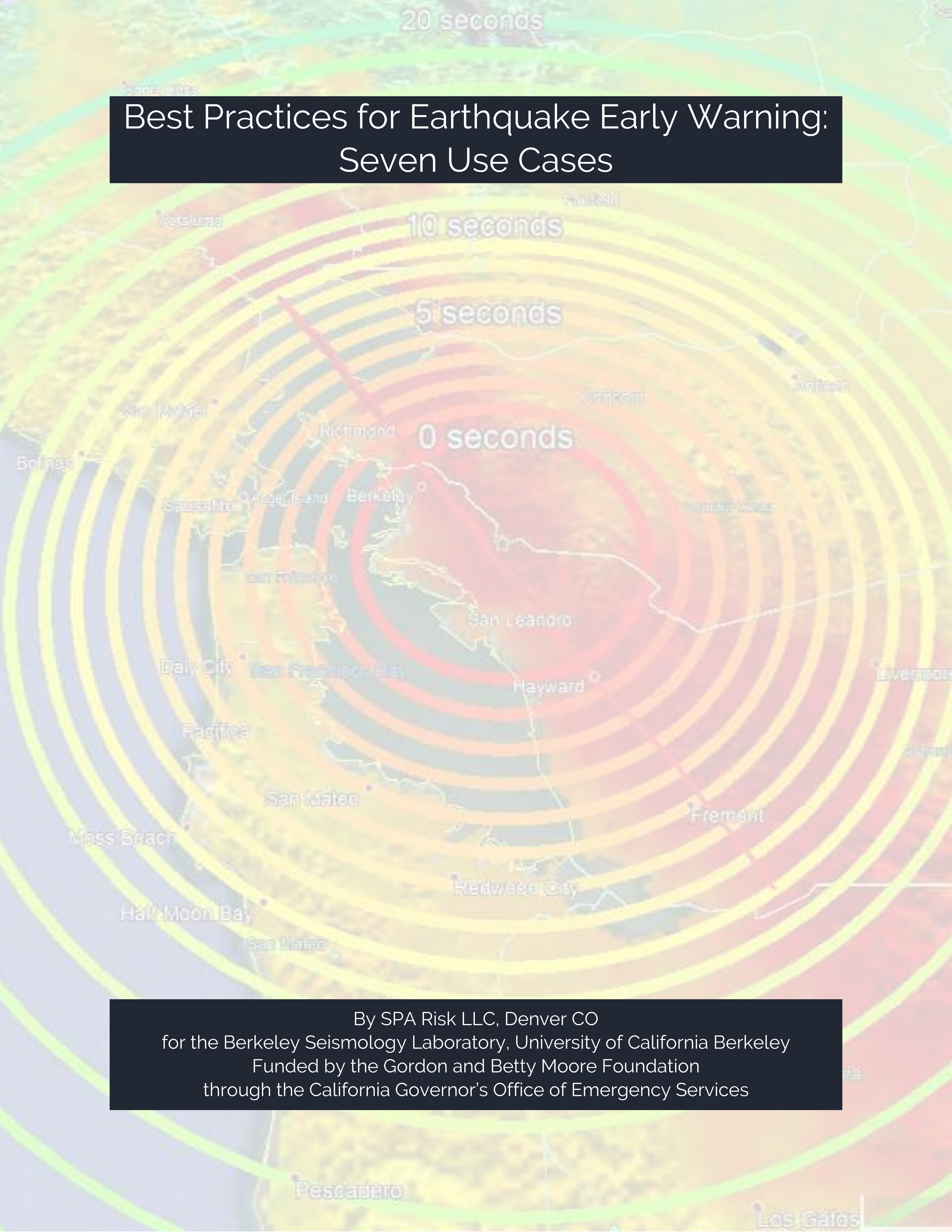
Best Practices for Earthquake Early Warning: Seven Use Cases



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Earthquake Early Warning Use Cases

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they have begun, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. Different organizations can use earthquake early warning in different ways. These pages briefly explain best practices for seven leading applications, called use cases:

1. Public warning for self-protective action
2. Audible warning for selected personnel
3. Medical activity alert
4. Elevator recall
5. Slow or stop a train
6. Open fire station bay doors
7. Protect utility of industrial activities

The next few pages answer key questions for people who need to decide whether and how to adopt earthquake early warning for their organization and their use case. They may have one, two, or more uses, but nobody has all seven, so the following use cases are written as stand-alone documents that address one use case. Each use case answers the same key questions:

- Essence of the practice: How would early warning work for me or my organization?
- Context: Under what conditions would it work?
- Realistic expectations: What degree of success can I expect?
- Clear behavior: What should one do when a warning arrives?
- Vulnerabilities: What can go wrong, and how can I prevent it?
- Implementation cost: What will it cost in time and money?
- Hardware and software requirements: What equipment or apps do I need?
- Training, education, and outreach: How do I make people aware of the system?
- Maintenance requirements: What should I do to make sure it will work when needed?
- Examples of past use: Which of my peers has implemented it and what was their experience?
- References: Where can one get more written information about earthquake early warning?

This compendium of best practices for earthquake early warning was prepared by some of the country's leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including the people who developed, implemented, and actually use earthquake early warning systems in real life.

Public Warning for Self-Protective Action

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to issue public warning for self-protective action. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

An audible warning, visible warning, or both are announced by a mobile app, by a public address system with speakers or sign-speakers, IP telephone, or dedicated appliance. The warning alerts people to imminent shaking and may instruct them to take immediate self-protective action such as drop, cover, and hold on.

