2013. She is engaged mainly in work on the Earthquake Early Warning System in California, USA. E-mail: wang.hl07@gmail.com