synthetic aperture radar imagery. *Journal of Geophysical Research*, **110**, B09406, doi:10.1029/2004JB003338.
Hanks, T. C., and Kanamori, H., 1979. A moment magnitude scale. *Journal of Geophysical Research*, **84**, 2348–2350.
Haugerud, R. A., Harding, D. J., Johnson, S. Y., Harless, J. L., Weaver, C. S., and Sherrod, B. L., 2003. High-resolution Lidar topography of the Puget Lowland. Washington: GSA Today, pp. 4–10.
Heki, K., Miyazaki, S., and Tsuji, H., 1997. Silent fault slip following an interplate thrust earthquake at the Japan Trench. *Nature*, **386**, 595–598.
Ide, S., Beroza, G. C., Shelly, D. R., and Uchide, T., 2007. A scaling law for slow earthquakes. *Nature*, **447**, 76–79, doi:10.1038.
Johanson, I. A., Fielding, E. J., Rolandone, F., and Bürgmann, R., 2006. Coseismic and postseismic slip of the 2004 Parkfield earthquake from space-geodetic data. *Bulletin. Seismological Society of America*, **96**, 4b.
Jones, C. H., Unruh, J. R., and Sonder, L. J., 1996. The role of gravitational potential energy in active deformation in the southwestern US. *Nature*, **381**, 37–41.
Kanamori, H., and Kikuchi, M., 1993. The 1992 Nicaragua earthquake – a slow tsunami earthquake associated with subducted sediments. *Nature*, **361**, 714–716.
Larson, K. M., Kostoglodov, V., Miyazaki, S., and Santiago, J. A. S., 2007. The 2006 aseismic slow slip event in Guerrero, Mexico: New results from GPS. *Geophys Res Lett*, **34**, L13309, doi:10.1029/2007GL029912.
Linde, A. T., Gladwin, M. T., Johnston, M. J. S., and Gwyther, R. L., 1996. A slow earthquake sequence on the San Andreas fault. *Nature*, **383**, 65–68.
Manaker, D. M., Calais, E., Freed, A. M., Ali, S. T., Przybylski, P., Mattioli, G., Jansma, P., Prepetit, C., and de Chabalier, J. B., 2008. Interseismic Plate coupling and strain partitioning in the Northeastern Caribbean. *Geophysical Journal International*, **174**, 889–903, doi:10.1111/j.1365-246X.2008.03819.x.
Matsu'ura, M., Jackson, D. D., and Cheng, A., 1986. Dislocation model for aseismic crustal deformation at Hollister, California. *Journal of Geophysical Research*, **91**, 12661–12674.
McCaffrey, R., 2002. Crustal block rotations and plate coupling. In Stein, S., and Freymueller, J. (eds.), *Plate Boundary Zones*. AGU Geodynamics Series 30, pp. 101–122.
McCaffrey, R., Qamar, A. I., King, R. W., Wells, R., Ning, Z., Williams, C. A., Stevens, C. W., Vollick, J. J., and Zwick, P. C., 2007. Plate locking, block rotation and crustal deformation in the Pacific Northwest. *Geophysical Journal International*, doi:10.1111/j.1365-246X.2007.03371.x.
McCaffrey, R., Wallace, L. M., and Beavan, J., 2008. Slow slip and frictional transition at low temperature at the Hikurangi subduction zone. *Nature Geoscience*, **1**, 316–320.
Mogi, K., 1985. *Earthquake Prediction*. Tokyo: Academic.
Obara, K., 2002. Nonvolcanic deep tremor associated with subduction in southwest Japan. *Science*, **296**, 1679, doi:10.1126/science.1070378.
Okada, Y., 1992. Internal deformation due to shear and tensile faults in a half-space. *Bulletin. Seismological Society of America*, **82**, 1018–1040.
Reid, H. F., 1910. The Mechanics of the Earthquake, The California Earthquake of April 18, 1906, Report of the State Investigation Commission, Vol. 2, Washington, DC: Carnegie Institution of Washington.
Rogers, G., and Dragert, H., 2003. Episodic tremor and slip on the cascadia subduction zone: The chatter of silent slip. *Sciencexpress*, doi: 10.1126/science.1084783.
Rubenstein, J. L., Shelley, D. R., and Ellsworth, W. L., 2010. Nonvolcanic tremor: a window into the roots of fault zones. In Cloetingh, S., Negendank, J. (eds.), *New Frontiers in Integrated Solid Earth Sciences.* International Year of Planet Earth, doi: 10.1007/978-90-481-2737-5_8.
Scholz, C., 2002. *The Mechanics of Earthquakes and Faulting*, 2nd edn. Cambridge: Cambridge University Press, 471 pp.
Segall, P., 2010. *Earthquake and Volcano Deformation*. Princeton: Princeton University Press.
Shelly, D. R., Beroza, G. C., Ide, S., and Nakamula, S., 2006. Low frequency earthquakes in Shikoku, Japan, and their relationship to episodic tremor and slip. *Nature*, **442**, 188–191.