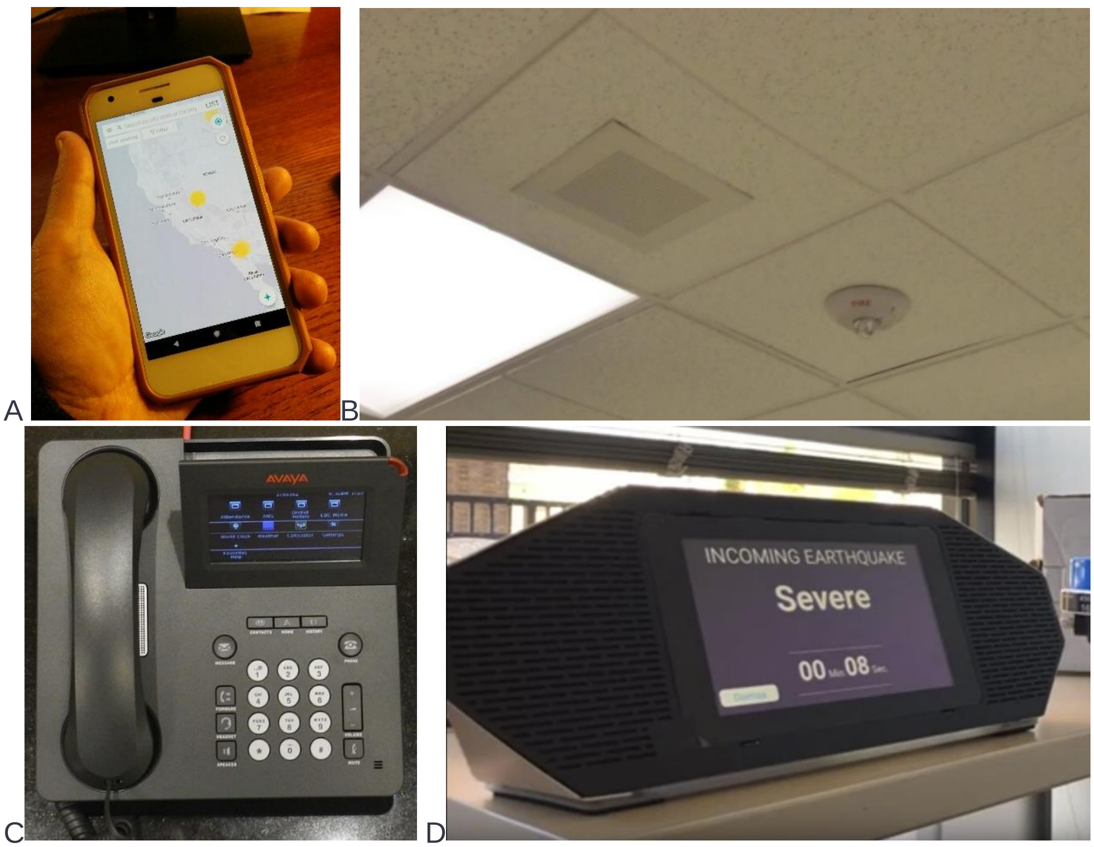

Figure 1. Public warning can be delivered by (A) MyShake mobile app, (B) public-address system, (C) IP telephones, or (D) a dedicated appliance. (Images: A,B: author, C: Geek2003 Creative Commons Attribution-Share Alike 3.0 Unported, D: A. Cantu, 2020, with permission.)

Context in Which the Use Case Would Work

Works in places with Internet connectivity and (except for mobile app) electric power. Audible-only warnings may not work in places with ambient noise that is so loud that an alarm cannot be heard.

Realistic Expectations

Some fraction of users will be so close to the rupture that strong shaking arrives before the alert can reach them. Some fraction of users will take self-protective action. In Japan during the 2011 Tohoku earthquake, approximately 75% of people successfully took self-protective actions. Comparable U.S. statistics are not yet available. See "potential vulnerabilities" below for reasons why people might not successfully take self-protective actions. Expect injuries to be reduced but probably not eliminated through successful self-protective action; efficacy statistics for injury avoidance are unavailable.

Clear Behavior

Drop, cover, and hold on, and its alternative context-dependent actions are described in https://www.earthquakecountry.org/step5/. These include instructions for people with disabilities, in bed, in a highrise, in a store, outdoors, driving, in a stadium or theater, near a shore, or below a dam. In settings with a lot of warning time, such as Mexico City, users may evacuate buildings.

Potential Vulnerabilities

The system may fail to send an alarm because of

- Unexpected changes to the upstream warning system's application programming interface (API) or insufficient time to accommodate the API change. At least one vendor is less susceptible to such changes.
- Electric power or Internet connectivity is lost or cut off before the message is received or announced. This potentiality can be somewhat mitigated by the vendor monitoring power and Internet connectivity and alerting end users to loss of power and by providing backup power to the alerting system.
- Prior unnoticed or uncorrected damage to hardware. Constant monitoring by the vendor and following a frequent testing protocol can mitigate this problem.
- Failure to start software. The same monitoring and testing protocols can mitigate this problem.

The warning may or may not arrive long enough in advance of strong shaking because of proximity to the rupture and because of the time it takes for successful self-protective action. If the warning arrives before strong shaking, people may still fail to take self-protective action for any of several reasons. Users may be unable to hear or understand the alarm because of:

- Sleep
- Ambient noise (a crowd, a loud television, etc.)
- Hearing or vision impairment
- Language
- Ambiguous message. All these possibilities can be mitigated to some extent.

Users may be slow to react appropriately because of:

- Unfamiliarity with earthquake early warning
- Lack of drilling or experience
- Checking first to see what everyone else is doing
- Waiting for an authority figure to confirm the message
- Bravado
- Belief that the alarm is a mistake, false alarm, or meant for others

Physical constraints may prevent effective self-protective action because of:

- Mobility impairment
- Crowded or enclosed space (e.g., movie theater lobby, jail cell, toilet stall)

- Prevented or injured by others taking inappropriate action

Users may take inappropriate actions because of

- Misinformation (believing in the triangle of life)
- Obsolete advice (standing in a doorway)
- Panic (such as attempting to run out of the building). Panic can be reduced by greater preparation, such as through regular drills, and possibly through occupants' confidence in the strength of their building.

