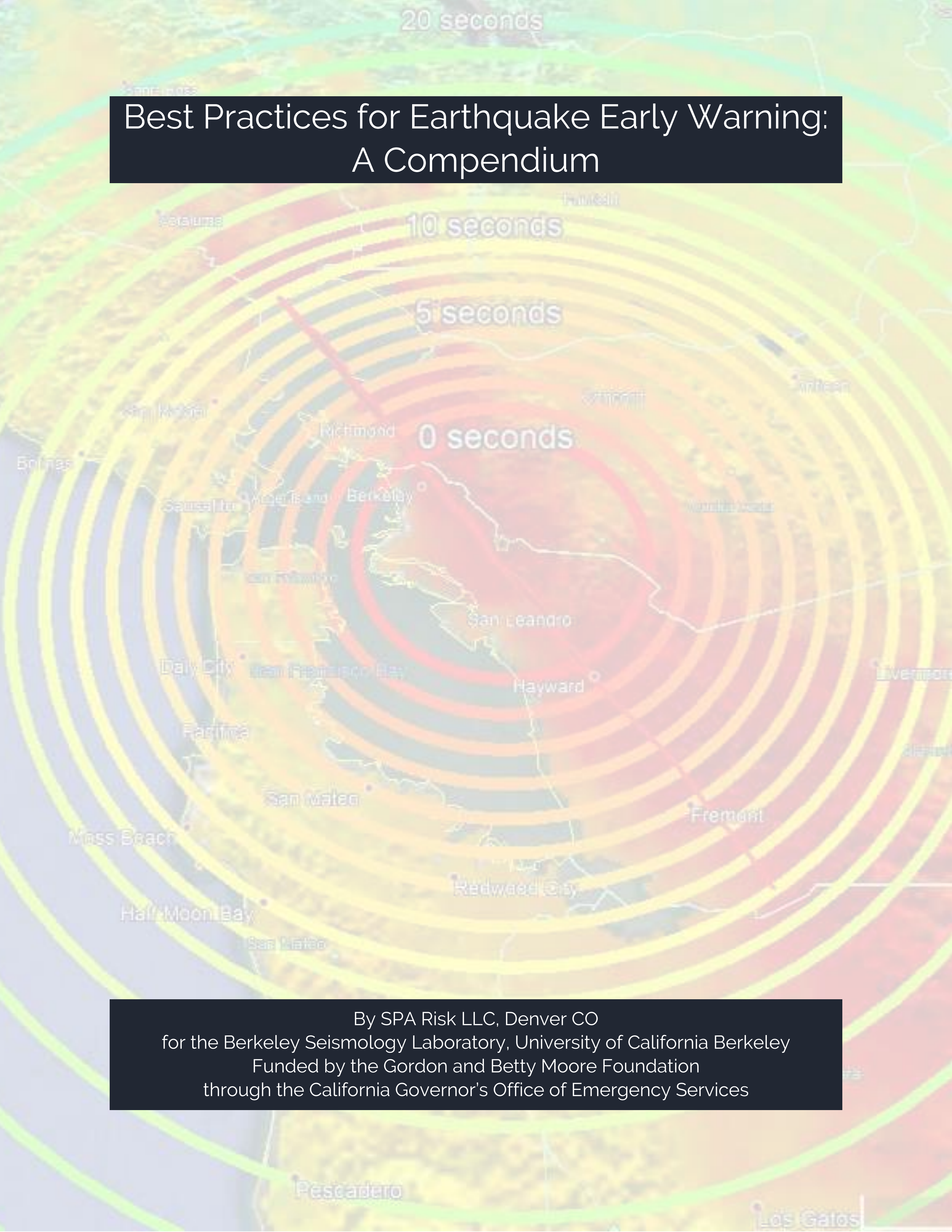
Best Practices for Earthquake Early Warning: A Compendium



By SPA Risk LLC, Denver CO
for the Berkeley Seismology Laboratory, University of California Berkeley
Funded by the Gordon and Betty Moore Foundation
through the California Governor's Office of Emergency Services

NOTICE: The results presented here have been generously funded by Gordon and Betty Moore Foundation Moore Foundation and managed by the California Governor's Office of Emergency Services and the Berkeley Seismology Laboratory, University of California Berkeley. This report is intended for the benefit of public- and private-sector individuals and organizations interested in better understanding the benefits of earthquake early warning. While representatives of the University of California and others provided data and expertise to the project team, their input was merely informative. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of the study funders or other participants. Additionally, SPA Risk LLC nor any of its principals, employees, or subcontractors make any warranty, expressed or implied, nor assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process included in this publication.

SUGGESTED CITATION: Porter, K.A. (2020). Best Practices for Earthquake Early Warning: A Compendium. SPA Risk LLC, Denver CO, 50 p., www.sparisk.com

Best Practices for Earthquake Early Warning: A Compendium

PREPARED FOR

The Berkeley Seismology Laboratory, University of California Berkeley
under Purchase Order BB01219869
and the California Governor's Office of Emergency Services

PREPARED BY

SPA Risk LLC
Denver Colorado

WITH THE SUPPORT OF

The Gordon and Betty Moore Foundation

Executive Summary

Earthquake early warning refers to the rapid detection of earthquakes, real-time assessment of the shaking hazard, and notification of people prior to shaking. Applications date to the 1980s Japan and several countries now have active systems. But earthquake early warning is young in the United States. A notable example: the California Earthquake Early Warning System (CEEWS) debuted on October 17, 2019. CEEWS marries a smartphone application with traditional alert and warning delivery methods such as Wireless Emergency Alerts (WEA). It uses ground motion sensors across the state to detect earthquakes before people can feel them and notifies Californians so that they can drop, cover, and hold on before earthquake shaking reaches them. The present document aims to help emergency managers and other executives learn about earthquake early warning and to decide whether to implement it. This document presents a set of stand-alone 2- to 4-page documents that explain one application, one use. A non-technical reader can read them in a few minutes with little prior knowledge of earthquake early warning. Each briefly explains the following:

- Essence of the practice
- Context in which the use case would work
- Realistic expectations for degree of success
- Clear behavior required from people who would use it
- Potential vulnerabilities that might cause the system to fail
- Implementation costs, on an order-of-magnitude basis
- Hardware and software requirements
- Training, education, and outreach requirements
- Maintenance requirements
- Examples of past use
- References cited

Seven use cases are offered here

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 or industrial activities

Several vendors offer hardware, software, and support for earthquake early warning. Governments are also involved, which raises concerns about equity between vendors and the appearance of a commercialism. To ensure a reasonable degree of equity, the author has attempted to speak with and name most current vendors active in the earthquake early warning market in the United States. New vendors may enter the market in the next few years and existing ones may exit. This document may quickly become obsolete or require frequent updates. But it seems better to provide valuable data with a short life than to omit short-term information and risk being useless.

Project Participants

Principal Investigator

Dr. Keith Porter, Principal, SPA Risk LLC, Denver, Colorado

UC Berkeley Project Manager

Dr. Jennifer Strauss, External Relations Officer, Berkeley Seismology Laboratory, University of California Berkeley

Facilitators

Emily Holland, Communication and Outreach Strategist, California Earthquake Early Warning Program, California Governor's Office of Emergency Services, Mather, California
Dr. Mouse Reusch, Regional ShakeAlert Coordinator, Department of Earth and Space Sciences, University of Washington, Seattle, Washington
Rachel Sierer Wooden, Seismic Hazards Branch Chief, California Governor's Office of Emergency Services, Mather, California
Bill Steele, Director of Communications and Outreach, Pacific Northwest Seismic Network, University of Washington, Seattle, Washington
Margaret Vinci, Manager, Office of Earthquake Programs, Seismological Laboratory, California Institute of Technology, Pasadena, California
Lucy Walsh, ShakeAlert Regional Coordinator, Earth Sciences Department, University of Oregon, Eugene, Oregon

Expert Users and Developers

Jill Barnes, Coordinator, Emergency Services, Los Angeles Unified School District, Los Angeles, California
Josh Bashioum, CEO, Early Warning Labs, Santa Monica, California
Alejandro Cantu, CEO, SkyAlert, Berkeley California
Chung-Soo Doo, Principal Engineer, Structural Engineering Division Maintenance & Engineering Department, Bay Area Rapid Transit, Oakland California
Dan Ervin, Executive Vice President, Engineer in Responsible Charge, Varius Inc.
Ah Sue Fiailoa, Senior Manager, Train Control Systems, Southern California Regional Rail Authority, Los Angeles, California
Paul Jewell, Emergency Coordinator, Beaverton School District, Beaverton, Oregon
Jeremy Kirchner, Emergency Services Manager, NBCUniversal, New York, New York
Rachel Lanigan, Project Manager, RH2 Engineering, Medford, Oregon
Roberts McMullin, Associate Civil Engineer, East Bay Municipal Utility District, Oakland, California
Patrick Rochon, Injury Prevention Coordinator Emergency Preparedness Coordinator, Providence Health & Services, Medford, Oregon
Roger Steinberg, Product Marketing Manager, Valcom, Roanoke, Virginia
Ryan Tuchmayer, Associate Director, Disaster Preparedness & Response, Cedars-Sinai Health System, Los Angeles, California

