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An Introductory Overview of Earthquake Early Warning[1]

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Earthquake early warning (EEW) is discriminated from earthquake prediction by using initial seismic waves to predict the severity of ground motion and issue the warning information to potential affected area. The warning information is useful to mitigate the disaster and decrease the losses of life and economy. We reviewed the development history of EEW worldwide and summarized the methodologies using in different systems. Some new sensors came and are coming into EEW giving more developing potential to future implementation. The success of earthquake disaster mitigation relies on the cooperation of the whole society.

Key words: Earthquake early warning; Disaster mitigation; New sensors; Seismic network; Geodetic network

INTRODUCTION

"Earthquake early warning" (EEW) is a concept that can be dated back as early as 1868 by J.D. Cooper who proposed the idea of an EEW system for San Francisco, California (Nakamura Y. et al., 1988; Kanamori H., et al., 1997) used to describe real-time earthquake information issuance to potential devastating area before strong ground shaking. The first few seconds seismic waves are used to estimate the epicenter, magnitude and the severity of ground motion near seismic source. Response time may range from a few seconds to several tens of seconds depending on the distance to focal location (Heaton T.H., 1985; Kanamori H., et al., 1997).

1 HISTORY OF EEW DEVELOPMENT

Facing the exposure of high seismic risk, several seismic active countries took a great effect to develop and implement the EEW systems to reduce the losses of disaster earthquakes. With the developments of seismic instrumentation, methodology and communication, the first EEW system, the onsite UrEDAS system, was implemented for railways in Japan in 1984 (Nakamura Y.,

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1984). One modern conceptual model for real time EEW network is proposed by Heaton in 1985. Subsequently, the Seismic Alert System (SAS) was started for Mexico City in 1991 (Aranda J. E. M. et al., 1995) providing warning information to schools and subway. The EEW system was first operated in Taiwan, China in 2001. Several years later, a new system with smaller blind zone replaced it and the information was issued to emergency management agency, railway and rapid transit company. China developed a pilot EEW system in Fujian in 2009 and tested online in 2012 (Zhang Hongcai et al., 2016). The Korean Earthquake Early Warning System began operation by Korea Meteorological Administration in 2015 to issue warning information for earthquake of magnitude 5.0 and more (Sheen D. H. et al., 2017). A lot more countries are actively working on EEW system, including India, Israel, Chile, Nepal and so on.

2 TRADITIONAL METHODOLOGY

2.1 Front Detection

Front detection is to detect strong ground shaking at one location (The ground shaking exceeds a threshold) and issue an information ahead of the seismic energy for a distance place and needs prior knowledge of the locations of potential events (Aranda J. E. M. et al., 1995; Allen R. M. et al., 2003; Allen R. M. et al., 2009b).

Japan first used this concept to deploy seismometers along their railway tracks to trigger the power shut-off system of the trains when the ground shaking level exceeded one threshold in late 1960s (Nakamura Y., 1984, 1988). They placed a network along the east coast to detected the strong shaking of offshore large earthquake and sent the EEW information to the railroad away from the coast. Up to now, front detection is still one of important approaches for Japanese high speed railway EEW system.

Front detection is used in the SAS for Mexico City and the warning systems for Bucharest, Romania and Istanbul, Turkey (Aranda J. E. M. et al., 1995; Böse M. et al., 2007; Alcik H. et al., 2019). These systems possess the same character that the warning area is some distance from the potential earthquake sources providing more warning time.

2.2 Approaches Based on P-Wave

P-wave is the first arrive wave of earthquake that can be used to determine the location and size of an event. Given that the most severe ground shaking usually arrives at the time around or after the S-wave, the utilization of the P-wave can potentially provide more warning time.

Several different observed P-wave parameters are developed to access the intensity of future ground shaking. The parameters are based on frequency and amplitude of an earthquake, because there are some relationships between the P-wave period (or amplitude) and earthquake magnitude. Nakamura first used the predominant period of the first few seconds of P-wave for early warning in 1988. The maximum predominant period, τ_p^{max}, can be extracted from continuous time series and converted to estimate the magnitude. This method could evaluate the initial magnitude of earthquake using the first three or four seconds P-wave and the magnitude can change with time. The robust of τ_p^{max} are tested in the EEW system implementation worldwide (Nakamura Y., 2004; Lockman A. B. et al., 2007; Tsang L. L. H. et al., 2007; Wurman G. et al., 2007; Brown H. M. et al., 2009, Allen R. M. et al., 2009a, 2009b; Hsiao N. C. et al., 2009; Fleming K. et al., 2009).