Implementation Costs

The user's cost of a mobile app such as MyShake is negligible. Cost to implement an audible or visible alarm through a public address system: $10,000s if done through a vendor, potentially $1,000s if the earthquake early warning is added to an existing IP-controlled system. Unknown cost to develop in-house. Drilling can involve 1 hour of staff preparation per drill, perhaps annually. In 2018, Los Angeles Unified School District estimated a cost of approximately $450,000 to implement an earthquake early warning system to issue public audible warning for its 724,000 students, plus faculty and staff (Los Angeles Unified School District 2018, p 5-28), ().

Hardware and Software Requirements

In the case of a mobile app such as MyShake, the user must have an Android or iOS mobile device with Internet connectivity. In the case of public address (PA) systems, the user must have a public address system that is capable of receiving and relaying messages. Systems are available for both digital and analog public-address systems.

Training Materials, Requirements, and Frequency of Training

Earthquake Country Alliance provides ample training materials and requirements. See https://www.earthquakecountry.org/step5/. In the US, annual training on ShakeOut day seems to represent the consensus on appropriate frequency. See https://www.shakeout.org/ for information about ShakeOut day. Beaverton School District performs monthly evacuation drills with annual training and hands out 1-2 pages of written materials with the annual training.

Maintenance Requirements

Maintain the public address system, perform annual testing, and ensure remote monitoring and system updates from the vendor or in-house developer.

Examples of Past Use

Hoshiba (2014) summarizes a mail and web survey of 817 Tohoku District residents who received warnings by television, radio, cellphone, or other, prior to the 201 Tohoku earthquake. Most Tohoku District respondents (74.3%) successfully acted. Of this group, 61.6% had decided on the actions to take before the earthquake, and most of those (66.0%) succeeded or mostly succeeded in taking their pre-planned self-protective action. The survey does not quantify the efficacy of injury avoidance.

A condominium building in Marina del Rey, California, Regatta Seaside Residences, installed such a system in 2017. The alert is sent through the fire control system, causing it to emit an audible alarm through each of the building's 224 condominium units in the event of an imminent earthquake expected to cause shaking above a specified intensity. The building demonstrates that earthquake early warning has significant market value; a sales agent asserted that "someone could pay up to 10 percent more just to have that survival comfort." (Zhao 2017).

Biola University, in La Miranda, California, implemented a campus-wide audible alert system (Loumagne 2019), alongside seismic assessment and retrofits of campus buildings, new emergency response teams, awareness initiatives, guidebooks, a campus public address system, and a full functional emergency operations center with an emergency generator. For information, contact Biola University Office of University Communications, 1-562-903-6000.

People with a smart device in Los Angeles, California, can use ShakeAlertLA, an app for users physically in Los Angeles County (City of Los Angeles 2020, Lin 2020). People with a smart device anywhere in California can use the QuakeAlertUSA app, currently available for Android and iPhone.

Other facilities with such systems include Los Angeles City Hall and Los Angeles School District. Los Angeles School District implemented earthquake early warning at Eagle Rock High School in 2019 (Lara 2019). For information, contact Jill Barnes, Los Angeles Unified School District Emergency Services, jill.barnes@lausd.net, 1-213-241-3889.

Beaverton School District in Oregon is trying to implement a pilot program for drop, cover, and hold on, but it is also considering earthquake early warning for evacuation purposes. It is considering evacuation because of its inventory of about 50 highly vulnerable buildings and its unusual seismic setting: in the event of a rupture of the Cascadia Subduction Zone, schools could have up to 3 minutes of warning. Children exercise monthly in fire evacuation, and the school district has found that it can evacuate up to 90 percent of 40,000 building occupants within 90 seconds.

Vendors as of spring 2020 include at least the following, although more may currently exist and new vendors may enter the market after this writing:
Early Warning Labs, 1-424-238-0060, Info@EarlyWarningLabs.com
RH2, 1-541-326-4437, rballard@rh2.com
SkyAlertUSA, 1-415-374-1214, contact@skyalertusa.com
Valcom, 1-352-359-0579, rsteinberg@valcom.com

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City of Los Angeles (2020). Download the ShakeAlertLA Early Earthquake Warning App. https://earthquake.lacity.org/shakealertla [accessed April 28, 2020]

Hoshiba, M. (2014). Review of nationwide earthquake early warning in Japan during its first five years. In Wyss, M., and Shroder, J.F., eds., *Earthquake Hazard, Risk, and Disasters*. Elsevier, Waltham MA, p. 505-528

Lara, J. (2019). Eagle Rock High School becomes 1st in CA with earthquake warning system. Eyewitness News ABC 7, July 10, 2019, Los Angeles, California, https://abc7.com/earthquake-warning-lausd-school/5387518/ [accessed April 28, 2020]

Lin, R.G. II (2020). California's new early warning earthquake app features a shaking countdown. Los Angeles Times, February 12, 2020. https://www.latimes.com/california/story/2020-02-12/californias-new-early-warning-earthquake-app-features-a-shaking-countdown [accessed April 28, 2020]

Loumagne, J. (2019). Biola University to Host 2019 Great ShakeOut SoCal Full-Scale Exercise. Biola University, La Miranda California, https://www.biola.edu/events/2019/southern-california-2019-great-shakeout [accessed April 28, 2020]

Zhao, H. (2017). Quake alert system takes crack at condo tower. *Los Angeles Business Journal* June 9, 2017. https://labusinessjournal.com/news/2017/jun/09/quake-alert-system-takes-crack-condo-tower [accessed April 28, 2020]

Audible Warning for Selected Personnel

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to issue audible warnings to selected personnel. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

An audible warning is announced either through a radio system to select people carrying a two-way radio, or through the telephone system to select extensions. The warning instructs people to take immediate self-protective action against imminent ground shaking such as drop, cover, and hold on.