Acronyms and Abbreviations

API	application programming interface
Cal OES	California Governor's Office of Emergency Services
CEEWS	California Earthquake Early Warning System
COVID-19	Coronavirus Disease 2019
EEW	Earthquake early warning
FEMA	Federal Emergency Management Agency
g	Acceleration due to gravity, 9.81 meters per second per second
HMGP	Hazard Mitigation Grants Program
IP	Internet Protocol
km	kilometers
km/sec	kilometers per second
M	magnitude
mph	miles per hour
M_W	moment magnitude
PA	Public address
SAS	Seismic Alert System (of Mexico City)
SCADA	Supervisory control and data acquisition
sec	seconds
UC	University of California
UreDaS	Urgent earthquake Detection and alarm System
U.S.	United States
USGS	United States Geological Survey
WEA	Wireless Emergency Alert

Contents

Index of Figures

1. Introduction

1.1 Earthquake Early Warning

Electronic signals travel near the speed of light, 300,000 km/sec, fast enough to go to the moon and back in about two seconds. Seismic waves travel 75,000 times slower, up to about 4 km/sec. The difference means that once an earthquake occurs, it can be detected by instruments in the epicentral region, which can send an advance warning that hugely outpaces the seismic waves and can be received by people just a few kilometers or tens of kilometers from the epicenter. That advanced warning gives the people a few seconds to protect themselves before strong earthquake shaking reaches them.

With a few seconds' warning—called earthquake early warning—tens of thousands of people can drop, cover, and hold on before the floor starts to shake beneath their feet and the furniture starts to fall on their unprotected bodies. Thousands of elevators full of passengers can stop at the nearest floor and open their doors. Dozens of surgeons can withdraw sharp instruments from patients. Several fast-moving trains can slow to a stop. Numerous other uses exist, and still more will certainly be invented.

Earthquake early warning in the United States can prevent deaths and injuries, reduce urban search and rescue demands, and prevent property losses. The risk-mitigation benefits of earthquake early warning in just one large metropolitan earthquake can reach hundreds of millions of dollars, perhaps billions, and avoid thousands of injuries or more. At least, that opportunity is one of its many potential benefits when earthquake early warning is integrated into people's homes, workplaces, and public spaces.

The earthquake early warning systems addressed include the multi-state U.S. Geological Survey's ShakeAlert® (2019) and California Earthquake Early Warning System (CEEWS, California Governor's Office of Emergency Services 2019), among others. The systems comprise sensors, field telemetry, computers and software that process the telemetry to issue alert messages. They also include the messages that are sent to devices and end users and the software that displays on acts on those messages. One form of the end-user display software, called ShakeAlertLA, was released on December 31, 2018 (City of Los Angeles 2019a) to users within Los Angeles County.

But if earthquake early warning were the telephone system, the situation in the United States would be like having the telecommunications satellites in orbit, thousands of central offices with millions of switching computers installed in major cities, and cell towers distributed across the countryside, but few people have cellphones, there are no Apple stores, and almost everybody communicates via postal mail. Well, not quite so bad as that. Seven countries are farther along: Japan, Mexico, Turkey, Romania, China, Italy, and Taiwan. They have solved the second half of the problem and are already well up the learning and adoption curve. The United States is still near the bottom, beginning the climb, under the leadership of Cal OES, the Moore Foundation, UC Berkeley, and others. This short document aims to serve as a guide to the top, summarizing best practices of how to adopt and use earthquake early warning, drawing on the lessons of past use in other counties and the advice of U.S. and foreign experts.

1.2 Objectives

This project gives current and future end users of earthquake early warning a best-practices guide to implementing solutions. It draws on a survey and follow-up conversations with a broad stakeholder group to identify use cases for each of many user sectors, documenting survey respondents' proposed best practices as applied to that use case. These use cases are compiled for further evaluation by a small working group of advanced users and facilitators. The working group has edited the respondents' recommendations, technical requirements, estimated implementation costs, and recommendations for implementation.

1.3 Organization

This section introduced the problem addressed by this compendium. Section 2 presents notable literature on the promise and practice of earthquake early warning, organized under a framework for best practices as recommended by management science. Section 3 presents the research plan. Section 4 documents use cases including costs and outreach opportunities. Section 5 documents references cited.

2. Literature Review

2.1 Scholarly Literature

This chapter is intended for seismologists, engineers, emergency planners, and software developers, so it seems worthwhile to begin by reviewing exactly what is meant by "best practice," when the term is used by the people who invented it or most commonly use it.

2.1.1 What Does "Best Practice" Mean and What are its Elements?

In the field of business administration, and particularly strategic management, best practice means "A method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark." (WebFinance, Inc., 2019). Bardach (2004) offers a theoretical framework for establishing best practices, including five steps:

(1) ***Realistic expectations.*** Develop realistic expectations, because the practice may not actually solve the problem it is supposed to address. Good research does not necessarily produce good outcomes.
(2) ***Clear behavior.*** Specify clear and concrete behavior that solves the problem or achieves the goal under consideration while taking advantage of an idle opportunity at a low cost and little risk.
(3) ***Essence of the practice.*** Identify the essence of the practice while allowing flexibility for how it is implemented so it remains sensitive to local conditions.
(4) ***Vulnerabilities.*** Describe potential vulnerabilities that could lead the practice to fail either through poor management or inherent weakness in the practice itself. And
(5) ***Context.*** Ensure that the context from which the practice is derived is comparable to the context in which it will be applied.

What does the scholarly literature on earthquake early warning recommend on these five heads? The scholarly literature is vast, so for convenience and practicality, let us consider a few large compilations, and simply filter prominent aspects of their contents through Bardach's framework. A few large or recent works were examined for this literature review. By necessity, approaching the literature review this way will almost certainly overlook many seminal or otherwise important works.

Wenzel and Zschau (2014) offer a recent compilation of 19 works on various aspects of early warning systems and for earthquakes, tsunamis, landslides, and volcanos. Allen et al. (2009) offer a wide-ranging literature review as part of their introduction to a special issue in Seismological Research Letters on earthquake early warning. Gasparini et al. (2007) compiled 17 international works focused on earthquake early warning, covering mitigation, seismology, automated decision-making, and specifics of several systems. Zschau and Kuppers (2003) compiled 100 works on various aspects of early warning systems, including organization, communication, various use cases, several different perils (earthquake early warning one of many), issues of economic development and nation size, and future technology needs. A few other convenient or relevant works that fall outside the scope of the foregoing references were also considered.

2.1.2 Realistic Expectations

Different target groups have different information needs. Wachter and Uslander (2014): "Effective targeted warning dissemination depends on a detailed description of the information needs of potential target groups. Finally, this prepared information is disseminated via dedicated channels." Wachter and Uslander (2014): "The specifications [of a warning system] typically have to satisfy expectations of readers with different competences and technical backgrounds." Iervolino (2014):

Frequency of false alarms should be allowed to vary by application, e.g., DCHO can tolerate more false alarms than shutting down power plants.

Woo and Marzocchi (2014) consider but dismiss the possibility that earthquake early warning can be used for evacuation purposes: “Realistically, evidence of an imminent earthquake will never be unambiguous enough to warrant the evacuation of even a small town.” Wyss et al. (2014) make an opposite claim about schools: “Although it is generally not recommended to run outside of buildings in a city in case of earthquakes because of falling debris, schools may be successfully evacuated because they are surrounded by open areas for recreation and sports. Also, in some earthquake prone regions, like in Lima, Peru, most schools have only two floors, which allows evacuation in 5–15 sec.” However, anyone who has seen busy classrooms and school hallways at the beginning of recess may reasonably doubt that any activities start in a classroom and finishes 15 seconds later in the playground.

Training must be adequately funded. Cuellar et al. (2014): “If dissemination and training campaigns launched among the population exposed to natural hazards continue to be insufficiently funded, any early warning system will be exposed to failure to comply with its main objective for which it was designed.”