One slightly different parameter, τ_c, was formulated by Kanamori in 2005. τ_c calculates the average period of P-wave over a three seconds time window. The tests in California and Taiwan

(Wu Y. M. et al., 2005a, 2007) show similar scaling between the average period of P-wave and the magnitude. τ_c and τ_p^{max} both use the frequency content of the P-wave and can be combined in real work (Shieh J. T. et al., 2008).

Besides the period parameters, the amplitude of P-wave is also valuable for magnitude estimation. The peak amplitude of acceleration, velocity or displacement of the first three or four seconds of the P-wave has a clear scale with magnitude and intensity of ground motion (Wu Y. M. et al., 2005a, 2005b, 2008a; Zollo A. et al., 2006; Böse M. et al., 2007). The peak ground displacement, P_d, can be provided by integration from velocity record or double integration of acceleration record and is usually the most stable parameter. P_v is found to be useful when P_d is not robust duo to noisy accelerometers or intensity meters (Wurman G. et al., 2007). China adopt a revised method, continuous calculation of P_d, to accommodate the real situation (Jin Xing et al., 2012; Zhang Hongcai et al., 2016).

Envelope function is used in several approaches. The Virtual Seismologist uses the real-time calculated peak acceleration, velocity and displacement to trigger earthquake and estimate the magnitude (Cua G. et al., 2007). The PreSEIS method use cumulative absolute velocity (Böse M. et al., 2008) or of other envelope parameters to estimate the location and ground motion (Allen R. M. et al., 2009b; Köhler N. et al., 2009).

Due to the saturation of magnitude estimation with short time window of the P-wave (Zollo A. et al., 2006; Wurman G. et al., 2007; Murphy S. et al., 2009), several methods try to use longer time windows or continuous time window to update magnitude estimation with time to avoid the problem (Zollo A. et al., 2006; Jin Xing et al., 2012; Zhang Hongcai et al., 2016).

2.3 *Onsite Warning*

The onsite (single-station) warning is a concept predicting the strongest ground motion with single P-wave and issues the early warning information for the same site. The principal is the scaling relation between the amplitude and the peak ground motion (Wu Y. M. et al., 2005b). Although recent study shows larger earthquake may share the similar initial P-wave (Ide S., 2019; Abercrombie R. E., 2019), there still some frequency difference between larger and small event. UrEDAS is a successful example of onsite warning and the long term operation shows the advantage of the method (Nakamura Y., 1988, 1996, 2004; Nakamura Y. et al., 2007a, 2007b). The $\tau_c - P_d$ method is another applicable combination of amplitude and period in onsite warning (Wu Y. M. et al., 2005a, 2005b, 2007, 2008a, 2008b).

2.4 *Geodetic Data Application*

As an effective complement of seismic network, Global Navigation Satellite System (GNSS) data help to provide more robust magnitude estimation of large earthquakes. In 2009, Crowell B. W. et al. pictured a prototype warning system using Global Positioning System (GPS) data. The geodetic observations are useful for near real time magnitude determination using peak ground displacement (PGD) scaling relationships (Crowell B.W. et al., 2013; Melgar D. et al., 2015), rapid Centroid Moment Tensor (CMT) for determination of size and orientation of earthquake (Melgar D. et al., 2012, 2015), and estimation of the slip on the fault using finite fault method (Crowell B. W. et al., 2009, 2012; Allen R. M. et al., 2011; Ohta Y. et al., 2012; Böse M. et al., 2013). The Geodetic First Approximation of Size and Time (G-FAST) geodetic early warning system was tested by simulated displacements and real operated system with peak ground displacement scaling and CMT driven finite fault slip modeling (Crowell B. W. et al., 2016, 2018).

2.5 Regional Warning

EEW system also shares the advantages of traditional seismic network and monitoring system that the signals of a deployed network are transmitted to data processing center and the earthquake location and magnitude are estimated from the signals (Kanamori H. et al., 1997; Allen R. M. et al., 2009a). At last, the information is issued to the government, public and users. Regional warning combines the front detection, P-wave approaches and onsite warning together.