A

B

Figure 2. Audible warning for selected personnel can be delivered by (A) IP telephones or (B) two-way radios. (Images: A: Geek2003 Creative Commons Attribution-Share Alike 3.0 Unported, B: Evan Forester, public domain)

Context in Which the Use Case Would Work

This use case is intended for workplaces. During working hours, the warning triggers actions to take self-protective action.

Realistic Expectations

Some fraction of users will be so close to the rupture that strong shaking arrives before the alert can reach them. Some fraction of users will take self-protective action. In Japan during the 2011 Tohoku earthquake, approximately 75% of people successfully took self-protective actions. Comparable statistics for the U.S. are not yet available. See "potential vulnerabilities" below for reasons some people might not take self-protective action. Expect injuries to be reduced but probably not eliminated through successful self-protective action; efficacy statistics are unavailable.

Clear Behavior

Drop, cover, and hold on, and its alternative context-dependent actions are described in https://www.earthquakecountry.org/step5/. These include instructions for people with disabilities, in bed, in a highrise, in a store, outdoors, driving, in a stadium or theater, near a shore, or below a dam.

Potential Vulnerabilities

The system will not work if radio repeaters have lost power and battery backup has run down. It will not work on telephones without power or telephone connectivity.

The system may fail to send an alarm because of

- An IP phone system can suffer from added latency (longer time to transmit the message) and potential failure of software integration.
- Electric power or Internet connectivity is lost or cut off before the message is received or announced. This potentiality can be somewhat mitigated by the vendor monitoring power and Internet connectivity and alerting end users to loss of power and by providing backup power to the alerting system.
- Prior unnoticed or uncorrected damage to hardware. Constant monitoring by the vendor and following a frequent testing protocol can mitigate this problem.
- Failure to start software. The same monitoring and testing protocols can mitigate this problem.

The warning may or may not arrive long enough in advance of strong shaking because of proximity to the rupture and because of the time it takes for successful self-protective action. If the warning arrives before strong shaking, people may still fail to take self-protective action for any of several reasons. Users may be unable to hear or understand the alarm because of:

- Sleep
- Ambient noise (a crowd, a loud television, etc.)
- Hearing impairment
- Language
- Ambiguous message. All these possibilities can be mitigated to some extent.

Users may be slow to react appropriately because of:

- Unfamiliarity with earthquake early warning
- Lack of drilling or experience
- Checking first to see what everyone else is doing
- Waiting for an authority figure to confirm the message
- Bravado
- Belief that the alarm is a mistake, false alarm, or meant for others

Physical constraints may prevent effective self-protective action because of:

- Mobility impairment
- Crowded or enclosed space (e.g., movie theater lobby, jail cell, toilet stall)
- Prevented or injured by others taking inappropriate action

Users may take inappropriate actions because of

- Misinformation (believing in the triangle of life)
- Obsolete advice (standing in a doorway)
- Panic (such as attempting to run out of the building). Panic can be reduced by greater preparation, such as through regular drills, and possibly through occupants' confidence in the strength of their building.

Implementation Costs

Cost to implement an audible alarm through a radio system: low $10,000s. For an IP phone system, $1,000s. Drilling can involve 1 hour of staff preparation per drill, perhaps annually. Costs to develop a system in-house are unknown.

Hardware and Software Requirements

For a two-way radio system, the user must have such a system, and new hardware is added. For address through an IP phone system, only new software is required.

Training Materials, Requirements, and Frequency of Training

Earthquake Country Alliance provides ample training materials and requirements. See https://www.earthquakecountry.org/step5/. In the US, annual training on ShakeOut day seems to represent the consensus on appropriate frequency. See https://www.shakeout.org/ for information about ShakeOut day.

Maintenance Requirements

Maintain the radio or IP telephone system, perform annual testing, and ensure remote monitoring and system updates from the vendor.

Examples of Past Use

NBC Universal Studios and Cedars-Sinai Medical Center implemented such a system. At Cedars-Sinai, hospital staff were trained on how to react to the alerts and staff have gone through drills (Lin 2020, Healy 2014). For information, contact Early Warning Labs, 1-424-238-0060, Info@EarlyWarningLabs.com.

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Medical Activity Alert

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Essence of the Practice

A public address system sounds an audible alert in a medical setting (Figure 3). Medical professionals hear the alert, secure sharp instruments, and take action to protect themselves, patients, or both. These actions can vary widely by setting: in a phlebotomy lab, withdraw needles and activate the safety feature; in a surgery, protect a patient from dust and prepare the patient for a delay in the continuance of the operation; secure dangerous equipment such as cauterizers; in a nuclear medical laboratory, shut down hazardous equipment; in other settings, warn patients to take a safe seat or lock wheelchair brakes.

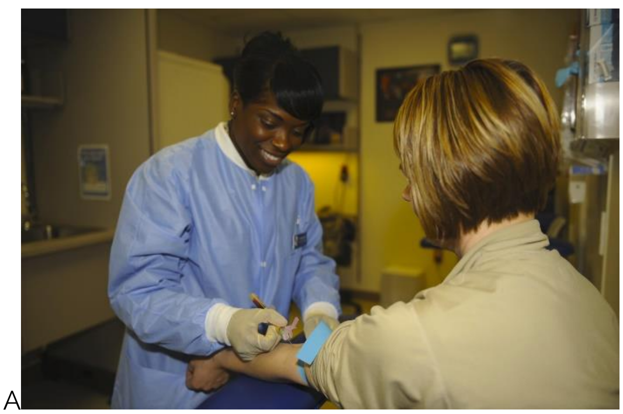
A 

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Figure 3. Earthquake early warning could help to avoid injuries in medical settings such as (A) phlebotomy labs. (B) Cedars-Sinai Medical Center in Los Angeles has implemented such a system (images: A: U.S. Air Force Senior Airman Ciara Wymbs, public domain; B: Jorobeq, 2006, Creative Commons Attribution 2.5 Generic)

Context in Which the Use Case Would Work

The use case works in a medical setting in which medical professionals are using potentially dangerous equipment on patients and it is practical to secure the equipment and the patient quickly to prevent harm before strong shaking arrives.