There is a zone too close to the earthquake source for people to receive a warning before shaking reaches them. Earthquake early warning can provide up to tens of seconds of warning. Allen et al. (2009) point out that regional earthquake early warning can provide “tens of seconds of warning to areas that can expect damage, [with a no-warning] zone around the epicenter where no warning is available [because of] the time lost transmitting data to a processing center, processing the data, and sending out a warning.”

There will be missed events and false alarms. Allen et al. (2009) point out that the first operational earthquake early warning system, Mexico’s SAS system, missed two events and had one false alarm among 65 public and preventative warnings (a public warning alerts users to a strong earthquake, meaning $M \geq 6$; a preventative warning to a moderate earthquake, $5 \leq M < 6$). Bose et al. (2014) offer statistics of ElarmS between March and December 2011: 77% success rate (message sent in a real earthquake) and 25% false alert rate. Strauss (project manager of the present project, written commun., Oct 16, 2019) advises that improved station distribution should improve message sensitivity and specificity, that is, increase probabilities of sending a message when earthquake shaking is coming and reduce probabilities of sending false alarms.

There will be imperfect success in safety systems. Continuing the topic of realistic expectations, Allen et al. (2009) discuss Japan’s front-detection earthquake early warning system and its use to shut off power to Shinkansen bullet trains. The system successfully shut power and triggered automatic braking of four trains during the 2004 Niigata Ken Chuetsu earthquake, but one train still derailed, although only one of its carriages came off the tracks.

People will imperfectly respond to warnings. Twigg (2003) warns that “even where EW systems do deliver timely and accurate warnings, people at risk may not respond as desired or expected. This indicates that there is a third key element of success in [early warning] systems, that is often missing: appropriate communication of warnings, based on an understanding of communities' perceptions and needs.” It also suggests that developers should not expect people to respond as desired even after warnings have been appropriately communicated. Behavioral economic theories such as Von Neumann and Morgenstern’s utility theory and Kahneman and Tversky’s prospect theory repeatedly diverge systematically from what actual people do, in part because they treat people using relatively simple, homogeneous, and unrealistic caricatures, not as the infinitely diverse, changeable, unpredictable, messy beings we are.

As the U.S. government increasingly engages in science denial, Americans may come to distrust warnings. Segreda (2003) warns that in Costa Rica, political forces caused public distrust of government statements about floods. The public had come to perceive that the government and nongovernmental organizations were not giving "due attention to their needs," which influences their behaviors and perceptions of risk. Not long ago, public distrust of government might not have been an issue in the United States. But the Trump White House has been lying about science warnings. On September 4, 2019, the White House released a video in which President Trump displayed a NOAA map of the forecast track and intensity of Hurricane Dorian, which the president had altered with a black Sharpie, apparently in an effort to justify an earlier, erroneous tweet (Cappucci and Freedman 2019). He then coerced NOAA officials into endorsing the falsified track forecast (Baker et al. 2019). Politicized science has infected FEMA (Gonzalez 2018) and the US Geological Survey as well (Waldman, 2019), with the Trump administration successfully editing the FEMA strategic plan and USGS news releases to remove mentions of climate change. Politically-stoked skepticism about science in general could bleed over into earthquake early warning. Association with these agencies and simple confusion could reduce public trust in Cal OES, CGS, and UC Berkeley. Developers of U.S. earthquake early warning may have to work to counter increasingly justifiable suspicion of government warnings.

2.1.3 Clear and Concrete Behavior

Drop, cover, and hold on, and variations. Allen et al. (2009) recap the individual actions that the Japan Meteorological Agency urge people to take, including drop, cover, and hold on; slowing one's automobile, and holding on to straps and handrails in trains. Porter and Jones (2018) estimate the number of nonfatal injuries that can be avoided in a particular, large metropolitan earthquake through the combination of earthquake early warning and drop, cover, and hold on (about 1,500 as an upper bound given a hypothetical M_w 7.0 Hayward Fault earthquake on a workday afternoon). The study considers the clear and concrete actions shown in training materials that Earthquake Country Alliance and ShakeOut.org disseminate.

Step away from hazards at the workplace. Allen et al. (2009) recap how the "Kajima Corporation uses the warnings at its facilities…. On construction sites, workers move away from or out of hazardous locations." Allen and Melgar (2019) suggest that individuals receiving an earthquake early warning could "step away from hazards at the workplace."

Automated shutdown of hazardous chemical systems. Allen et al. (2009) mention that the OKI semiconductor factory installed "an automated earthquake early warning response system that shuts down hazardous chemical systems and moves sensitive equipment to a safe position."

Automated actuation of shut-off valves in natural-gas pipelines. Allen et al. (2009) describe a control system for natural gas distribution: "the Istanbul Natural Gas Distribution Network… plans to use the system to actuate shut-off valves."

Automating braking and cut-off of power for rail systems. Cuellar et al. (2014) list behaviors of Mexican rail operators—the Public Electric Transportation System and the METRO—using the Seismic Alert System of Mexico City (called SAS). "In case of a seismic warning, the manager of the control center gives proper instructions for the train operators to stop in the nearest station or delay their start and keep the doors open for passengers' safety." Several authors mention Japanese rail actions: electric power shutdown and emergency brake activation (e.g., Nakamura and Tucker 1988, Nakamura 2004, Allen et al. 2009)

Insert control rods in nuclear reactors. In Bucharest, Romania, Allen et al. (2009) note that an earthquake early warning system "gives warning to the Horia Hulubei National Institute of Physics and Nuclear Engineering, where it is used to place a nuclear source in a safe position." Gasparini and Manfredi (2014) mention how the Ingalina nuclear power plant in Lithuania used earthquake early warning: "The system generated an alert when the ground acceleration at one station exceeded a threshold value of 0.025 g. The alarm was meant to be used to stop nuclear reactions by the insertion of control rods."

Stop elevators. Allen et al. (2009) describe earthquake early warning systems to control elevators: "At Kogakuin University in Tokyo, elevators currently open at the nearest floor and alert systems are being installed in all the classrooms." The Kajima Corporation has a similar system in its office building elevators.

Initiate active control systems. Picozzi et al. (2014) suggest that "early warning information should be exploited through active or semi-active control systems," and Iervolino et al. (2007) suggest that earthquake early warning systems "may be used for the real time set-up of active or semi-active structural control."

Public-information campaigns. Allen et al. (2009) point to Japan's public-education campaign "to provide information about the purpose and limitations of [earthquake early warning] and the proper actions to be taken. This included distributing leaflets, short informational videos broadcast on television, posters, conducting seminars, and posting information on the JMA Web site…." They describe how "The public warnings from JMA are communicated to the public via various means…" including television and radio, public loud-speaker system, via cellphone, and as messages that service providers incorporate into a variety of systems, such as a wall-mounted device that issues an audible warning and countdown. They describe a Tokyo school in which "The students complete three earthquake drills each school year. In the first drill, students are warned when the drill will occur; in the second, they know the week during which it will occur; and the third can be at any time." The school district in Miyagi Prefecture "developed and installed its own warning system in the classrooms of four schools. Training programs and videos were prepared and implemented, and the students drill regularly."

2.1.4 Essence of the Practice

The essence of earthquake early warning seems to require:

1. ***Training and education.*** Repeated training of people to take particular actions when they receive a warning. Allen et al. (2009): "Implementation of [earthquake early warning] does require a broad public education campaign as was carried out in Japan," and the lack of which caused serious problems in Taiwan and Mexico.
2. ***Automated systems.*** Some uses of earthquake early warning require the installation of automated systems to take particular actions upon receipt of a warning, such as the equipment that shuts off power and applies braking in electric rail systems, equipment that moves elevators to the nearest floor and opens doors, etc.
3. ***Detection and notification***. This is the part of earthquake early warning system that seismologists and engineers tend to focus on. Some authors suggest that a general instruction to "prepare for strong shaking" may be sufficient, but Bardach's (2004) thrust seems to be that people need instructions to take clear and concrete actions.
4. ***Individual actions***. A variety of individual actions can follow receipt of a warning. The Earthquake Country Alliance and ShakeOut.org's instructions for drop, cover, and hold on in various situations seem to cover most of the territory.

Nakamura and Saita (2007) list the essential elements of an early warning system in a different way:

1. ***Fully automated:*** As the time margin is limited, the facility should be directly controlled without human judgment.
2. ***Quick and reliable***: As there is limited time to respond to earthquake motion, this kind of system is required to be quick and reliable.