## Cross-references

Earthquake Precursors and Prediction
Earthquake, Aftershocks
Earthquakes, Volcanogenic
GPS, Tectonic Geodesy
Paleoseismology
SAR Interferometry
Seismic Hazard
Seismicity, Intraplate
Seismicity, Subduction Zone
Slow Earthquake

# EARTHQUAKES, EARLY AND STRONG MOTION WARNING

Richard M. Allen
Berkeley Seismological Laboratory, Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

## Synopsis

Strong motion earthquake warning (also known as earthquake early warning) is the rapid detection of an earthquake underway, the estimation of the ground shaking likely to result, and the issuance of an alert to people in the region where the ground shaking is likely to be hazardous. The last decade has seen rapid development of methodologies for early warning, which include the use of strong motion observations close to the epicenter to provide warnings at greater distances, the use of P-wave observations across a network to locate the event and map the distribution of likely strong ground motion, and the use of a P-wave detection at a single station to estimate the likely shaking intensity at the same station. These approaches have been listed in the order of increasing warning time, but the additional warning time comes at the expense of certainty. The earlier a warning is provided the greater the likelihood of false and missed alarms and the greater the uncertainty in the estimated shaking intensity. Typical warning times range from a few seconds to tens of seconds; the upper limit is about 1 min. Identified applications include personal protective measures where individuals move to a safe-zone within a few feet; automated mechanical response including stopping trains and isolating sensitive and hazardous machinery and chemicals; and situation awareness by large organizations that can help prevent cascading failures and be available before shaking disrupts communications. Large-scale public warning systems are currently operational in

Mexico and Japan, and smaller systems are used in Romania, Turkey, and Taiwan. Testing is underway by seismic networks in many other countries; however, implementation will require significant financial, political, and sociological hurdles to be crossed.

## Introduction

Strong motion earthquake warning, more commonly referred to as earthquake early warning (EEW), is the rapid detection of an earthquake underway, estimation of the intensity of ground shaking likely to result, and issuance of a warning in the area likely to experience damaging strong motion. It provides high-probability warnings of shaking likely to occur within seconds to tens of seconds. The ability to provide warnings is relatively new and due to recent scientific development of methodologies to rapidly estimate the size of earthquakes underway, coupled with modern engineering of rapid communications to collect seismic data and distribute warnings, and a political will to operate state-of-the-art geophysical networks for the purpose of both scientific discovery and societal benefit.

EEW is one of three categories of earthquake warnings. Long-term warnings provide relatively low probabilities of earthquakes over long time periods, typically decades, and are usually referred to as earthquake forecasts. On these long timescales, earthquake likelihood can be estimated based on historic earthquake recurrence intervals and plate motion rates, linked together with deformation models incorporating fault geometries. For example, the probability of an $M > 6.7$ earthquake on the Hayward-Rodgers Creek fault that crosses the UC Berkeley campus is estimated to be 31% over 30 years (Working Group on California Earthquake Probabilities, 2007). These forecasts are also translated into estimates of ground shaking intensity that can be used to define building codes designed to prevent new buildings from collapse in the forecast of earthquakes.

The other end-member is earthquake prediction. The term prediction usually means a high probability of a large, damaging earthquake over a short time interval. For example, predicting an $M > 7$ earthquake on the Hayward Fault next week (Allen, 1976). Earthquake prediction is currently not possible, as we have not been able to identify a precursory signal that consistently occurs before earthquakes, and most seismologists agree that prediction will not be possible in the near future. EEW is intermediary in that it is possible to provide warning before shaking is felt, however, the warnings are only a few seconds to tens of seconds.

## Uses of early warning

Uses of EEW that have been identified to date fall into three broad categories (Allen et al., 2009d): personal protection, automated mechanical actions, and situation awareness. The first use that people think about when introduced to early warning is personal protection. For most people, given that there will only be a few to a few tens of seconds of warning, the appropriate action is to move to a "safe-zone" within a few meters of your current location – under a sturdy table, away from falling hazards including windows, bookshelves, etc. These safe-zones need to be identified ahead of time in the locations that people spend most of their time, that is, in their homes and offices or workplaces. In most cases there is not sufficient time to evacuate buildings, and EEW is no substitute for building standards that prevent building collapse. It currently takes schoolchildren in Japan and Mexico ~5 s to get under their desks in response to audible warnings. Outdoors, people should move away from buildings, masonry walls, and other falling hazards including broken glass, street signs, etc. In hazardous work sites including construction sites, manufacturing and chemical facilities, the same principle applies: move to predefined safe-zones.

The second category is automated mechanical control. Within the transportation sector, implemented warning systems are currently used to slow and stop trains, stop airplanes from landing by issuing a go-around command, and to bring traffic to a halt. They could also be used to turn metering or tollbooth lights to red at the entrance to vulnerable road bridges, tunnels, and overpasses. Within buildings, warnings are now used to stop elevators at the next floor and open the doors, open emergency exit doors and window blinds, and turn on lights. Industrial facilities use the warning to place machinery or product into a safe mode. For example, a chip manufacturer in Japan places sensitive micro-robots into a hold mode to reduce damage, and isolates hazardous chemical systems to minimize any resulting leaks. In Japan, engineers are also experimenting with using warnings within automated structural control systems that change the mechanical properties of the building to better withstand the expected shaking. This is an area where there are a myriad of possible applications, most of which are very specific to individual users.

Finally, situation awareness is very important to organizations with responsibilities for large infrastructures and/or people. These include government agencies, utility, and transportation companies. While these groups may take early warning actions, they also have a need to rapidly understand why part or all of their system is failing. For example, an electrical power grid may start to fail in one area, and operators need to rapidly understand why it is failing in order to reduce cascading failures throughout the system. EEW can provide this information more rapidly than any of the existing post-earthquake information systems. EEW also has the advantage that much of the data needed to map out the likely shaking is collected before significant shaking has occurred. This means that the information can be transmitted across data-networks and out to users before strong shaking has the opportunity to disrupt communications.