Realistic Expectations

Some fraction of users will be so close to the rupture that strong shaking arrives before the alert can reach them. With regular training, one can expect a reduction in staff and patient injuries and infection resulting from shaken or falling objects and hazardous materials. Do not expect complete success. Securing machinery and initiating protective actions can accelerate the resumption of patient care after the earthquake.

Clear Behavior

Varies by setting. Different behaviors apply to clinical, non-clinical, and surgical settings.

Potential Vulnerabilities

High turn-over rates for medical staff may make it difficult to maintain awareness for all staff. The human tendency to "just complete this one thing" (e.g., finish filling tubes) prior to taking immediate action could allow avoidable harm. Challenges with directing patients to take defensive action due to language barriers and disabilities, although this is addressed in employee training.

Implementation Costs

Cost to implement an audible alarm through a radio system can cost in the low $10,000s. For an IP phone system, $1,000s. Drilling can involve 1 hour of staff preparation per drill, perhaps once or twice annually. Can exceed $100,000 for a large medical complex because of the number of facilities in the complex and because of significantly greater regulation in medical facilities as opposed to others. System testing and certification and staff training and drills can take a few days. In some settings, staff might review emergency actions for a few minutes just prior to each operation.

Implementation costs vary by the products selected. The Cedars-Sinai Medical Center found that their early warning system hardware cost on the order of $20,000 per unit, with one unit required per fire panel. They found that fire panels can be interconnected for audio announcements, in which case only one unit is required for each such group of interconnected panels. A large hospital campus can require several units.

A hospital complex can provide hand-held radios to security personnel, plant operators, and others as a backup to announcements over the fire alarm system. In such a case, the hospital complex can connect the early warning system hardware to a two-way radio transmitter. Cedars-Sinai found that the equipment required to connect the early warning hardware to the two-way radio system cost on the order of $800.

Permits and engineering can cost $10,000 for a hospital building regulated by the California Office of Statewide Health Planning and Development (OSHPD). For a building not under OSHPD jurisdiction, local permitting can cost about $1,500 for mechanical and electrical diagrams of the fire-panel solution.

Hardware and Software Requirements

For a two-way radio system, the user must have such a system, and new hardware is added. For address through an IP phone system, only new software is required. Fire marshal and manufacturer certified interfaces are required. Installation requires approval and inspections by the fire department and possibly by state hospital regulators.

Training Materials, Requirements, and Frequency

State and federally compliant standard operating procedures must be prepared. Handouts and presentations must be prepared. The Center for Medicare and Medicaid Services accreditation requires end users to perform training and drills at least twice a year. Providence Health and Services posts signs in common spaces to inform visitors how to react in case of an alert. It also distributes an instructional video as part of ongoing education.

Maintenance Requirements

Typically, a vendor will perform the maintenance and test equipment annually and whenever attached equipment such as fire panels are changed or added. Code requirements and testing may vary by region: local fire departments and state regulators may each have their own requirements. This work may already be part of existing maintenance activities.

Example of Past Use

Cedars-Sinai Medical Center implemented such a system. Hospital staff were trained on how to react to the alerts and staff have gone through drills (Lin 2020). For information, contact Early Warning Labs, 1-424-238-0060, Info@EarlyWarningLabs.com or the Cedars-Sinai Emergency Management Department, 1-310-423-4336, disaster@cshs.org.

Providence Health and Services in the Oregon region (eight acute-care hospitals) will begin using such a system by the end of 2020. For more information, contact the Providence Health and Services Oregon Region Emergency Management, 1-503-893-7543.

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Elevator Recall

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to recall elevators before strong shaking arrives. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

In a large urban daytime earthquake, it is plausible that more than 20,000 people would be riding in elevators with the doors closed and the elevator in motion between floors when power is lost, trapping them until power is restored or until firefighters can extricate them, which could be days in either case (Porter 2018; Figure 4). To reduce this problem, elevator cars connected to the earthquake early warning system receive a warning signal, automatically stop at the closest floor, and open the doors, enabling passengers to safely exit the elevator before shaking occurs or power is lost. If desired, the elevator can be returned to normal operation after a temporary hold, e.g., after a few minutes.

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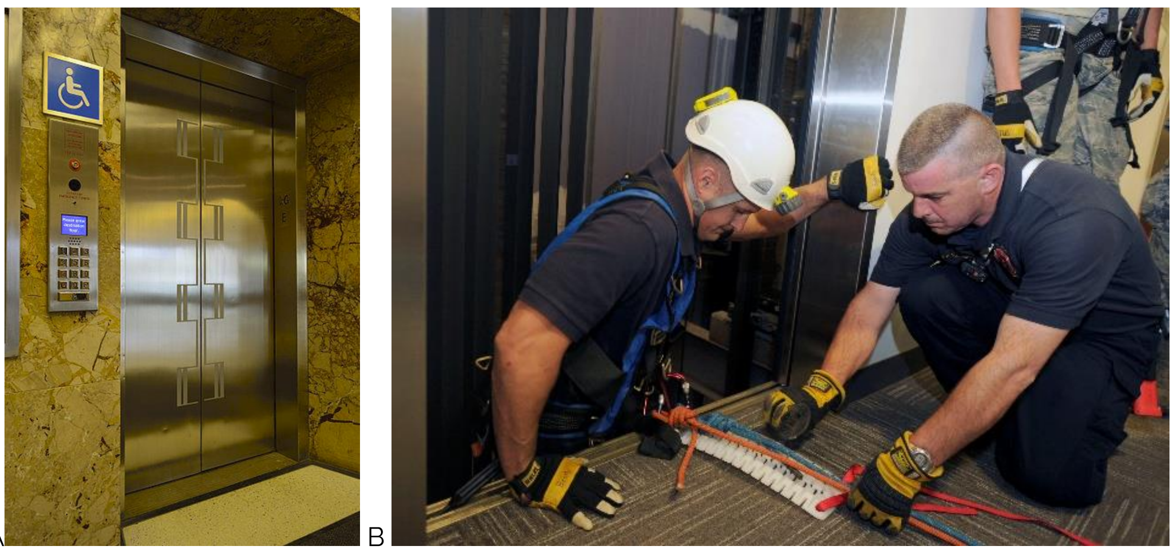