3. ***Small and cheap***: To install easily, the system must be small and cheap.
4. ***Independence***: To issue fail-safe alarms, the system must be independent of other systems.
5. ***Easy to connect network***: To deliver the earthquake information, the system must be easy to connect network.
6. ***Accuracy is better:*** For the alarm, accuracy of the information is not such a serious problem.

2.1.5 Potential Vulnerabilities

Inadequate funding and outreach. On the subject of potential vulnerabilities, Allen et al. (2009) warn that the Mexican SAS system suffers from funding and outreach shortcomings that "will likely result in failure of the system to reduce the impacts of earthquakes on the population," and that Mexico's SAS system has never had an implementation strategy "to identify institutions and critical facilities and lifelines that could benefit from the SAS system…."

Neglect of socioeconomic status, language, and culture. Fothergill and Peek (2004) offer an important caution about the failure of warning systems to protect disadvantaged populations: "People who are of a lower socioeconomic status are more likely to be involved in higher risk or more hazardous occupations…. [L]ower socioeconomic status has been associated with denial or minimization of chronic risks…. [G]roups of people with lower socioeconomic status were especially likely not to receive, understand, or believe earthquake warnings" and that therefore, "socioeconomic status should be considered as a possible contributor to, and predictor of, how risks are perceived and interpreted." They also stress the importance of language and culture in the receipt and comprehension of warnings.

Privacy concerns and smartphone power usage. When it was released, the smartphone app ShakeAlertLA raised some privacy concerns: passwords accidentally leaked by the software, and the requirement that the smartphone provide continuous location information (Lin 2019a). Giving an app access to location information may require that the geographic positioning system (GPS) sensor be powered on, which many users might disable to preserve battery life.

2.1.6 Context—Will it Work Here?

To answer the question of how context may affect the effectiveness of earthquake early warning in California, the author searched the reference works for mentions of culture, history, politics, economics, and experience. Leading lessons follow. Spahn et al. (2014) discuss how culture has impacted earthquake early warning in Indonesia. They point out that the majority religion, Islam, engenders a certain amount of fatalism among the population, which hints that non-fatalistic cultures might take earthquake early warning more seriously. They also mention how traditional culture in Aceh prepared the residents to recognize a tsunami threat and retreat to higher ground. The authors partly credit the high survival rate of the 2004 tsunami to traditional culture, which passed on its lessons through songs and lullabies. The Indonesian Institute of Sciences took culture seriously, making a deliberate effort to disseminate preparedness lessons through guidebooks, minimum requirements and checklists, interactive games and exercises, comics, art, and music to develop a preparedness culture in a very rich, broad sense. In the same work, Goseberg et al. (2014) and Wachter and Uslander (2014) similarly the developers of warning systems consider cultural norms and beliefs. The implication is that earthquake early warning systems might benefit from a deliberate effort to promote awareness of earthquakes and earthquake early warning into popular culture.

Spahn et al. (2014) also mention how politics and economics matter to the success of an earthquake early warning system: "People's full potential [to reduce disaster risks] can only be utilized if government and civil society build partnerships, based not only on local participation and ownership but also on political and economic support from national institutions." As an example, they cite how a national institution with the United Nations support adapted existing awareness, preparedness and educational materials to the context, culture, and languages of three other southeast Asian countries.

On the topic of experience, Bonn et al. (2014) describe how German trains use earthquake early warning systems to slow or stop trains based on experience rather than from derailment criteria, suggesting that earthquake early warning on US rail lines might take time—meaning, earthquake experience—before settling on train-control decision criteria.

2.2 Influential or Notable Press Coverage

The Los Angeles Times reported on the perceived failure of ShakeAlertLA to alert Angelenos to the magnitude-6.4, Ridgecrest California foreshock of July 4, 2019 (Lin 2019b). The system did not technically fail to perform as designed: it was only supposed "to alert users of cellphones physically located in Los Angeles County if there was a decent chance of destruction." The shaking in Los Angeles, "while seemingly scary, was actually not that bad. It was forecast by the earthquake early warning system as bringing shaking too weak to cause significant damage in Los Angeles County." The city seems to be re-thinking the threshold: "Officials with the city of Los Angeles, who manage the ShakeAlertLA app, suggested they would consider lowering the threshold for alerts. 'We hear you and will lower the alert threshold,' the city's Twitter account said." Strauss (project manager of the present project, written commun., October 16, 2019) advises that the threshold has been lowered to modified Mercalli intensity III. A variety of other press coverage is presented in the use cases.

2.3 Developer Literature

Yurekuru Call (Google Play 2019) claims 5 million users in Japan, and offers an intensity estimate at the user's location, a countdown to arrival of strong motion, maximum intensity estimate, epicentral location, and a few features that will be useful primarily after the cessation of strong motion. It does not offer instructions about actions to take beyond "be prepared for strong tremors."

ShakeAlertLA's web literature (City of Los Angeles 2019b) shows an app whose alert resembles an Amber alert: a simple text-based message ("An earthquake is happening. You may feel shaking"), a claxon that sounds three times in about 1 second, and no instruction as to what action to take.

Early Warning Labs (2019) offers its app, QuakeAlert. Its web literature highlights the information the app provides: expected arrival time, expected intensity, epicentral distance, magnitude, and suggested safety measures, especially to drop, cover, and hold on.

The MyShake app, developed by UC Berkeley with funding by Cal OES, serves the dual purposes of delivering alerts and providing a sensor network. The public alert debuted on October 17, 2019 after California Governor Newsom announced it. It delivers an audio message to people's cellphones, telling them, "Earthquake! Drop, cover, and hold on. Shaking expected" (Sanders 2019).

3. Research Plan

3.1 Outline of Use Cases

The use case outline is based on Bardach's (2004) theoretical framework for establishing best practices, rearranged for easier reading and supplemented with additional information that readers of this document will probably want: costs, hardware and software requirements, education and outreach materials, maintenance requirements, examples of past use, and references to relevant publications. The sections are as follows. Note the emphasis on brevity.

Essence of the Practice

In perhaps one paragraph (but taking as much space as required), identify the essence of the practice while allowing flexibility for how it is implemented so it remains sensitive to local conditions. Describe in the most general terms that still constrain the use case.

Context in Which the Use Case Would Work

In 1-2 sentences, explain the setting where the use case would work. Ensure that the context from which the practice is derived is comparable to the context in which it will be applied.

Realistic Expectations

In 2-4 sentences, explain to users what they can realistically expect in terms of degree and likelihood of success. In some instances, actions taken may not completely alleviate all negative impacts caused by shaking.

Clear Behavior

Specify clear and concrete behavior that solves the problem or achieves the goal under consideration.

Potential Vulnerabilities

Describe potential vulnerabilities that could lead the practice to fail either through poor management or inherent weakness in the practice itself.

Implementation Costs

What resources are required to implement the use case, in monetary or labor terms?

Hardware and Software Requirements

What equipment and software are needed?

Training, Education, and Outreach Materials

What training materials must be developed or acquired? How are they to be distributed to users? How are users to be trained, by whom, with what frequency? Who will update the training materials, and how frequently?

Maintenance Requirements

Who must maintain the hardware and software? How shall they be reminded, who will check that maintenance has been carried out, and how shall everybody involved remember to do maintenance?

Examples of Past Use

What organization serves as an example? Have they written or spoken about actual use? Can they claim successes that would inspire a new user to implement the use case?

References

Provide bibliographic citations with a URL in a standard format such as that of the American Psychological Association, commonly used in the social sciences.

3.2 Web Survey

The web survey is intended as a purposive, critical-case sample to gather insight into similar cases. The survey focuses on a subset of the elements of the use-case outline, those that seem most general and highest value. The survey asked respondents to reflect on their own use cases for earthquake early warning. From their responses, we draw insight into a broader set of cases. For example, one respondent is a phlebotomist. Her story provides insight into using earthquake early warning for other medical treatments such as surgery, where one seeks to avoid harm by withdrawing sharp objects before shaking occurs. Purposive sampling is different from probability sampling. The sample is *not* intended to provide quantitative insight into attributes of a population, so representativeness is not an issue.

A web-based survey was administered between October and December 2019, to a group of people known by the research team and an informal advisory group to have developed or used earthquake early warning. The survey elicits essay answers to Bardach's questions, plus identifying information for possible follow-up. Each survey response addresses one use case. Box 3-1 shows the draft survey instrument, administered using the Qualtrics software, with responses by invitation only.