One of the main concerns expressed in response to the early warning concept is panic: will people panic when they receive the warning and injure themselves or others as a result. Social scientists have long studied this issue and find that it is not the source of concern that many seismologists think it is (Quarantelli, 1956; Goltz, 2002). The experience that we now have from public warnings in Mexico and Japan provides no evidence that warnings result in panic (Espinosa Aranda et al., 2009; Kamigaichi et al., 2009). There is no evidence for traffic accidents resulting from warnings and no evidence of public stampedes. Implementation of EEW does require an educational campaign to educate people about what EEW can do and help them identify the appropriate actions in their locations (Kamigaichi et al., 2009).

## Approaches to early warning

All EEW methodologies must use just a few seconds of data to detect an earthquake underway and rapidly assess its intensity. There is generally a trade-off between the amount of warning time and the accuracy or certainty of the warnings. Greater certainty requires more data from one or more stations, but waiting for that data reduces the warning time. The challenge when building an early warning system is to determine whether additional accuracy is worth the increasing delay.

*Strong-motion-based warning.* The first warning methodologies used this approach. When strong ground shaking is observed at one location, close to the earthquake epicenter, the shaking intensity at greater distances can be estimated using ground motion prediction equations and a warning transmitted ahead of the ground shaking. This approach is called front detection and is used in Mexico City where the earthquake source zone is ~300 km from the city. Figure 1 shows the time at which peak ground shaking was observed at all available stations recording nine $M \geq 6$ earthquakes. A strong-motion-based warning would be possible at some point between 10 s and 20 s after the origin time for these events, depending on the proximity of the closest station(s). By 20 s, the onset of strong shaking is ~60 km from the epicenter meaning that warnings based on peak-shaking observations near the epicenter are only available at distances greater than ~60 km. The region within ~60 km of the epicenter would get no warning and is referred to as the "blind zone."

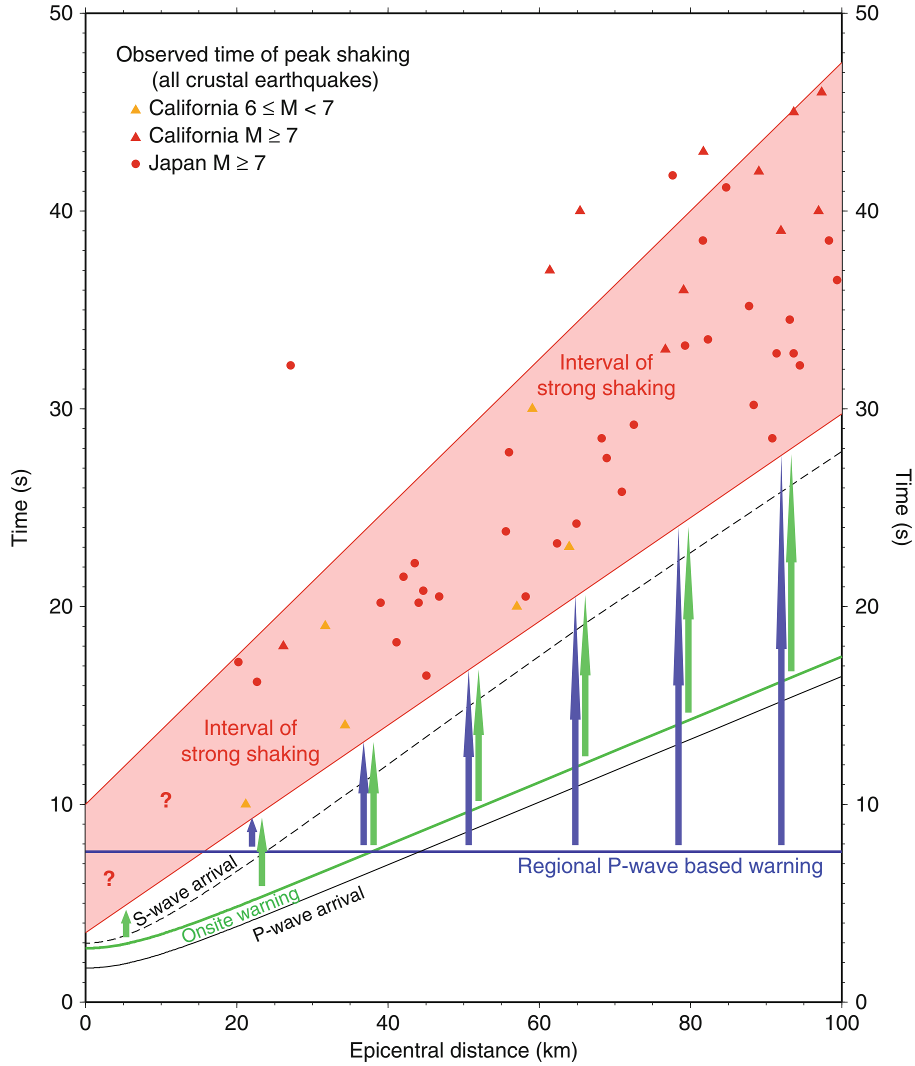
*P-wave based warning.* To reduce the size of the blind zone, P-wave based methodologies are used. These approaches use a few seconds of the P-wave to estimate either the magnitude or the peak-shaking amplitude. In order to estimate the magnitude, a variety of parameters have been developed that are measures of the frequency content (Nakamura, 1988; Allen and Kanamori, 2003; Kanamori, 2005) or the amplitude (Kamigaichi, 2004; Wu and Kanamori, 2005b; Zollo et al., 2006; Cua and Heaton, 2007; Wurman et al., 2007; Böse et al., 2008; Wu and Kanamori, 2008b; Köhler et al., 2009). In order to estimate magnitude, amplitude-based parameters need to be corrected for epicentral distance. However, the frequency-based parameters have been found to be insensitive to epicentral distance provided the observations are made within ~100 km of the epicenter. For all of these parameters empirical scaling relations between the observation and earthquake magnitude have been developed so that magnitude (plus or minus some uncertainty) can be estimated from an observation at one or more stations.