Figure 4. A. Elevators can lose power in earthquakes, trapping occupants. Automated elevator recall can move elevators to a nearby floor and open doors. B. In a large urban earthquake, it may take days or more before urban search and rescue personnel can extricate all occupants trapped in stalled elevators (Image credit: A. Raysonho @ Open Grid Scheduler / Grid Engine, 2015, Creative Commons CC0 1.0 Universal Public Domain Dedication; B. Public domain).

Context in Which the Use Case Would Work

In elevators over 10 floors, the system has worked with virtually every traction elevator that complies with current fire code. In elevators under 10 floors, earthquake early warning seems to be cost prohibitive because of current code requirements, permitting, and mechanical integration.

Realistic Expectations

For the best system, and elevators with emergency power, if the elevator successfully receives earthquake early warning alert, the user can expect successful recall for most elevators, even if the elevator is close to the epicenter.

Clear Behavior

No human behavior is involved. Elevators automatically move to a nearby floor and open their doors.

Potential Vulnerabilities

Power could be lost before the signal can reach the elevator or before the elevator can reach the nearest floor and open the doors. The upstream alerting system's application programming interface (API) can change and the earthquake occurs before the elevator warning system is adapted to the new API. Some vendors are more sensitive to API changes than others.

Implementation Costs

Cost is on the order of $10,000s for the first elevator, with an incremental cost of $1,000s per additional elevator.

Hardware and Software Requirements

In some cases, the elevator control software in the building is updated to receive earthquake early warning messages via the Internet and through application programming interface (API) in the control software. In other cases, a new hardware interface that is connected to a vendor's earthquake early warning system is added to the elevator control equipment in the building and activates elevator recall. At least one vendor requires that elevator recall be paired with audible notification within the building and within the elevator to instruct occupants how to behave, e.g., to drop, cover, and hold on, and to leave the elevator.

Training Materials, Requirements, and Frequency of Training

At least one vendor suggests distributing a brief handout to every occupant and employee explaining the nature of the earthquake early warning system and adding signage for visitors similarly explaining the system.

Maintenance Requirements

At least one vendor requires the building operator to perform annual testing. The vendor performs all software updates.

Examples of Past Use

Seismic Warning Systems installed elevator recall to four elevators at the San Francisco headquarters office of Pacific Gas & Electric (PG&E) Co. See Business Wire (2017) for details. Early Warning Labs is updating that system for PG&E. For more information, contact info@earlywarninglabs.com, 1-424-238-0060.

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United States Geological Survey, ch. M, p. 99-192, https://doi.org/10.3133/sir20175013 and www.sparisk.com/pubs/HayWired-2018-vol2.pdf [accessed May 6, 2020]

Slow or Stop a Train

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to slow or stop trains before strong shaking arrives. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

An earthquake early warning alert automatically causes trains to slow or stop, reducing the potential for derailment and injury. In the case of trains operated by a supervisory control and data acquisition (SCADA) system such as the Bay Area Rapid Transit (BART) system, an alert causes automatic braking to slow or stop the train (Figure 5). In the case of the Shinkansen, the alert causes power to be shut off at the substation, triggering emergency brakes on all moving trains. On BART, train control is switched from automatic (SCADA control) to manual (engineer control) mode. In the case of a train controlled by the engineer but equipped with positive train control, the alert will bring the train to a stop.

A  B 

Figure 5. Bay Area Rapid Transit implemented earthquake early warning in 2012. (A) Pittsburg/Bay Point-bound train approaching MacArthur station in June 2018. (B) BART Operations Control Center at the Lake Merritt station, 2016. (Image credits: A: Pi.1415926535 [2018] Creative Commons Attribution-Share Alike 3.0 Unported; B: public domain.)

Context in Which the Use Case Would Work

Earthquake early warning has worked in electrically powered trains where a SCADA system can shut off power at the substation and where loss of electric power automatically causes braking to occur (as in the case of the Shinkansen). It has also worked in trains under supervisory control (that is, where the vehicles are operated by a SCADA system as in BART). It seems likely to work in engineer-controlled trains with positive train control, but as of this writing, rail operations staff at the California High Speed Rail Authority are unaware of any transit or rail operator in North America using earthquake early warning technology with positive train control (M. Flores, Information Officer, California High Speed Rail Authority, written commun., May 6, 2020).

Realistic Expectations

Earthquake early warning has successfully fully stopped trains in real earthquakes. However, once an alert reaches a train, it can take 10 seconds for the train to decelerate by 30 mph, e.g., from 70 mph to 40 mph. Alerts can reach trains too late to fully stop. Thus, earthquake early warning will not prevent all damage and injury. But a speed reduction should reduce derailments and injuries and increase the chance of keeping the system operational. Expect some false alerts, in which trains stop without an earthquake occurring. False alerts have not caused significant delays for BART.

Clear Behavior

Train braking is automated; no human action is required. In the case of BART, operators can then determine whether it is safe to proceed, e.g., at slower speed, how far to proceed, and where to stop. In other cases, the alert could trigger preestablished response procedures based on distance, shaking, or other earthquake parameters.