Respondents were sent advanced notice, with the survey arriving the next day. The request was worded roughly as follows:

> Dear X, In light of your experience with earthquake early warning (EEW), I am writing to request your advice about EEW best practices, via a brief web survey that you will receive within a day or so. The survey supports an effort by the California Governor's Office of Emergency Services, the UC Berkeley Seismology Laboratory, and the Gordon and Betty Moore Foundation. The survey aims to give current and future end users of EEW, particularly as embodied in ShakeAlert and related applications, a best-practices guide to implementing EEW solutions. Please watch for an email from Dr. Keith Porter of SPA Risk LLC (cc'd here). Dr. Porter is helping us to compile the best-practices guide. His email will direct you to the web survey. Thanks in advance for helping Californians and others benefit from your experience.

SPA Risk LLC emailed the invitation to participate in the survey with the following message:

> Dear X, I hope you saw an email within the last day or so from the California Governor's Office of Emergency Services (Cal OES) or the UC Berkeley Seismology Laboratory (BSL), alerting you to this request. I am writing to ask for your advice to Cal OES, BSL, and the Gordon and Betty Moore Foundation on best practices for earthquake early warning. At the end of this email is a link to an anonymous web-based survey that asks 8 questions and will take 5-10 minutes to complete. Your response will contribute to the public good. In thanks for your time, you will also be entered in a drawing for one of three $50 debit cards and one of three $50 cash gifts in your honor to a nonprofit that serves traditionally disadvantaged groups in California. Kindly click on the following link to respond to the survey.
> https://cuboulder.qualtrics.com/jfe/form/SV_5stZncnronOimwJ

Box 3-1 Draft survey instrument

This survey elicits your advice for best practices to use earthquake early warning systems such as ShakeAlert. The survey is part of an applied research effort by California Governor's Office of Emergency Services (Cal OES) to maximize the safety and economic benefits of earthquake early warning. It asks 8 questions and will take you 5 to 10 minutes to complete. Your response will contribute to the public good. In thanks for your time, you will also be entered in a drawing for one of three $50 debit cards and one of three $50 cash gifts in your honor to a nonprofit of your choice that serves traditionally disadvantaged groups in California. Your identity will be held confidential by the research team, but we ask for your contact information for possible follow-up questions and to enter you in the raffle. Your name and other contact information will not be shared with anyone without your express written permission. You do not have to allow us to share that information to be entered in the drawing.

1. ***Use case name.*** Think of one use case of ShakeAlert or other earthquake early warning system, that is, one situation in which you have implemented or used earthquake early warning in your personal or work life. Feel free to complete separate forms for additional use cases. Please name your use case. [Required text box response]
2. ***Realistic expectations.*** What problem is the system supposed to address? To what extent has it produced the desired outcomes? [Required essay box response]
3. ***Clear behavior.*** Describe clear, concrete behavior that the system is supposed to trigger. [Required essay box response]
4. ***Essence of the practice.*** What is the core essence of the practice that other people in other conditions can imitate? [Required essay box response]
5. ***Vulnerabilities.*** What potential vulnerabilities in the system could lead it to fail either through poor management or inherent weakness in the practice itself? [Required essay box response]
6. ***Context.*** In what situations will your use case work? Please consider time of day, physical settings, people's language, culture, age, and disabilities. [Required essay box response]
7. ***How many times have you actually exercised the system?*** Never, a few times (1-3), several times (4-10), many times (11+)
8. ***Any clarifying advise or commentary?*** [Optional essay text box]
9. ***Contact information***. Name, title, organization, phone, email, and preferred mode of contact.

In collaboration with University of California Berkeley and an advisory group of facilitators, we sent 36 invitations to people with practical recent experience with earthquake early warning. All but three invitations included advanced notice, the invitation, and two reminders. We received eight responses, a response rate of 22%. However, this was a non-probability sample, the low response rate in no way invalidates the responses we did receive. Appendix 1 presents detailed responses regarding eight use cases:

1. Public warning for self-protective action
2. Securing industrial and nuclear processes
3. Securing industrial processes and trains
4. Structural analysis and self-protective actions in a university building
5. A regional or national general-purpose warning system
6. Power down a reservoir pump station
7. Suspending a medical procedure
8. Automated shut-off valves for water supply reservoirs and tanks

3.3 Facilitators and Advanced Users

3.3.1 Workshops

The research began before the COVID-19 pandemic and envisioned a series of four half-day workshops in which facilitators would convene a working group of advanced users and developers. The workshops were scheduled to take place near Caltech, UC Berkeley, University of Oregon, and University of Washington in March and April 2020. Invitees to the stakeholder workshop were to include at least the following:

- California Earthquake Early Warning Advisory Board
- USGS External Advisory Committee
- Mutual Aid Regional Coordination Committees
- Statewide or regional associations, e.g., Association of Contingency Planners; SoCal Critical Lifelines Workgroup and their northern California colleagues; the Building Owners and Managers Association; and the National Institute of Building Sciences Academy for Healthcare Infrastructure
- Possibly others, e.g., FEMA National Advisory Council, FEMA Mitigation Directorate, and representatives of other states' offices of emergency services

3.3.2 Facilitator Discussions

Considering the pandemic, the project team instead held two series of conference calls: one with facilitators and a second with users and developers. The facilitator series included everyone listed in the project participants pages of this document. Facilitators were first sent an in-progress draft version of this document for review and commentary. The draft contained the literature review, research plan, and draft use cases from survey responses. Participants reviewed and commented on the report, identified use case themes to examine in detail, and recommended expert users and developers to contact for information about each use case.

3.3.3 User and Developer Discussions

In the user and developer series, SPA Risk LLC held one-on-one conversations with users and developers for each use case. Conversations took place in a telephone call or web meeting that lasted between 30 minutes and 2 hours. In each discussion, the author briefly introduced himself and the project, explained the purpose, intended audience, length, and outline of the use cases, and then asked the discussant for insight on any or all sections of the use case, focusing on those that the discussant would know best. See the project participants list for users and developers with whom the author spoke. A few users declined to respond to emailed inquiries.

3.4 Budget Data

Budget data were acquired from vendors and users who sold or adopted earthquake early warning systems. Note that the market for earthquake early warning in the United States is young and costs are volatile. Costs for new system could rise relative to early users who received a low price from vendors to establish market presence. Or they could fall as the market becomes more competitive or as vendors are more able to take advantage of economies of scale.

4. 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.

A B C D

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

References

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.

References

Healy, P. (2014). Private Sector Takes Role in Advancing Quake Early Warning. NBC Los Angeles, September 6, 2014. https://www.nbclosangeles.com/news/private-sector-takes-role-in-advancing-quake-early-warning/93964 [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]

Medical Activity Alert

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 for people engaged in medical 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

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.

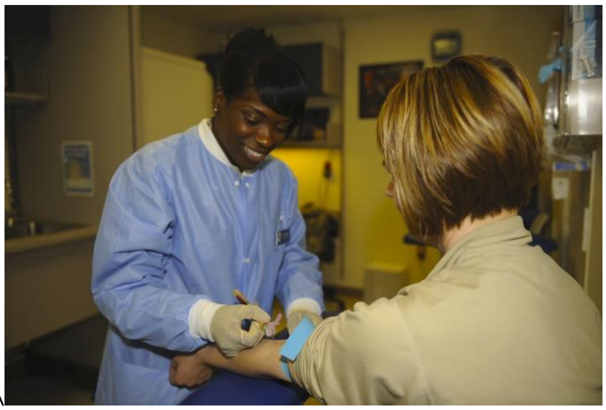
A  B 

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.

References

Lin, RG 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]

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.

A 

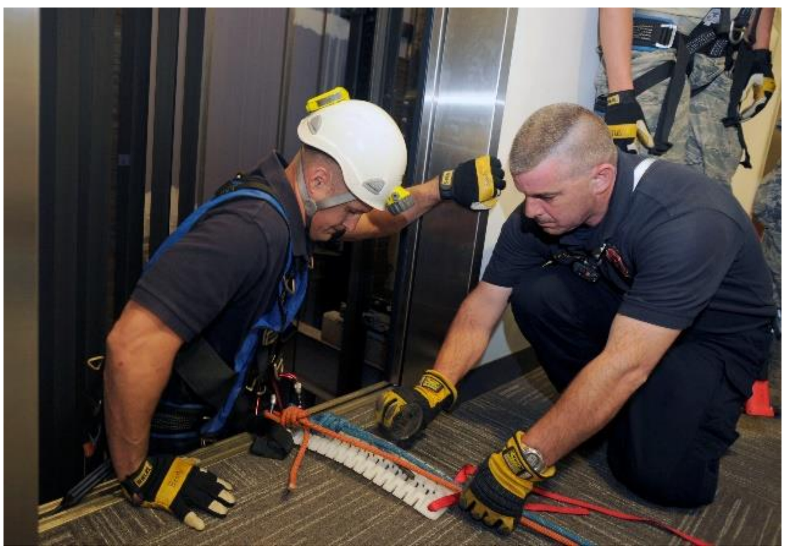
B 

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.