*Regional warning.* When a regional network is available, P-wave based estimates of magnitude can be combined with an estimate of the earthquake location to then map the distribution of strong ground motion using ground motion prediction equations. In their simplest form these maps are a "bulls-eye" centered on the epicenter. Corrections can also be made for site amplification effects. Examples of this approach include ElarmS (Allen, 2007; Wurman et al., 2007; Allen et al., 2009a; Brown et al., 2009), Presto (Zollo et al., 2009), the Virtual Seismologist (Cua and Heaton, 2007; Cua et al., 2009), and the NIED approach in Japan (Horiuchi et al., 2005).

When using a regional network, P-wave observations at multiple stations can be combined in order to verify that an earthquake is underway and improve the accuracy of the magnitude estimate. Generally, the more stations used, the better the accuracy of the warnings and the fewer false alarms. The time at which a warning is available therefore depends on the number of station detections required and the number of seconds of P-wave data required at each station. Figure 1 illustrates the amount of warning time available using this approach. The horizontal blue line at 7.6 s represents the time at which a warning is available for a particular scenario (Figure 1). In this case, the size of the blind zone is ~15 km and the amount of warning time increases linearly with distance beyond 15 km. There would be ~9 s warning at 50 km and ~22 s warning at 100 km.

*Onsite warning.* Onsite warning provides the most rapid approach to earthquake warning by removing the need for communications. The delay in issuing a warning is minimized by using a seismic station at the location where the warning is needed. Onsite methodologies are intended to estimate the intensity of ground shaking at the same location that the P-wave is detected (Odaka et al., 2003; Wu and Kanamori, 2005a, b; Nakamura and Saita, 2007a, b; Wu et al., 2007; Wu and Kanamori, 2008a, b; Böse et al., 2009a, b). The challenge with onsite warning is to provide enough accuracy that the warnings are useful. The character of P-wave arrivals is variable at different locations for the same earthquake due to variability in source radiation and also local site effects. Using a single station (or several stations within a few hundred meters) does not allow for averaging of this variability as in the case of regional methodologies. However, the onsite approach is faster.

Figure 1 illustrates the best-case scenario for onsite warning in which the warning is available using 1 s of P-wave data and the earthquake is at a sufficient depth that there is more than 1 s between the P-wave arrival and the onset of peak shaking at the epicenter. This means that there is no blind zone and a warning is available at the epicenter. The warning time increases with distance as the




**Earthquakes, Early and Strong Motion Warning, Figure 1** Plot showing the time of observed peak shaking for large magnitude events and illustrating the time at which warnings could be available using various methods. The time of peak shaking was determined for all available stations in nine $M \geq 6$ earthquakes from California (triangles, magnitudes 6.0, 6.5, 6.7, 7.1, 7.1, and 7.5) and Japan (circles, magnitudes 7.0, 7.1, and 7.3) and is plotted as a function of epicentral distance. All events are crustal earthquakes with epicentral depths of 21 km or less. The *red* shaded region illustrates the approximate interval of strong shaking when most of the peak-shaking observations are made. Note that there are few observations close to the epicenter due to the stations spacing of networks in California and Japan. The P-wave (*solid black line*) and S-wave (*dashed black line*) arrival times for a 10 km depth earthquake are also shown. The *blue line* and *arrows* illustrate available warning times for a regional P-wave based warning system. The horizontal line is the time at which a warning is available. It assumes that the required number of stations for a warning have detected a P-wave once the P-wave front reaches 25 km (at 4.6 s), that 1 s of P-wave is required to estimate magnitude (available at 5.6 s), and that an additional 2 s is needed for communications. The purpose-built seismic network in Japan provides data to the network centers within 1 s, and we assume that an additional 1 s is required to get the warning out to users. This means that the warning reaches users at 7.6 s after the origin time. The onset of strong shaking has reached ~15 km from the epicenter at this time. The available warning time increases linearly (shown by *blue arrows*) from 0 s at 15 km to ~22 s at 100 km. The *green line* and *arrows* illustrate the available warning time using the onsite P-wave based warning approach. It is assumes that 1 s of P-wave data is needed and the time of warning (*green line*) is therefore 1 s after the P-wave arrival. As shown, it is possible to provide a warning at the epicenter if the earthquake is more than ~10 km deep meaning there could be no blind zone. The warning time then increases with distance as the time between the P-wave arrival and peak shaking increases. Warning times (*green arrows*) range from ~2 s at 10 km to ~12 s at 100 km.

time-separation of the P-wave and peak shaking increases. Typical warning times are ~2 s at 10 km, ~7 s at 50 km, and ~12 s at 100 km. The onsite approach provides the most warning close to the epicenter. However, for locations at greater distances, regional warning provides more warning time that onsite warning as alerts are transmitted electronically ahead of ground motion. In the scenarios shown in Figure 1, the crossover when the regional method provides more warning than onsite is at ~35 km.