The earliest triggered station can be used together with front detection network to get more early warning time. Multi-station onsite warning can improve the accuracy of estimated event location and magnitude. The onsite warning provides more warning time but high probability of false or missed alarms, whereas the multi-station P-wave is based on algorithms to solve the problem. The combination balances the warning time and probability of false or missed alarm.

Besides, regional warning can collect and process different kinds of observation meanwhile to achieve the best EEW effect. Seismic network provides high quality velocity record that is more sensitive in event location; strong motion network provides non-clipped near source acceleration record for fast and accurate magnitude or shaking estimation; GNSS network measures the direct ground displacement that is efficient in magnitude estimation. China EEW system and US ShakeAlert system both utilize the multi-observation EEW system.

3 NEW DEVELOPMENT

3.1 Using of New Sensors

In consideration of the expensive cost of construction of the seismic and geodetic networks, traditional EEW systems are only operating in several countries. Smartphones are much more prevalent than traditional containing accelerometers. Smartphone network is tested to be sensitive enough to separate earthquakes $\geqslant M5.0$ from daily shakes using 1-10Hz band passed signal (Kong Qingkai et al., 2016). MyShake is a smartphone base EEW app and the 2 version is in testing with ShakeAlert that will provide public service in fall 2019.

Low cost intensity meter is widely used in EEW system in Japan and China (including Taiwan area). The new study shows dense low cost network has good performance in real time shake map generation helping the calculation of rupture directivity that is crucial for hazard estimation and the application in eastern Taiwan are in good agreement with the observed damage (Wu Y.M. et al., 2019; Jan J. C. et al., 2018).

Other types of geophysical sensors also present the potential using in EEW. Strainmeter measuring elastodynamic strain could be reliably and efficiently used for the calculation of source characterization as a geodetic measurement (Barbour A. J. et al., 2017). Pre-P-wave elastogravitational signal is detected by superconducting gravimeter during the 2011 Tohuku earthquake (Montagner J. P. et al., 2016; Vallée M. et al., 2017) which gives the prospect using in EEW.

3.2 Machine Learning Application

The urbanization and human activities polluted the seismic observation and may be much worse in the future. Seismic phases discrimination is the first step of early warning. It is more difficult to detect phases in noise contaminative waveforms with tradition method. With the fast development of artificial intelligence technology, machine learning is used in EEW data processing. A Bayesian probabilistic method is tested to be faster than traditional $\tau_c - P_d$ EEW classification (Yin L. et al., 2018). Generative adversarial network (Li Zefeng et al., 2018) method and convolutional neural network (CNN) method (Ross Z. E. et al., 2018) are efficient to detect P waves and S waves that can decrease the false phases triggered probability. CNN deep learning method shows the robust ability in earthquake location. These new methods may make the future EEW system more reliable and efficient.

4 PERSPECTIVES AND CHALLENGES

Despite plenty of debates about whether the rupture of earthquake can be determined or whether the initial part of P-wave is identical for small and large events (Olson E. L. et al., 2005, 2006; Ide S., 2019; Abercrombie R. E., 2019), EEW systems were conducted in Japan, and Mexico and have some achievements. China, United States, European countries, Korea and some other countries are on their way developing the network and EEW system (Zhang Hongcai et al., 2016; Clinton J. et al., 2016; Sheen D. H. et al., 2017; Allen R. M. et al., 2019). The experience of Japan EEW system in 2011 Tohoku earthquake gives us some suggestions. The point source designed system may underestimate the magnitude of large event and the initial several (seven in this case) seconds of high-sensitive acceleration data is not enough to accurately calculate the size of $M_W 9.0$ earthquake. The utility outage (power, network) may lead to false alarms and missed alarms of large destructive aftershocks (Yamasaki E., 2012). Besides, Tohoku earthquake is an offshore event, if it is an intraplate earthquake, it will have large blind area where suffers the most severe damage. EEW system may take effect in the relative low intensity region for users willing to take actions (Minson S. E. et al., 2018). The alerting strategy is also important that the users could not receive the warning information because of the set high threshold even when the location and magnitude are accurate estimated (Minson S. E. et al., 2019).