References

Business Wire (2017). PG&E Adds Earthquake Early Warning System to Some Elevators at its Headquarters. September 28, 2017, https://www.businesswire.com/news/home/20170928006112/en/PGE-Adds-Earthquake-Early-Warning-System-Elevators [accessed April 7, 2020]

Porter, K.A. (2018). An earthquake urban search and rescue model for earthquake response and its application to the HayWired scenario. Detweiler, S.T. and Wein, A.M. eds., The HayWired Earthquake Scenario—Engineering Implications. Scientific Investigations Report 2017–5013–I–Q, Reston, VA:

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

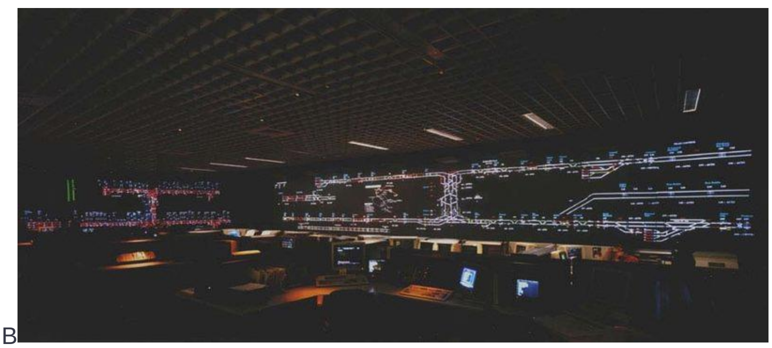
B


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.

References

Associated Press (2012). BART Installs Quake Early-Warning System. October 1, 2012. Retrieved from https://www.claimsjournal.com/news/west/2012/10/01/214462.htm [accessed May 5, 2020]

KPIX5 (2012). Earthquake Early-Warning Sensors To Be Installed On BART System. CBS San Francisco. September 28, 2012. Retrieved from https://sanfrancisco.cbslocal.com/2012/09/28/bart-system-getting-early-earthquake-warning-system [accessed May 5, 2020]

Southgate, R. J., Roth, C., and Schneider, J. (2013). Case study 4: an earthquake early warning for Japanese bullet trains. In *Using Science for Disaster Risk Reduction: Report of the ISDR Scientific and Technical Advisory Group, 2013*. United Nations Office for Disaster Risk Reduction (UNISDR). P. 20-21 http://www.unisdr.org/files/32609_stagreport2013assembled.pdf [accessed May 5, 2020]

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. Fourfold 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.

References

Perry, T.S. (2019). A 30-second earthquake warning gives a Menlo Park fire station a chance to protect itself. IEEE Spectrum. (June 25, 2019). Retrieved from https://spectrum.ieee.org/view-from-the-valley/at-work/start-ups/a-30-second-earthquake-warning-gives-a-menlo-park-fire-station [accessed May 6, 2020]

Xia, R., and Lin, R.G. II (2014). Earthquake early alert system ready to expand in California. Los Angeles Times November 23, 2014. https://www.latimes.com/local/california/la-me-1123-earthquake-early-warning-20141123-story.html [accessed April 28, 2020]

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.

References

Anacortes City Council (2019). City Council Minutes – February 25, 2019. Anacortes, Washington, 6 p. https://www.anacorteswa.gov/AgendaCenter/ViewFile/Minutes/_02252019-866 [accessed May 7, 2020]

Federal Emergency Management Agency (2011). FEMA E-74: Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide. Washington, DC, 775 pp., https://www.fema.gov/media-library/assets/documents/21405 [accessed May 7, 2020]

Lakewood Water District (2020). Emergency Preparedness. https://www.lakewoodwater.org/lwd/page/emergency-preparedness [accessed May 7, 2020]

Northeast Sammamish Sewer and Water District (2020). Northeast Sammamish Sewer and Water District. http://www.nesswd.org [accessed May 7, 2020]

Porter, E. (2018). Sammamish Utility first to install earthquake early warning technology. KIRO7. July 10, 2018, https://www.kiro7.com/news/local/sammamish-utility-first-to-install-earthquake-early-warning-technology/787172766 [accessed May 7, 2020]

Silverdale Water District. (2020). New Earthquake Detection Technology. Silverdale, Washington, February 3, 2020 https://www.swd16.org/news_detail_T7_R14.php [accessed May 7, 2020]

5. References Cited

Allen, R.M., Gasparini, P., Kamigaichi, O., and Bőse, M. (2009). The status of earthquake early warning around the world: an introductory overview. *Seismological Research Letters* 80 (5): 682–693. doi: https://doi.org/10.1785/gssrl.80.5.682 [accessed August 25, 2019]

Allen, R. M., and Melgar, D. (2019) Earthquake early warning: advances, scientific challenges, and societal needs. *Annual Review of Earth and Planetary Sciences*. 47: 361:388

Baker, P., Friedman, L., & Flavelle, C. (2019). Trump pressed top aide to have weather service 'clarify' forecast that contradicted Trump. *The New York Times*, Sept. 11, 2019. https://www.nytimes.com/2019/09/11/us/politics/trump-alabama-noaa.html [accessed August 25, 2020]

Bardach, E. (2004) *A Practical Guide for Policy Analysis*, 2nd Ed. CQ Press, Washington DC, 149 p.

Bonn, G., Buchmann, A., Hilbring, D., Hohnecker, E., Titzschkau, T., and Wenzel, F. (2014). Earthquake early warning for transport lines. Chapter 8 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Böse, M., Allen, R., Brown, H., Gua, G., Fischer, M., Hauksson, E., Heaton, T., Hellweg, M., Liukis, M., Neuhauser, D., and Maechling, P. (2014). CISN ShakeAlert: an earthquake early warning demonstration system for California. Chapter 3 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

California Governor's Office of Emergency Services (2019). California Earthquake Early Warning Program. https://www.caloes.ca.gov/cal-oes-divisions/earthquake-tsunami-volcano-programs/california-earthquake-early-warning-program [accessed May 11, 2020]

Camp, R.C. (1989). Benchmarking: the search for industry best practices that lead to superior performance. Sourcing Industry Group, http://src.sig.org/docs/Benchmarking-Guidelines.doc [accessed August 25, 2019]

Cappucci, M., & Freedman, A. (2019). President Trump showed a doctored hurricane chart. Was it to cover up for 'Alabama' Twitter flub? *Washington Post*. Retrieved from https://www.washingtonpost.com/weather/2019/09/04/president-trump-shows-doctored-hurricane-chart-was-it-cover-up-alabama-twitter-flub [accessed August 25, 2019]

City of Los Angeles (2019a). Mayor Garcetti launches nation's first publicly available earthquake early warning mobile app. https://www.lamayor.org/mayor-garcetti-launches-nation%E2%80%99s-first-publicly-available-earthquake-early-warning-mobile-app [accessed August 25, 2019]

City of Los Angeles (2019b) Download the ShakeAlertLA Early Earthquake Warning App | Recent LA Area Earthquakes. https://earthquake.lacity.org/shakealertla [accessed February 1, 2020]

Cuéllar, A., Espinosa-Aranda, J. M., Suárez, R.,. Ibarrola, G., Uribe, A., Rodríguez, F. H., Islas, R., Rodríguez, G. M., García A., and Frontana, B. (2014). The Mexican Seismic Alert System (SASMEX): its alert signals, broadcast results and performance during the M 7.4 Punta Maldonado earthquake of March 20th, 2012. Chapter 4 in Wenzel, F., and Zschau, J., eds. Early Warning for Geological Disasters. Springer, New York, NY, 382 p.

Early Warning Labs (2019). Earthquake Early Warning Mobile App – QuakeAlert. Retrieved from https://earlywarninglabs.com/mobile-app [accessed August 25, 2019]

Fothergill, A., and Peek, L. A. (2004). Poverty and disasters in the united states: a review of recent sociological findings. *Natural Hazards* 32:89-110

Gasparini, P., and Manfredi, G. (2014). Development of earthquake early warning systems in the European Union. Chapter 5 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Gasparini, P., Manfredi, G., and Zschau, J. eds. (2007). *Earthquake Early Warning Systems*. Springer. New York, NY, 363 p.