## Implementations of early warning

There are currently two large-scale implementations of early warning in Mexico and Japan (Figure 2). The first public system started to provide warnings to Mexico City in 1993. It was built following the 1985 M8.1 earthquake that killed 10,000 people in the city. The system uses a line of seismometers deployed near the coastline to detect offshore earthquakes and transmit the warning 300 km to the city ahead of strong shaking (Espinosa Aranda et al., 1995). The offset between the source region and the city allows the use of a front detection approach and still provides more than 60 s of warning time. These warnings are broadcast by 58 radio stations and 6 TV channels in the city. There are also more than 250 users who receive the warning through dedicated radio links including schools and universities, emergency and civil protection agencies, government buildings, and the subway system.

Japan Railways first began to experiment with early warning in the 1960s. These systems became increasingly sophisticated including the first P-wave based application of UrEDAS in the 1980s (Nakamura, 1988). With the growth of computerized communication systems in the 1990s automated remote sensing of earthquakes expanded. Following the 1995 Kobe earthquake that killed 6,000 people, Japan installed dense seismic networks across the entire country (Okada et al., 2004). This network led to the development and implementation of a nationwide regional warning system that became operational in 2007 and is operated by the Japan Meteorological Agency (JMA). These warnings are now broadcast by the majority of TV and radio stations in Japan, through the government operated J-Alert system that issues warnings to municipalities (many of which relay the warning to loudspeaker systems in public spaces), by cell phone companies, and by a myriad of private providers and purpose-built consumer devices (Kamigaichi et al., 2009). The various Japanese systems use both onsite and regional warning systems. In the 2004 $M_w$7.2 Niigata earthquake the emergency brakes of one of the bullet trains were triggered by the onsite UrEDAS system (Nakamura and Saita, 2007a), and the regional warning system operated by JMA has issued warnings for multiple earthquakes including the 2008 $M_w$7.2 Iwate-Miyagi Nairiku earthquake (Kamigaichi et al., 2009).

Smaller scale and user-specific warning systems have also been implemented in various locations around the world. In Bucharest, warnings are provided to a nuclear research facility (Ionescu et al., 2007). Istanbul has warning systems for a power plant and a large banking building, and a more general use warning system has also been implemented in the last few years using a new strong motion network (Alcik et al., 2009). In Taipei, a test warning system provided warnings to the rail system, the university, and a hospital (Wu and Teng, 2002). Finally, in the US, a temporary warning system was implemented following the 1989 Loma Prieta earthquake (Bakun et al., 1994).

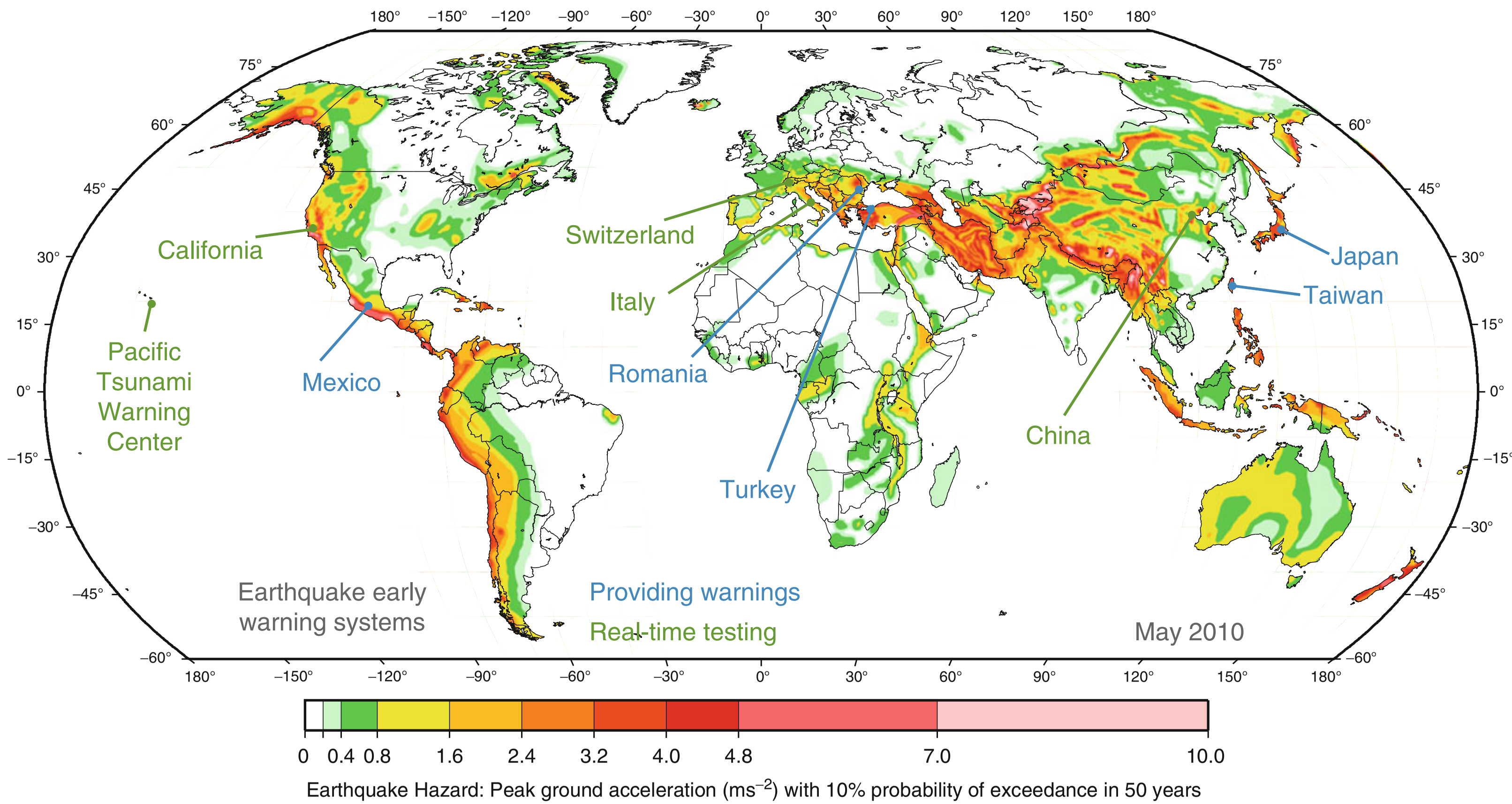
Testing of early warning methodologies is now underway on an increasing number of regional seismic networks around the world. This includes networks in California, China, Italy, at the Pacific Tsunami Warning Center, and in Switzerland (Figure 2). In many of these cases the technical feasibility of providing warnings has been demonstrated. Whether these test systems will transition to implementation of public warning systems will therefore be largely determined by financial, political, and sociological factors.