Potential Vulnerabilities

The potential exists for false alarms and missed alarms from the earthquake early warning system, and for a train to be so close to the earthquake that strong shaking arrives before the warning. Even if the warning arrives promptly, it takes time to slow trains, so they could still be traveling fast when shaking arrives. Train control logic can involve incorrect assumptions about soil conditions and the shaking at which damage can occur. Thus, the railroad might set the system's action triggers too high or too low. The format of the alert occasionally changes (in California, formats have changed as frequently as every two months), and the earthquake could happen while the vendor or railroad is upgrading its system to support the changes to the alert format. The potential exists for earthquake shaking, ground failure, or other secondary hazards to damage viaduct, at-grade rail, or tunnels close to the train, so that despite slowing, vehicles are still damaged.

Implementation Costs

Software development to add modules to train control took BART a few hundred hours of labor. BART also spent some time consulting with experts. The total cost to BART amounted to less than $100,000. Metrolink expects implementation to cost on the order of $5 million.

Hardware and Software Requirements

BART required no additional hardware. BART information technology personnel wrote new control modules to receive and interpret the warning data, estimate ground motion at approximately 10 locations, and code train control decisions.

Training, Education, and Outreach

BART train operators and personnel at operations control centers perform quarterly drills related to several perils. Earthquake early warning is added to this training.

Maintenance Requirements

Minimal system maintenance is required, but the user should maintain an ongoing relationship with the provider of the alert data. The railroad must commit to long-term maintenance and monitoring to ensure that the system continues to operate as expected.

Examples of Past Use

Japan Rail introduced the Urgent earthquake Detection and alarm System (UreDaS) to its Shinkansen (bullet train) system in 1992. In the March 11, 2011, Tohoku earthquake, UreDaS triggered the emergency brakes on 27 bullet trains ten seconds before shaking reached mainland Japan. None of the 19 trains running through the affected area were derailed and no casualties were sustained on the trains (Southgate et al. 2013).

BART adopted earthquake early warning in 2012 (Associated Press 2012, KPIX5 2012). When the alarm is triggered, the train control system sends a speed restriction command to trains. This system removes human response time and can even slow trains down before the shaking arrives, depending on how far away the earthquake is centered. Trains are converted to manual operation with automatically reduced speed. They proceed slowly to the next destination to make sure that no tracks are damaged. Once tracks are deemed safe, trains resume normal operations. For more information, contact Chung-Soo Doo, BART Principal Engineer, Structural Engineering Division Maintenance & Engineering Department, CDoo@bart.gov, 1-510-287-4753.

The author could find no instance of earthquake early warning yet implemented in engineer-controlled trains with positive train control. Metrolink is in the process of adding earthquake early warning to its positive train control technology and expects to be the first such railroad. For more information, contact Metrolink, 1-800-371-5465.

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Open Fire Station Bay Doors

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to open fire station bay doors before shaking arrives. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

A device receives an alert via the Internet and through a hardware interface to the door controls, opens fire station bay doors to reduce the chance that doors will be jammed closed by racking damage to the station structure (Figure 6). The device also causes an audible alert to be broadcast through the fire station public address system, two-way radio system, or both.

Figure 6. Earthquake early warning can automatically open fire station bay doors and sound an audible alarm through the fire station public address system, two-way radio system, or both (image: anonymous, CC-BY-SA 4.0)

Context in Which the Use Case Would Work

The alert works in a facility with electrically operated doors. It will not work in places without power or without Internet connectivity.

Realistic Expectations

Expect success when the fire station is far enough away from the epicenter that the alert can be received before strong shaking arrives with enough time to open fire station bay doors. Overhead doors can take less than 10 seconds to open in some facilities and up to 20 seconds in others. Four-fold doors can take 7 seconds or more to open. Thus, when an earthquake occurs in a large metropolitan area, many fire stations may be so close to the epicenter that fire station bay doors do not completely open before strong shaking arrives; some fire stations will experience strong shaking before the alert arrives and doors begin to open.

Clear Behavior

No human action is required. Doors open automatically.

Potential Vulnerabilities

The system may fail to send an alarm because of

- Unexpected changes to the upstream warning system's application programming interface (API) or insufficient time to accommodate the API change. At least one vendor is less susceptible to such changes.
- Electric power or Internet connectivity is lost or cut off before the message is received or the doors can fully open. This potentiality can be somewhat mitigated by the vendor monitoring power and Internet connectivity and alerting end users to loss of power and by providing backup power to the alerting system and to the doors.
- Prior unnoticed or uncorrected damage to hardware. Constant monitoring by the vendor and following a frequent testing protocol can mitigate this problem.
- Failure to start software. The same monitoring and testing protocols can mitigate this problem.
- The alert may or may not arrive long enough in advance of strong shaking because of proximity to the rupture and because of the time it takes to open doors.

Implementation Costs

One vendor charges in the low $10,000s for initial installation at a single facility, plus $1,000s per year for maintenance, with economies of scale at multiple locations.

Hardware and Software Requirements

A proprietary hardware interface controls the bay doors. The device also includes an audio output that announces an alert through the public address system in the fire station, the two-way radios, or both.

Training, Education, and Outreach Materials

None is required.

Maintenance Requirements

Maintain the public address system, perform annual testing, and ensure remote monitoring and system updates from the vendor.

Examples of Past Use

The Los Angeles County Fire Department installed an early warning system in station 51 that opens firehouse doors. A successful test was performed in September 2014 (Xia and Lin 2014). Interested readers can contact the Deputy Chief of Special Operations & Hazardous Materials, California Governor's Office of Emergency Services, 1-916-845-8751, or Early Warning Labs, 1-424-238-0060, Info@EarlyWarningLabs.com. Menlo Park, California implemented such a system in 2019 (Perry 2019). Interested readers can contact Alejandro Cantu, SkyAlert, 1-415-374-1214, alejandro@skyalertusa.com. Vendors and user contact people may change in the near term.