Gonzalez, R. (2018). FEMA drops 'climate change' from its strategic plan. NPR, March 15, 2018, Retrieved from https://www.npr.org/sections/thetwo-way/2018/03/15/594140026/fema-drops-climate-change-from-its-strategic-plan [accessed August 25, 2019]

Google Play Apps (2019) Yurekuru Call. https://play.google.com/store/apps/details?id=jp.co.rcsc.yurekuru.android [accessed August 25, 2019]

Goseberg, N., Lämmel, G., Taubenböck, H., Setiadi, N., Birkmann J., and Schlurmann, T. (2014). The last-mile evacuation project: a multi-disciplinary approach to evacuation planning and risk reduction in tsunami-threatened coastal areas. Chapter 11 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

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

Iervolino, I. (2014). Engineering earthquake early warning via regional networks. Chapter 17 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Iervolino, I., Convertito, V., Giorgio, M., Manfredi, G., and Zollo, A. (2007). The crywolf issue in earthquake early warning applications for the Campania region. Chapter 11 in Gasparini, P., Manfredi, G., and Zschau, J. eds. *Earthquake Early Warning Systems*. Springer. New York, NY, 363 p.

Lin, R.-G. (2019a). ShakeAlertLA users are concerned about earthquake app's security issues, bugs and crashes. *Los Angeles Times* March 1, 2019 https://www.latimes.com/local/lanow/la-me-ln-earthquake-early-warning-app-privacy-20190301-story.html [accessed August 25, 2019]

Lin, R.-G. (2019b). Why L.A.'s early warning system didn't send an alert before the magnitude 6.4 quake. *Los Angeles Times* July 4, 2019 https://www.latimes.com/local/lanow/la-me-earthquake-early-warning-system-64-quake-20190704-story.html [accessed August 25, 2019]

Los Angeles Unified School District (2018). *LAUSD Local Hazard Mitigation Plan Update July2018 Public Review Draft*. Los Angeles, CA, 454 p. https://achieve.lausd.net/cms/lib/CA01000043/Centricity/Domain/135/LAUSD%20LHMP%20Update%20Public%20Review%20Draft%20w_out%20Appendices.pdf [accessed May 20, 2020]

Nakamura, Y. (2004) UrEDAS, urgent earthquake detection and alarm system, now and future. *Proc. 13th World Conference on Earthquake Engineering, Vancouver, BC, August 1–6, 2004*

Nakamura Y., and Tucker B. (1988). Japan's earthquake early warning system: Should it be imported to California? *Calif. Geol.* 41:33–40

Nakamura, Y., and Saita, J. (2007). UrEDAS, the earthquake warning system: today and tomorrow. Chapter 13 in Gasparini, P., Manfredi, G., and Zschau, J. eds. *Earthquake Early Warning Systems*. Springer. New York, NY, 363 p.

Picozzi, M., Milkereit, C., Fleming, K., Fischer, J., Jaeckel, K-H., Bindi, D., Parolai, S., and Zschau, J. (2014) Applications of a low-cost, wireless, self-organising system (sosewin) to earthquake earlywarning and structural health monitoring. Chapter 14 in Wenzel, F., and Zschau, J., eds. Early Warning for Geological Disasters. Springer, New York, NY, 382 p.

Sanders, R. (2019). California rolls out first statewide earthquake early warning system. *Berkeley News*. https://news.berkeley.edu/2019/10/17/california-rolls-out-first-statewide-earthquake-early-warning-system/ [accessed May 14, 20120]

Segreda, L. S. (2003) Psychological interventions in disaster situations. Chapter 3.6 in Zschau, J., and Kuppers, A.N., eds. (2003). *Early Warning Systems for Natural Disaster Reduction*. Springer, New York, NY, 834 p.

ShakeAlert (2019). ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States. https://www.shakealert.org/ [accessed August 25, 2019]

Spahn H., Hoppe, M., Kodijat, A., Rafliana, I., Usdianto, B., and Vidiarina, H.D. (2014) Walking the last mile: contributions to the development of an end-to-end tsunami early warning system in Indonesia. Chapter 10 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Twigg, J. (2003). The human factor in early warnings: risk perception and appropriate communications. Chapter 1.3 in Zschau, J., and Kuppers, A.N., eds. (2003). *Early Warning Systems for Natural Disaster Reduction*. Springer, New York, NY, 834 p.

Wächter, J., and Usländer, T. (2014). The role of information and communication technology in the development of early warning systems for geological disasters: the tsunami show case. Chapter 12 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Waldman, S. (2019). Trump officials deleting mentions of 'climate change' from U.S. Geological Survey press releases. , *E&E News*, *Science*, doi: 10.1126/science.aay6617WebFinance, Inc. (2019). Best practice. BusinessDictionary.com. http://www.businessdictionary.com/definition/best-practice.html [accessed August 25, 2019]

Wenzel, F., and Zschau, J., eds. (2014). *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Woo, G., and Marzocchi, W. (2014). Operational earthquake forecasting and decision-making. Chapter 18 in Wenzel, F., and Zschau, J., eds. Early Warning for Geological Disasters. Springer, New York, NY, 382 p.

Wyss, M., Wenzel, F., and Daniell, J. (2014). How useful is early warning and can it be made more effective? Chapter 19 in Wenzel, F., and Zschau, J., eds. *Early Warning for Geological Disasters*. Springer, New York, NY, 382 p.

Zschau, J., and Kuppers, A.N., eds. (2003). *Early Warning Systems for Natural Disaster Reduction*. Springer, New York, NY, 834 p.

Appendix 1. Web Survey Responses

Response 1: Public self-protective actions such as drop, cover, and hold on

Use case name: To Secure People's Life (and Prevent Injury) from Strong Ground Shaking

Realistic expectations. The system is intended to issue alert to users before strong shaking. The alert gives us time to act for securing safety. In many cases, alerts are successfully issued before strong shaking. But we have to remember that in some cases, they are later than strong shaking. In some cases, alerts are issued for very weak shaking (excessive alert).

Clear behavior. To secure user's safety under desk or other safety places. To hold handrails firmly on trains or buses. To slow down smoothly when driving car. At least, mental preparedness.

Essence of the practice. Do not panic. Strength of the building is an important factor for effective earthquake early warning (EEW). Strong building relieves us even during strong shaking, which avoids panic. Regular experience of actual EEW alerts (or drills) is also important to remember dos and don'ts.

Vulnerabilities. From system side: the system cannot always issue the alert successfully: sometimes it is late (or no alert) and sometimes it is excessive alert. From user side: it may cause more confusion if users do not know the meaning of the alert (users understanding is important for effective EEW).

Context. In daytime, it triggers actions to secure safety. When sleeping, it is wake up call. In both cases, at least it helps us for mental preparedness.

Experience. How many times have you exercised the system? Many times (11+)

Any clarifying advice or commentary? There are variety of actual actions to secure safety depending on the situations. I believe regular experience of actual EEW alerts (or drills) is a key for effective EEW for public.

Follow-up questions. The author asked by email: Any sense of how many people have taken self-protective action as a consequence, even as an order-of-magnitude guess? Do you have any case studies in which DCHO actually avoided injury, e.g., with stuff falling where a person had been before receiving the warning? The respondent provided a paper (Hoshiba 2014) summarizing a mail and web survey of 817 Tohoku District residents who received warnings by TV, radio, cellphone, or other, prior to the 201 Tohoku earthquake. Most Tohoku District respondents (74.3%) successfully took action. 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.

Response 2: Securing industrial and nuclear processes

Use case name: Earthquake Early Warning for Emergency Situation Departments

Realistic expectations. To announce the authorities for the production of an earthquake in the Vrancea Romania area. To block the dangerous infrastructures that can affect the population. In the case of Romania, nuclear infrastructures except nuclear power plants.

Clear behavior. For the earthquakes produced in the Vrancea area such a system can warn the users in Bucharest with about 25s-30s before the arrival of the shock caused by the destructive wave "S" and for the users from the Cernavoda area or the southern area of Romania the interval can be about 30s - 35s. This time interval, although short, can be successfully used when interlocking dangerous installations and activating rescue means. For the earthquakes produced in the Vrancea area such a system can warn the users in Bucharest with about 25s-30s before the arrival of the shock caused by the destructive wave "S" and for the users from the Cernavoda area or the southern area of Romania the interval can be about 30s - 35s. This time interval, although short, can be successfully used when interlocking dangerous installations and activating rescue means.

Currently the information from REWS is received by the officers located at the command points of the inspectorates for emergency situations and they act in accordance with the local procedures. Informs the superiors, ensures that they can be evacuated after the earthquake ends and sends to the intervention teams the reports issued by National Institute for Earth Physics-Romania (NIEP) regarding the affected areas. For infrastructures NIEP develops an interface that activates or deactivates a process of the installation to make it secure.