To enhance the accuracy of prediction of ground motion, several groups developed methods for real time rupture tracing (Böse M. et al., 2012, 2017; Wu Y.M. et al., 2019; Jan J. C. et al., 2018). The improved finite source detector FinDer is implemented with ShakeAlert and will take effect in EEW (Böse M. et al., 2015, 2017). Jan J. C. et al. (2018) developed a new method for near real time rupture directivity estimation using low cost seismic network and the performance is reliable with Hualien Earthquake in 2018 (Wu Y. M. et al., 2019). But the efficient and reliability of the method are still not tested by large events, much more effort is needed for combining seismic networks and new sensors.

Now EEW information is on its way, but how to issue it needs further discussions. The disaster mitigation effect is the combination of EEW system, issuance policy and users' actions. Public education about EEW is one fundamental part directly related to the successful of system. People should know how to react with different level warning information to protect their body and relief their mood.

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REFERENCES

Abercrombie R. E. Small and large earthquakes can have similar starts[J]. *Nature*, 2019, 573(7772): 42-43.

Alcik H., Ozel O., Apaydin N., Erdik M. A study on warning algorithms for Istanbul earthquake early warning system[J]. *Geophysical Research Letters*, 2019, 36(4): L00B05.

Allen R. M., Kanamori H. The potential for earthquake early warning in southern California[J]. *Science*, 2003, 300(5620): 786-789.

Allen R.M., Brown H., Hellweg M., Khainovski O., Lombard P., Neuhauser D. Real-time earthquake detection and hazard assessment by ElarmS across California[J]. *Geophysical Research Letters*, 2009a, 36(5): L00B08.

Allen R.M., Gasparini P., Kamigaichi O., Böse M. The status of earthquake early warning around the world: An introductory overview[J]. *Seismological Research Letters*, 2009b, 80(5): 682-693.

Allen R.M., Ziv A. Application of real-time GPS to earthquake early warning[J]. *Geophysical Research Letters*, 2011, 38(16): L16310.

Allen R.M., Melgar D. Earthquake early warning: Advances, scientific challenges, and societal needs[J]. *Annual Review of Earth and Planetary Sciences*, 2019, 47: 361-388.

Aranda J.E.M., Jiménez A., Ibarrola G., Alcantar F., Aguilar A., Inostroza M., Maldonado S. Mexico city seismic alert system[J]. *Seismological Research Letters*, 1995, 66(6): 42-53.

Barbour A.J., Crowell B.W. Dynamic strains for earthquake source characterization[J]. *Seismological Research Letters*, 2017, 88(2A): 354-370.

Böse M., Ionescu C., Wenzel F. Earthquake early warning for Bucharest, Romania: Novel and revised scaling relations[J]. *Geophysical Research Letters*, 2007, 34(7): L07302,.

Böse M., Wenzel F., Erdik M. PreSEIS: A neural network-based approach to earthquake early warning for finite faults[J]. *Bulletin of the Seismological Society of America*, 2008, 98(1): 366-382.

Böse M., Heaton T.H., Hauksson E. Real-time finite fault rupture detector (FinDer) for large earthquakes[J]. *Geophysical Journal International*, 2012, 191(2): 803-812.

Böse M., Heaton T.H., Hudnut K.W. Combining real-time seismic and GPS data for earthquake early warning (Invited). In: American Geophysical Union, Fall Meeting 2013. AGU, 2013.

Böse M., Felizardo C., Heaton T.H. Finite-fault rupture detector (FinDer): Going real-time in Californian ShakeAlert warning system[J]. *Seismological Research Letters*, 2015, 86(6): 1692-1704.

Böse M., Smith D.E., Felizardo C., Meier M.A., Heaton T.H., Clinton J.F. FinDer v.2: Improved real-time ground-motion predictions for $M2-M9$ with seismic finite-source characterization[J]. *Geophysical Journal International*, 2017, 212(1): 725-742.

Brown H.M., Allen R.M., Grasso V.F. Testing ElarmS in Japan[J]. *Seismological Research Letters*, 2009, 80(5): 727-739.

Clinton J., Zollo A., Marmureanu A., Zulfikar C., Parolai S. State-of-the art and future of earthquake early warning in the European region[J]. *Bulletin of Earthquake Engineering*, 2016, 14(9): 2441-2458.

Crowell B.W., Bock Y., Squibb M.B. Demonstration of earthquake early warning using total displacement waveforms from real-time GPS networks[J]. *Seismological Research Letters*, 2009, 80(5): 772-782.

Crowell B.W., Bock Y., Melgar D. Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment[J]. *Geophysical Research Letters*, 2012, 39(9): L09305.