## Summary

The last decade has seen rapid development of earthquake early warning methodologies (e.g., Gasparini et al., 2007; Allen et al., 2009b, c) by multiple research groups around the world. A range of methodologies has been developed that generate warnings based on observations of strong shaking near the epicenter, estimation of shaking hazard maps using P-wave detections across a network, and single-station detections of P-waves to estimate hazard at the same location. Warning times typically range from a few seconds to tens of seconds with an upper limit of around 1 min. With all these methodologies there is a trade-off between the accuracy of the warning and the amount of warning time. The challenge is to identify the optimal threshold at which to provide a warning.

There are now several implementations of public warning systems around the world, most notably in Mexico and Japan. These provide insight to the potential uses of earthquake alerts, which fall into three categories. Personal protection is about actions of individuals to protect themselves. For individuals it is important to identify "safe-zones" at home and work. These are spaces that are reachable within a few seconds where they will be protected from falling hazards. Automated mechanical control can be used to further reduce the impacts of earthquakes. This category includes slowing trains, opening elevators at the nearest floor, and isolating sensitive or hazardous machinery or chemicals. Finally, early warning can provide situational awareness information to large organizations that may be used to limit cascading failures and initiate response. This information could be available before much of the shaking, and therefore increases the likelihood that the information can be transmitted before communications are lost.

While 5 years ago there were many technical questions about the feasibility of earthquake early warning, today the primary hurdles to implementation are financial,




**Earthquakes, Early and Strong Motion Warning, Figure 2** Map of seismic hazard around the world (*pink* represents the greatest hazard) showing regions where earthquake early warnings are currently being provided (*blue* labels) and the regions where real-time testing on existing seismic networks is underway (*green* labels) (after Giardini, 1999).

political, and sociological. The existing public warning systems in Mexico and Japan were built following major destructive earthquakes. The challenge for the hazard mitigation communities in other countries is to generate the necessary will to implement these systems before the next earthquake.

## Bibliography


Alcik, H., Ozel, O., Apaydin, N., and Erdik, M., 2009. A study on warning algorithms for Istanbul earthquake early warning system. *Geophysical Research Letters*, **36**, L00B05.

Allen, C. R., 1976. Responsibilities in earthquake prediction. *Bulletin Seismological Society of America*, **66**, 2069–2074.

Allen, R. M., 2007. The ElarmS earthquake warning methodology and application across California. In Gasparini, P., and Zschau, J. (eds.), *Seismic Early Warning.* New York: Springer, pp. 21–44.

Allen, R. M., and Kanamori, H., 2003. The potential for earthquake early warning in southern California. *Science*, **300**, 786–789.

Allen, R. M., Brown, H., Hellweg, M., Khainovski, O., Lombard, P., and Neuhauser, D., 2009a. Real-time earthquake detection and hazard assessment by ElarmS across California. *Geophysical Research Letters*, **36**, L00B08, doi:10.1029/2008GL036766.

Allen, R. M., Gasparini, P., and Kamigaichi O. (eds.), 2009b. Earthquake early warning. *Seismological Research Letters*, **80**, 682–782.

Allen, R. M., Gasparini, P., and Kamigaichi, O. (eds.), 2009c. New methods and applications of earthquake early warning. *Geophysical Research Letters*, **36**, L00B05, L00B08, L00B03, L00B04, L00B02, L00B06, L00B01, L00B07.

Allen, R. M., Gasparini, P., Kamigaichi, O., and BöSe, M., 2009d. The status of earthquake early warning around the world: an introductory overview. *Seismological Research Letters*, **80**, 682–693, doi:610.1785/gssrl.1780.1785.1682.

Bakun, W. H., Fischer, F. G., Jensen, E. G., and Vanschaack, J., 1994. Early warning system for aftershocks. *Bulletin Seismological Society of America*, **84**, 359–365.

Böse, M., Wenzel, F., and Erdik, M., 2008. PreSEIS: a neural network-based approach to earthquake early warning for finite faults. *Bulletin Seismological Society of America*, **98**, 366–382.

Böse, M., Hauksson, E., Solanki, K., Kanamori, H., and Heaton, T. H., 2009a. Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29 2008 Mw5.4 Chino Hills earthquake. *Geophysical Research Letters*, **36**, L00B03, doi:10.1029/2008GL036366.