Essence of the practice. There are some systems on the market for gas locking using local locking.

Vulnerabilities. The main vulnerabilities that can lead to the failure of REWS are:
- system maintenance
- updates made to the software without strong checks.
- communication between the issuing point and the beneficiary.

Context. Rapid Earthquake Warning System in Romania has been operational since 2013. So far (2019) it has issued only one false alert due to software changes (2013). Another fake alert that was perceived by the population as an alert was generated by a hacker through a mobile application. The mobile application is a news application that received alerts from REWS in order to try to educate the population how to behave in the earthquake. The seism alert channel was protected and could not be broken by the hacker but it generated an alert through a text message in the application.

Experience. How many times have you exercised the system? Many times (11+)

Any clarifying advice or commentary? Please read above.

Follow-up questions. Are any of the actions automated, or do they all require human intervention? [No response as of this writing.]

Response 3: Securing industrial processes and trains

Use case name: Lisbon 1755 Earthquake

Realistic expectations. Early warning in SW Iberia. To stop factory processes such as Huelva (chemical industries). Alert for the high-velocity train (AVE Madrid-Seville and Madrid-Malaga). Alert for tsunami. Please note that this is a theoretical objective. Our EEWS is not operative at the present time.

Clear behavior. The system must give an early warning for the above objectives.

Essence of the practice. S. Portugal (Algarve and Lisbon region) and the Atlantic coast of Morocco.

Vulnerabilities. No information.

Context. We don't have analyzed it.

Experience. How many times have you exercised the system? Never.

Any clarifying advice or commentary? [No answer]

Follow-up questions. Do the developers intend automated actions, human intervention, all of the above? [No response as of this writing.]

Response 4: Structural analysis and self-protective actions in a university building

Use case name: School of Engineering of the University of Naples Federico II

Realistic expectations. The system has embedded a structural model in it and it was connected a regional seismic network monitoring the region (100km apart) from which large earthquakes are expected. When an earthquake occurs, the system performs real-time probabilistic seismic demand analysis based on the information coming from the network about the event.

Clear behavior. The system could (but actually did not) trigger an alarm to students and personnel occupying the building.

Essence of the practice. Real-time probabilistic demand and loss assessment to establish whether the impending earthquake requires a security action to be undertaken.

Vulnerabilities. Large uncertainties in prediction, mostly related to uncertainty in GMPEs and limited warning time in some cases.

Context. It will work if recipients are trained so as to respond adequately to the alarm.

Experience. How many times have you exercised the system? Several times (4-10)

Any clarifying advice or commentary? Earthquakes detected and structural response estimated before the ground motion reached the building. However, earthquakes were always below M4, so no alarm was issued.

Follow-up questions. How accurately did the system predict the actual structural response? What are occupants expected or trained to do: drop, cover, and hold on, or something else, or some combination depending on their role?

Response 5: A regional or national general-purpose warning system

Use case name. EEWS-Mexico, SASMEX

Realistic expectations. Effective dissemination of the seismic warnings ahead of time for the population. Mexican early warning system is in constant improvements to reduce the processing time to provide the major time of anticipation

Clear behavior. The seismic warning must be activated considering seismic danger parameters such as instrumental intensity, PGA expected, magnitude and epicentral distance. The seismic warning trigger can be different for each region, according with the seismic risk knowledge for each specific region.

Essence of the practice. Best practices about resilience, availability, reliability for early warning system focused in provide an effective early warning, mainly in monitoring and dissemination subsystems.

Vulnerabilities. Lack or non-regular investment. Vandalism. To use one technology or simple communication channel as the main communication system to monitoring or dissemination.

Context. The complete EEWS must work continuously for the majority of people (with vulnerability mainly) as be possible

Experience. How many times have you exercised the system? Many times (11+)

Any clarifying advice or commentary? My answers were in the context of the Seismic Early Warning System of Mexico.

Follow-up questions. Is the system intended to deliver a signal to a receiver that then further transmits it, or does it send a message all the way to a human or automated actor at a final destination, or some combination, or something else? Can you provide a concrete example of the end use that you think in the past has provided or in the future will provide the most value, in terms of lives saved, property loss avoided, etc.?

Response 6: Power down a reservoir pump station

Use case name. NE Sammamish Crest Reservoir and Pump Station ShakeAlert Implementation

Realistic expectations. The Crest Reservoir is a buried .5 MG reservoir that cannot [flow by] gravity to the water system and must be pumped. With the ShakeAlert system we are able to receive the early earthquake warning and shut down the pumps at the station prior to the earthquake's damaging waves hitting the station. This preserves the pumps and the water in the reservoirs. In the event of an emergency, people could fill up jugs, etc. at the reservoir. We have been able to successfully test this numerous times but have not had an earthquake large enough to trigger a shut down.

Clear behavior. Shutting down of pumps to prevent fire and damage to the pumps and preserve water in the reservoir.

Essence of the practice. All water systems with telemetry systems and access to the ShakeAlert system would be able to implement this technology at all pump stations.

Vulnerabilities. We could get a false alarm that would cause pumps to shut down for no reason. Even if that happens, water pumps start and stop all the time so it wouldn't be damaging.

Context. It will work at any time of day and would preserve water for all people.

Experience. How many times have you exercised the system? Several times (4-10)

Any clarifying advice or commentary? [No answer]

Follow-up questions. Is this an automated system, that is, do the pumps power down without human intervention? If so, how did you connect ShakeAlert to the pump controls?

Response 7: Suspending a medical procedure

Use case name. Phlebotomy Alert

Realistic expectations. If an earthquake occurs during daytime hours, phlebotomists in laboratory outpatient blood draw may be in the middle of collecting blood samples from patients. Movement of the needle during phlebotomy can cause harm to both patients and phlebotomists, so alerting phlebotomists prior to ground movement starting will allow them to safely remove and secure the needle.

Clear behavior. When audible alert sounds, phlebotomists are expected to safely withdraw the needle from the patient and activate the safety feature to eliminate the sharps hazard. Phlebotomists should explain to the patient that the sound indicates the potential for an earthquake and direct the patient to a safe location if time permits.

Essence of the practice. Alert awareness, immediate action of securing the needle, then defensive action (Drop, Cover, Hold, etc.)

Vulnerabilities. High turn-over rates for phlebotomists so may be difficult to maintain awareness for all staff. Human tendency to 'just complete this one thing' (i.e. finish filling tubes) prior to taking immediate action.

Context. Alert sounds in one location which is in use during daytime hours. Challenges with directing patients to take defensive action due to language barriers and disabilities, although this is addressed in employee training.

Experience. How many times have you exercised the system? Never

Any clarifying advice or commentary? We are in the early stages of implementing, so this use case is planned but not yet implemented.

Follow-up questions. None.

Response 8: Automated shut-off valves for water supply reservoirs and tanks

Use case name. Municipal Water System Water Supply Protection

Realistic expectations. Water reservoirs and tanks often empty due to broken downstream watermains following a large earthquake. The water in the reservoirs is an important public resource; both for fire protection following the quake and for long-term health and safety as drinking water. Earthquake early warning is being used to close the outlet valves on the reservoirs before the damaging shaking begins, thereby saving the stored water in the reservoir for later use. More than 20 reservoirs and tanks Washington State are being protected in this manner and the system has proven to be reliable and effective during testing and simulations.

Clear behavior. The early warning alarm activates an electrical relay that is attached to either a hydraulic actuator or an electrical actuator which positions existing isolation valves.

Essence of the practice. The reliable and quick activation of an electrical relay. The relay could be attached to virtually any downstream device to cause automatic action including; stop rotating machinery, open a door, stop an elevator, stop an MRI machine, initiate a public-address message, sound an alarm, etc.

Vulnerabilities. The equipment that interfaces with the early warning alarm must operate reliably and quickly… our benchmark is 99.99% up-time and latency less than 1 second. The equipment should be able to discriminate and filter false alarms so that erroneous actions are not completed. The alarm threshold, and even the downstream actions, should be user adjustable so that users with different tolerances and/or non fail-safe actions can benefit adjust the actions to suit their unique needs.

Context. There are no situations where this system wouldn't work. Actions are taken automatically, without human intervention, so it does not rely on nor is it influenced by location, culture, time or situation.

Experience. How many times have you exercised the system? Many times (11+)

Any clarifying advice or commentary? [No answer]

Follow-up questions. What organization provides the earthquake early warning (EEW) signal? How did you connect the EEW signal to the electrical relay? Does the EEW service provider offer a standard application programming interface that is readily connected to a commercial relay, or did you have customer software written, or how did you bridge that last mile?