Crowell B.W., Melgar D., Bock Y., Haase J.S., Geng J.H. Earthquake magnitude scaling using seismogeodetic data[J] *Geophysical Research Letters*, 2013, 40(23): 6089-6094.

Crowell B.W., Schmidt D.A., Bodin P., Vidale J.E., Gomberg J., Hartog J.R., Kress V.C., Melbourne T.I., Santillan M., Minson S.E., Jamison D.G. Demonstration of the Cascadia G-FAST geodetic earthquake early warning system for the Nisqually[J]. *Seismological Research Letters*, 2016, 87(4): 930-943.

Crowell B.W., Schmidt D.A., Bodin P., Vidale J.E., Baker B., Barrientos S., Geng J.H. G-FAST earthquake early warning potential for great earthquakes in Chile[J]. *Seismological Research Letters*, 2018, 89(2A): 542-556.

Cua G., Heaton T. The Virtual Seismologist (VS) method: A Bayesian approach to earthquake early warning. In: Gasparini P., Manfredi G., Zschau J. (Editors). Earthquake Early Warning Systems. Berlin: Springer, 2007: 97-132.

Erdik M., Fahjan Y., Ozel O., Alcik H., Mert A., Gul M. Istanbul earthquake rapid response and the early warning system[J]. *Bulletin of Earthquake Engineering*, 2003, 1(1): 157-163.

Fleming K., Picozzi M., Milkereit C., Kühnlenz F., Lichtblau B., Fischer J., Zulfikar C., Özel O., the SAFER and EDIM Working Groups. The self-organizing seismic early warning information network (SOSEWIN)[J]. *Seismological Research Letters*, 2009, 80(5): 755-771.

Given D.D., Allen R.M., Baltay A.S., Bodin P., Cochran E.S., Creager K., de Groot R.M., Gee L.S., Hauksson E., Heaton T.H., Hellweg M., Murray J.R., Thomas V.I., Toomey D., Yelin T.S. Revised technical implementation plan for the ShakeAlert system—An earthquake early warning system for the West

Coast of the United States[R]. Rep. 2331-1258. Pasadena, CA: US Geological Survey.

Heaton T. H. A model for a seismic computerized alert network[J]. *Science*, 1985, 228(4702): 987-990.

Hoshiba M., Kamigaichi O., Saito M., Tsukada S.Y., Hamada N. Earthquake early warning starts nationwide in Japan[J]. *Eos*, *Transactions American Geophysical Union*, 2008, 89(8): 73-74.

Hsiao N. C., Wu Y.M., Shin T.C., Zhao L., Teng T.L. Development of earthquake early warning system in Taiwan[J]. *Geophysical Research Letters*, 2009, 36(5): L00B02.

Ide S. Frequent observations of identical onsets of large and small earthquakes[J]. *Nature*, 2019, 573(7772): 112-116.

Jan J.C., Huang H.H., Wu Y.M., Chen C.C., Lin C.H. Near-real-time estimates on earthquake rupture directivity using near-field ground motion data from a dense low-cost seismic network[J]. *Geophysical Research Letters*, 2018, 45(15): 7496-7503.

Jin Xing, Zhang Hongcai, Li Jun, Wei Yongxiang, Ma Qiang. Research on earthquake early warning magnitude estimate[J]. *Acta Seismologica Sinica*, 2012, 34(5): 593-610 (in Chinese with English abstract).

Kanamori H., Hauksson E., and Heaton T. Real-time seismology and earthquake hazard mitigation[J]. *Nature*, 1997, 390(6659): 461-464.

Köhler N., Cua G., Wenzel F., and Böse M. Rapid source parameter estimations of southern California earthquakes using PreSEIS[J]. Seismological Research Letters, 2009, 80(5): 748-754.

Kong Qingkai, Allen R.M., Schreier L., Kwon Y.W. MyShake: A smartphone seismic network for earthquake early warning and beyond[J] *Science Advances*, 2016, 2(2): e1501055.

Li Zefeng, Meier M. A., Hauksson E., Zhan Zhongwen, Andrews J. Machine learning seismic wave discrimination: Application to earthquake early warning[J]. *Geophysical Research Letters*, 2018, 45(10): 4773-4779.

Lockman A.B., Allen R.M. Magnitude-period scaling relations for Japan and the Pacific Northwest: Implications for earthquake early warning[J]. *Bulletin of the Seismological Society of America*, 2007, 97(1B): 140-150.