Böse, M., Hauksson, E., Solanki, K., Kanamori, H., Wu, Y.-M., and Heaton, T., 2009b. A new trigger criterion for improved real-time performance of on-site early warning in southern California. *Bulletin Seismological Society of America*, **99**, 897–905.

Brown, H., Allen, R. M., and Grasso, V. F., 2009. Testing ElarmS in Japan. *Seismological Research Letters*, **80**, 727–739, doi:710.1785/gssrl.1780.1785.1727.

Cua, G., and Heaton, T., 2007. The Virtual Seismologist (VS) method: a Bayesian approach to earthquake early warning. In Gasparini, P., Manfredi, G., and Zschau, J. (eds.), *Earthquake Early Warning Systems*. Berlin: Springer, pp. 97–132.

Cua, G., Fischer, M., Heaton, T., Wiemer, S., and Giardini, D., 2009. Real-time performance of the virtual seismologist method in southern California. *Seismological Research Letters*, **80**, 740–748, doi:710.1785/gssrl.1780.1785.1740.

Espinosa Aranda, J. M., Jimenez, A., Ibarrola, G., Alcantar, F., Aguilar, A., Inostroza, M., and Maldonado, S., 1995. Mexico city seismic alert system. *Seismological Research Letters*, **66**, 42–52.

Espinosa Aranda, J. M., Cuellar, A., Garcia, A., Ibarrola, G., Islas, R., and Maldonado, S., 2009. Evolution of the Mexican Seismic Alert System (SASMEX). *Seismological Research Letters*, **80**, 682–693, doi:610.1785/gssrl.1780.1785.1682.

Gasparini, P., Manfredi, G., and Zschau, J., 2007. *Earthquake Early warning systems*. Berlin: Springer, p. 350.

Giardini, D., 1999. The global seismic hazard assessment program (GSHAP) - 1992/1999. *Annali Di Geofisica*, **42**, 957–974.

Goltz, J. D., 2002. Introducing earthquake early warning in California: a summary of social science and public policy issues. Report of California Office of Emergency Services by the Caltech Seismological Laboratory, Disaster Assistance Division. Pasadena, California.

Horiuchi, S., Negishi, H., Abe, K., Kamimura, A., and Fujinawa, Y., 2005. An automatic processing system for broadcasting earthquake alarms. *Bulletin Seismological Society of America*, **95**, 708–718.

Ionescu, C., Böes, M., Wenzel, F., Marmureanu, A., Grigore, A., and Marmureanu, G., 2007. An early warning system for deep Vrancea (Romania) earthquakes. In Gasparini, P., Manfredi, G., and Zschau, J. (eds.), *Earthquake Early Warning Systems*. Berlin: Springer, pp. 343–349.

Kamigaichi, O., 2004. JMA earthquake early warning. *Journal of the Japan Association for Earthquake Engineering*, **4**, 134–137.

Kamigaichi, O., Saito, M., Doi, K., Matsumori, T., Tsukada, S., Takeda, K., Shimoyama, T., Nakamura, K., Kiyomoto, M., and Watanabe, Y., 2009. Earthquake early warning in Japan – warning the general public and future prospects. *Seismological Research Letters*, **80**, 717–726, doi:710.1785/gssrl.1780.1785.1717.

Kanamori, H., 2005. Real-time seismology and earthquake damage mitigation. *Annual Review of Earth and Planetary Sciences*, **33**, 195–214.

Köhler, N., Cua, G., Wenzel, F., and Böse, M., 2009. Rapid source parameter estimations of southern California earthquakes using PreSEIS. *Seismological Research Letters*, **80**, 748–754, doi:710.1785/gssrl.1780.1785.1748.

Nakamura, Y., 1988. On the urgent earthquake detection and alarm system (UrEDAS). In *Proceedings of the 9th World Conference on Earthquake Engineering*, Vol. 7, pp. 673–678.

Nakamura, Y., and Saita, J., 2007a. UrEDAS, the earthquake warning system: today and tomorrow. In Gasparini, P., Manfredi, G., and Zschau, J. (eds.), *Earthquake Early Warning Systems*. Berlin/Heidelberg: Springer, pp. 249–282.

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

Odaka, T., Ashiya, K., Tsukada, S., Sato, S., Ohtake, K., and Nozaka, D., 2003. A new method of quickly estimating epicentral distance and magnitude from a single seismic record. *Bulletin Seismological Society of America*, **93**, 526–532.

Okada, Y., Kasahara, K., Hori, S., Obara, K., Sekiguchi, S., Fujiwara, H., and Yamamoto, A., 2004. Recent progress of seismic observation networks in Japan – Hi-net, F-net, K-NET, KiK-net. *Earth, Planets and Space*, **56**, xv–xxviii.

Quarantelli, H., 1956. *The Condition of Panic*. Chicago: University of Chicago.

Working Group on California Earthquake Probabilities, 2007. The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2), US Geological Survey, p.104.

Wu, Y.-M., and Kanamori, H., 2005a. Experiment on an onsite early warning method for the Taiwan early warning system. *Bulletin Seismological Society of America*, **95**, 347–353.

Wu, Y.-M., and Kanamori, H., 2005b. Rapid assessment of damage potential of earthquakes in Taiwan from the beginning of P waves. *Bulletin Seismological Society of America*, **95**, 1181–1185.

Wu, Y.-M., and Kanamori, H., 2008a. Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake. *Earth, Planets and Space*, **60**, 155–160.