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Protect Utility or Industrial Activities

Earthquakes threaten 1 in 4 Americans. Earthquakes currently cannot be predicted, but people can act beforehand to reduce the harm when earthquakes occur. One way to do that is to implement earthquake early warning, which refers to a system that rapidly detects earthquakes just after they begin, quickly calculates how strongly the ground will shake, and notifies people or systems just a few kilometers or tens of kilometers from the epicenter before the shaking arrives. With a few seconds' warning, people and systems can take useful protective actions. The next few pages answer key questions for people deciding whether and how to adopt earthquake early warning to protect utility or industrial activities. This material was written by leading earthquake engineers, seismologists, emergency managers, and other pioneers of earthquake early warning, including people who developed, implemented, and use earthquake early warning in real life.

Essence of the Practice

An Internet-connected device (sometimes called a monitor or control) listens for the earthquake early warning message. When the message is received, the software evaluates the alert to determine whether it meets the criteria for acting. If so, the device operates an electrical relay, which either starts or stops electric equipment. The relay could be attached to almost any downstream device to cause an automatic action. For example, at a water or wastewater utility, the monitor could cause an outlet valve to close at a water supply reservoir, protecting the reservoir from draining through damaged buried pipe lower in the system. Other examples include stopping rotating machinery, opening a door, stopping a magnetic resonance imaging machine, sounding an alarm, or shutting off power to prevent an electrical fire.

Figure 7. Earthquake early warning can automatically close or open valves, start or stop electrical equipment, open doors, sound alarms, or shut off power to protect water and wastewater systems. (Image: Khepster, 2008, Creative Commons Attribution 3.0)

Context in Which the Use Case Would Work

The use case works in a facility with power and an Internet connection and where one wants to stop or start electrical or hydraulic equipment or operate valves automatically, without human intervention. It does not appear to be constrained by geographic location, time of day, or culture. The use case does not address the situation where a choice of actions must be made based on additional information beyond what is included in the early warning message.

Realistic Expectations

Expect approximately the same reliability as any automated supervisory control and data acquisition (SCADA) function, bearing in mind that earthquake shaking can damage equipment and other vulnerabilities listed below. Some actions can take several seconds or longer, such as closing a valve on a large-diameter pipe. Some locations will be too close to the epicenter to complete the action before the arrival of strong motion.

Clear Behavior

All the actions are automated and determined at the time of installation or as the user updates the actions that the device initiates. When a warning arrives, the device activates an electrical relay, for example one attached to a hydraulic or electrical actuator that positions existing isolation valves.

Potential Vulnerabilities

The potential exists for false alarms and missed alarms from the earthquake early warning system, and for the facility in which the device is installed to be so close to the earthquake that strong shaking arrives before the warning. Even if the warning arrives promptly, slow telemetry or and the large number of turns required close large valves could limit the number of actions that can be taken before shaking arrives. All mechanical and electrical equipment require testing and maintenance and eventually become inoperative. The potential exists for user error as well: the user might accidentally set the device's tolerances or non-fail-safe actions too high or too low and not learn of their error until after the earthquake. The user might accidentally shut off the device prior to the earthquake. The format of the alert occasionally changes (to date, on the order of every two months), and the earthquake could happen while the vendor is dealing with that change. The potential exists for earthquake shaking, ground failure, or other secondary hazards such as sloshing or seiche to damage the equipment being controlled. The user can manage the potential for such damage by having a structural engineer use the Federal Emergency Management Agency's document FEMA E-74 to examine and seismically secure equipment (Federal Emergency Management Agency 2011).

Implementation Costs

For a typical water system with a SCADA system and that has completed state-mandated requirements for emergency response planning, the systems currently range in total cost from $15,000 to $25,000, including design, hardware, software, startup, and training, but excluding valve actuators and other water-system hardware. The industry is young. Costs could vary as new vendors and products enter the market. A few large utilities may have the resources to develop and implement such a system in house.

Hardware and Software Requirements

The system requires the monitor or control, which is connected to the Internet and to the SCADA system. Absent a SCADA system, or if required for Internet security, a separate monitor or control can be connected to the Internet and to each piece of equipment that will be controlled.

Training Materials, Requirements, and Frequency of Training

At a minimum, the developer (whether a vendor or an in-house engineering team) trains SCADA operators on how to use and maintain the hardware and software when the system is first installed and again when new SCADA operators start work. Alternatively, the vendor or in-house developer may provide written documentation and the user can ensure that all SCADA operators read and learn the operation. Most users over the course of the first year of use have not requested refresher training from one vendor, although that might change as more vendors and devices enter the market and the length of use in practice grows.

Maintenance Requirements

The user generally does not have to maintain the device if the vendor or the in-house developer does so.

Examples of Past Use

Northeast Sammamish Sewer and Water District (2020) in Sammamish, Washington installed such a system on its water distribution system (Porter 2018). The system controls water wells, water pump stations, and water storage reservoirs. For example, the Crest Reservoir is a buried 0.5-million-gallon reservoir that cannot deliver water by gravity to the water system; water must be pumped. The earthquake early warning system shuts down the pumps at the pump station, preserving the pumps and the water in the reservoirs. In the event of an emergency, people could fill up jugs, etc. at the reservoir.

Lakewood Water District in Lakewood, Washington, has a similar system, monitoring wells, pump stations, and reservoirs (Lakewood Water District 2020).

Silverdale Water District in Silverdale, Washington, also monitors wells, pump stations, and reservoirs (Silverdale Water District 2020).

The City of Anacortes, Washington, monitors a water treatment plant. The device will shut off various treatment processes: blowers, pumps, chemical injection system, digesters, among other actions. (Anacortes City Council 2019).

Currently, Varius Inc. sells such a device, a commercial product called OmniMonitor. For more information, contact the Engineer in Responsible Charge Dan Ervin, dan.ervin@variusinc.com, 1-425-269-8479.

RH2 sells a commercial product called Advanced Seismic Control (ASC). For more information, contact RH2's Seismic Resilience Planning Project Manager, 1-541-665-5233.

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