Melgar D., Bock Y., Crowell B.W. Real-time centroid moment tensor determination for large earthquakes from local and regional displacement records[J]. *Geophysical Journal International*, 2012, 188(2): 703-718.

Melgar D., Geng Jianghui, Crowell B.W., Haase J.S., Bock Y., Hammond W.C., Allen R.M. Seismogeodesy of the 2014 M_W6.1 Napa earthquake, California: Rapid response and modeling of fast rupture on a dipping strike-slip fault[J]. *Journal of Geophysical Research*: *Solid Earth*, 2015, 120(7): 5013-5033.

Minson S. E., Meier M. A., Baltay A.S., Hanks T.C., Cochran E.S. The limits of earthquake early warning: Timeliness of ground motion estimates[J]. *Science Advances*, 2018, 4(3): eaaq0504.

Minson S. E., Baltay A. S., Cochran E. S., Hanks T. C., Page M. T., McBride S. K., Milner K. R., Meier M. A. The limits of earthquake early warning accuracy and best alerting strategy[J]. *Scientific Reports*, 2019, 9(1): 2478.

Montagner J.P., Juhel K., Barsuglia M., Ampuero J.P., Chassande-Mottin E., Harms J., Whiting B., Bernard P., Clévédé E., Lognonné P. Prompt gravity signal induced by the 2011 Tohoku-Oki earthquake[J]. *Nature Communications*, 2016, 7: 13349.

Murphy S., Nielsen S. Estimating earthquake magnitude with early arrivals: A test using dynamic and kinematic models[J]. *Bulletin of the Seismological Society of America*, 2009, 99(1): 1-23.

Nakamura Y. Development of earthquake early-warning system for the Shinkansen, some recent earthquake engineering research and practical in Japan. *The Japanese National Committee of the International Association for Earthquake Engineering*, 1984: 224-238.

Nakamura Y. On the urgent earthquake detection and alarm system (UrEDAS). In: 9th World Conference on Earthquake Engineering. Tokyo-Kyoto Japan, 1988.

Nakamura Y., Tucker B.E. Japan's earthquake warning system: should it be imported to California?, National Emergency Training Center, 1988.

Nakamura Y. Real-time information systems for seismic hazards mitigation UrEDAS, HERAS and PIC[J]. *Quarterly Report-Rtri*, 1996, 37(3): 112-127.

Nakamura Y. UrEDAS, urgent earthquake detection and alarm system, now and future. In: Proceedings of the 13th World Conference on Earthquake Engineering, 2004.

Nakamura Y., Saita J. FREQL and AcCo for a quick response to earthquakes. In: Gasparini P., Manfredi G., Zschau J. (Editors). Earthquake Early Warning Systems. Berlin, Heidelberg: Springer, 2007a: 307-324.

Nakamura Y., Saita J. UrEDAS, the earthquake warning system: Today and tomorrow. In: Gasparini P., Manfredi G., Zschau J. (Editors). Earthquake Early Warning Systems. Berlin, Heidelberg: Springer, 2007b: 249-

281.

Ohta Y., Kobayashi T., Tsushima H., Miura S., Hino R., Takasu T., Fujimoto H., Iinuma T., Tachibana K., Demachi T., Sato T., Ohzono M., Umino N. Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (M_W9.0) [J]. *Journal of Geophysical Research: Solid Earth*, 2012, 117(B2): B02311.

Olson E.L., Allen R.M. The deterministic nature of earthquake rupture[J]. *Nature*, 2005, 438(7065): 212-215.

Olson E.L., Allen R.M. Earth science: Is earthquake rupture deterministic? (Reply) [J]. *Nature*, 2006, 442(7100): E6.

Perol T., Gharbi M., Denolle M. Convolutional neural network for earthquake detection and location[J]. *Science Advances*, 2018, 4(2): e1700578.

Ross Z. E., Meier M. A., Hauksson E., Heaton T. H. Generalized seismic phase detection with deep learning[J]. *Bulletin of the Seismological Society of America*, 2018, 108(5A): 2894-2901.

Rydelek P., Horiuchi S. Earth science: Is earthquake rupture deterministic? [J]. *Nature*, 2006, 442(7100): E5-E6.