Wu, Y.-M., and Kanamori, H., 2008b. Development of an earthquake early warning system using real-time strong motion signals. *Sensors*, **8**, 1–9.
Wu, Y.-M., and Teng, T.-L., 2002. A virtual subnetwork approach to earthquake early warning. *Bulletin Seismological Society of America*, **92**, 2008–2018.
Wu, Y.-M., Kanamori, H., Allen, R. M., and Hauksson, E., 2007. Experiment using the tau-c and Pd method for earthquake early warning in southern California. *Geophysical Journal International*, **170**, 711–717.
Wurman, G., Allen, R. M., and Lombard, P., 2007. Toward earthquake early warning in northern California. *Journal of Geophysical Research*, **112**, B08311, doi:08310.01029/02006JB004830.
Zollo, A., Lancieri, M., and Nielsen, S., 2006. Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records. *Geophysical Research Letters*, **33**, L23312.
Zollo, A., Iannaccone, G., Lancieri, M., Cantore, L., Convertito, V., Emolo, A., Festa, G., Gallovic, F., Vassallo, M., Martino, C., Satriano, C., and Gasparini, P., 2009. Earthquake early warning system in southern Italy: methodologies and performance evaluation. *Geophysical Research Letters*, **36**, L00B07.

## Cross-references

Earthquake Precursors and Prediction
Earthquakes, Intensity
Earthquakes, Shake Map
Earthquakes, Strong-Ground Motion
Seismic Hazard

## EARTHQUAKES, ENERGY

Domenico Di Giacomo, Peter Bormann
Department 2: Physics of the Earth, GFZ German Research Center for Geosciences, Potsdam, Germany

### Definition and calculation

During the earthquake process, the strain energy $W$ available for rupture is divided into fracture energy $E_G$, thermal energy $E_H$, and radiated seismic energy $E_S$. The stress conditions around the fault and the rheological and elastic characteristics of the Earth materials being ruptured determine the partitioning of the overall energy budget involved in the earthquake source process. In particular, $E_G$ and $E_H$ are the energies dissipated mechanically and as frictional heat during faulting, respectively, and $E_S$ is the energy fraction that goes into elastic seismic waves energy. The latter being of great importance for seismologists in evaluating an earthquake's shaking potential, in the following the relationship between the strain energy and radiated seismic energy is outlined.

After Knopoff (1958), the change in strain energy before and after an earthquake can be obtained from:

$$\Delta W = S\bar{D}\bar{\sigma}, \tag{1}$$

where $S$ = fault area, $\bar{D}$ = average displacement over the fault, and $\bar{\sigma} = (\sigma_0 + \sigma_1)/2$ is the mean stress (with $\sigma_0$ being the initial stress and $\sigma_1$ the final one). This energy represents the total work associated to the earthquake rupture process. The small energy fraction converted to $E_S$ is (e.g., Wyss and Molnar, 1972):

$$E_S = \frac{1}{2}\left(\sigma_0 + \sigma_1 - 2\sigma_f\right) \cdot S\bar{D}, \tag{2}$$

where $\sigma_f$ is the average frictional stress during faulting. It is also useful to relate $E_S$ and ΔW via the radiation efficiency $\eta_R = E_S/(E_S + E_G)$ (see, e.g., Wyss, 1970; Husseini, 1977):

$$E_S = \eta_R \Delta W. \tag{3}$$

The radiation efficiency $\eta_R$, spanning between 0 and 1, expresses the amount of work dissipated mechanically, therefore if an earthquake is effective in radiating $E_S$ then $\eta_R$ approaches 1 (that is to say about all the energy budget is converted into the seismic waves energy), whereas if $\eta_R$ is very small or = 0 then the energy is dissipated and no $E_S$ is radiated.

Assuming that the final stress $\sigma_1$ and the frictional stress $\sigma_f$ are identical (that is to say the stress drop $\Delta\sigma = \sigma_0 - \sigma_1$ is complete, Orowan, 1960), it has been shown by Kanamori (1977) that a measure of ΔW can be obtained considering another important physical parameter of the seismic source, that is the seismic moment $M_0$:

$$\Delta W = \left(\frac{\Delta\sigma}{2\mu}\right) M_0, \tag{4}$$

with $M_0 = \mu S\bar{D}$ (where $\mu$ = rigidity of the medium in the source area). $M_0$ is a measure of the overall static displacement caused by the fault rupture. It is a well determined seismological parameter (normally within a factor of 2) since it must be calculated from long and/or very long periods (usually >100 s for large earthquakes) of the recorded seismograms (Dziewonski et al., 1981), which are less affected than the short periods by the small-scale Earth heterogeneities along the path from the source to the receivers.

By assuming that the stress drop is complete and nearly constant (between some 20 and 60 bars = $2–6 \cdot 10^7$ dyn/cm$^2$ = 2–6 MPa) for very large earthquakes and that $\mu = 3–6 \cdot 10^{11}$ dyn/cm$^2$ = $3–6 \cdot 10^4$ MPa in the source area under average crust-upper mantle conditions, Kanamori (1977) showed that the ratio

$$E_S/M_0 = 5 \times 10^{-5} = \text{constant}. \tag{5}$$

Therefore, under these conditions (adopted also for introducing the moment magnitude *Mw*, see *Earthquake, Magnitude*), one could easily have an indirect estimation of $E_S$ from known $M_0$.

However, $M_0$ and $E_S$ are two distinct physical parameters. Indeed, $M_0$ is a static parameter that is not sensible to the details of the rupture history and does not bring any direct information about the frequency content radiated by the seismic source, whereas $E_S$ depends on the dynamic characteristics of the seismic source and, being related to velocity, it is more important than $M_0$ for evaluating the earthquake damage potential over frequencies of