Sheen D. H., Park J. H., Chi H. C., Hwang E. H., Lim I.S., Seong Y.J., Pak J. The first stage of an earthquake early warning system in South Korea[J]. *Seismological Research Letters*, 2017, 88(6): 1491-1498.

Shieh J. T., Wu Y.M., Allen R.M. A comparison of τ_c and τ_p^{max} for magnitude estimation in earthquake early warning[J]. *Geophysical Research Letters*, 2008, 35(20): L20301.

Tsang L.L.H., Allen R.M., Wurman G. Magnitude scaling relations from P-waves in southern California[J]. *Geophysical Research Letters*, 2007, 34(19): L19304.

Vallée M., Ampuero J.P., Juhel K., Bernard P., Montagner J.P., Barsuglia M. Observations and modeling of the elastogravity signals preceding direct seismic waves[J]. *Science*, 2017, 358(6367): 1164-1168.

Weber E., Iannaccone G., Zollo A., Bobbio A., Cantore L., Corciulo M., Convertito V., Di Crosta M., Elia L., Emolo A., Martino C., Romeo A., Satriano C. Development and testing of an advanced monitoring infrastructure (ISNet) for seismic early-warning applications in the Campania region of southern Italy. In: Gasparini P., Manfredi G., Zschau J. (Editors). Earthquake Early Warning Systems. Berlin, Heidelberg: Springer, 2007: 325-341.

Wenzel F., Oncescu M.C., Baur M., Fiedrich F., Ionescu C. An early warning system for Bucharest[J]. *Seismological Research Letters*, 1999, 70(2): 161-169.

Wu Y. M., Teng T. L. A virtual subnetwork approach to earthquake early warning [J]. *Bulletin of the Seismological Society of America*, 2002, 92(5): 2008-2018.

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*, 2005a, 95(1): 347-353.

Wu Y.M., Kanamori H. Rapid assessment of damage potential of earthquakes in Taiwan from the beginning of P waves[J]. *Bulletin of the Seismological Society of America*, 2005b, 95(3): 1181-1185.

Wu Y. M., Kanamori H., Allen R.M., Hauksson E. Experiment using the tau-c and P_d method for earthquake early warning in southern California[J]. *Geophysical Journal International*, 2007, 170: 711-717.

Wu Y. M., Kanamori H. Development of an earthquake early warning system using real-time strong motion signals [J]. *Sensors*, 2008a, 8(1): 1-9.

Wu Y. M., Kanamori H. Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake[J]. *Earth, Planets and Space*, 2008b, 60(2): 155-160.

Wu Y.M., Mittal H., Huang T.C., Yang B.M., Jan J.C., Chen S.K. Performance of a low-cost earthquake early warning system (P-alert) and shake map production during the 2018 M_W6.4 Hualien, Taiwan, earthquake [J]. *Seismological Research Letters*, 2019, 90(1): 19-29.

Wurman G., Allen R.M., Lombard P. Toward earthquake early warning in northern California[J]. *Journal of Geophysical Research: Solid Earth*, 2007, 112(B8): B08311.

Yamasaki E. What we can learn from Japan's earthquake early warning system[J]. *Momentum*, 2012, 1(1): 2.

Yao Jiayuan, Tian Dongdong, Sun Li, Wen Lianxing. Temporal change of seismic Earth's inner core phases: inner core differential rotation or temporal change of inner core surface? [J]. *Journal of Geophysical Research: Solid Earth*, 2019, 124(7): 6720-6736.

Yin L., Andrews J., Heaton T. Rapid earthquake discrimination for earthquake early warning: A Bayesian probabilistic approach using three-component single-station waveforms and seismicity forecast[J]. *Bulletin of the Seismological Society of America*, 2018, 108(4): 2054-2067.

Zhang Hongcai, Jin Xing, Wei Yongxiang, Li Jun, Kang Lanchi, Wang Shicheng, Huang Lingzhu, Yu Peiqing. An earthquake early warning system in Fujian, China[J]. *Bulletin of the Seismological Society of America*, 2016, 106(2): 755-765.

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(23): L23312.

Zollo A., Iannaccone G., Convertito V., Elia L., Iervolino I., Lancieri M., Lomax A., Martino C., Satriano C., Weber E., Gasparini P. Earthquake early warning system in southern Italy: Methodologies and performance evaluation[J]. *Geophysical Research Letter*, 2009, 36, 200B07.

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