The HayWired Scenario—Earthquake Early Warning Forecast and Potential Hazard Mitigation Actions

By Jennifer A. Strauss, Anne M. Wein, Jamie L. Jones, and Douglas D. Given

Chapter W of

The HayWired Earthquake Scenario—Societal Consequences

Edited by Shane T. Detweiler and Anne M. Wein

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Chapter W

The HayWired Scenario—Earthquake Early Warning Forecast and Potential Hazard Mitigation Actions

By Jennifer A. Strauss,[1] Anne M. Wein,[2] Jamie L. Jones,[2] and Douglas D. Given[2]

Abstract

The HayWired scenario is a hypothetical earthquake sequence that begins with a moment magnitude (M_w) 7.0 earthquake (mainshock) occurring on April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of the San Francisco Bay region, California. In the mainshock, the Hayward Fault ruptures along 86 kilometers (km)—from beneath San Pablo Bay southeast to the City of Fremont—rattling the greater San Francisco Bay region during the 30 seconds of sustained shaking. Using this scenario, the impacts of earthquake early warning (EEW) information and triggered automated controls are explored. EEW is the rapid detection of earthquakes, real-time assessment of the shaking hazard, and notification of people before the seismic waves that cause shaking arrive at their location. To assess the utility and efficacy of EEW for a significant earthquake in the San Francisco Bay region, alert times were calculated for the mainshock of the HayWired scenario. EEW alert times throughout the bay region were estimated for the mainshock based on expected performance of the ShakeAlert system, then mapped against shaking intensities, and used to envision plausible responses and mitigation actions. Less than 15 km from the epicenter (for example, in the cities of Oakland and Berkeley), strong shaking would arrive before the alert. However, outside of this “no-warning zone,” alerts could have widespread positive effects in the densely built urban environment. The most notable benefit for individuals is the possible reduction in injuries resulting from people having more time to take the self-protective “drop, cover, and hold on” (DCHO) actions. We summarize an initial estimate of the potential benefit of ShakeAlert and DCHO in the HayWired scenario, as well as assessments of elevator, transit, and hospital responses to highlight how prevention of cascading failures of lifeline infrastructure systems (such as highways, rail systems, telecommunications, and electric grids) is important for resiliency during and after the rupture. The HayWired scenario invites us to take a step back and assess both the built environment’s possible response to disasters of this scale and our own preparedness in a situation where we might not be able to rely on the communication and other systems of our interconnected, “wired” world.

Introduction

The HayWired scenario is a hypothetical yet scientifically realistic depiction of an earthquake sequence that begins with a moment magnitude (M_w) 7.0 earthquake (mainshock) occurring on Wednesday April 18, 2018, at 4:18 p.m. on the Hayward Fault in the east bay part of the San Francisco Bay region, California. The mainshock begins beneath the City of Oakland and ruptures 86 kilometers (km) of the fault—north to beneath San Pablo Bay and southeast to the City of Fremont. During the approximately 30 seconds of sustained shaking, people and structures throughout much of the greater San Francisco Bay region are rattled, and the fault in some places is offset by more than 2 meters (m), soils liquefy, and landslides occur. Afternoon rush hour in the bay region is in full swing by 4:00 p.m., and many people would be taking an elevator, sitting on a train, or on roads and bridges on their way home from work. Others would still be in their offices, at after-school activities, running errands, or at home. Family members could be in very different locations in the bay region during their afternoon commute times. This scenario allows readers to envision the physical, infrastructural, and societal consequences of the rupture.

Chapters in U.S. Geological Survey (USGS) Scientific Investigations Report (SIR) 2017–5013–A–H (v. 1) outlined the science behind the models used in the HayWired scenario and the implications to the ground, such as fault rupture, shaking intensities, landslides, and zones of liquefaction (areas where soils become liquid-like during shaking). Chapters in SIR 2017–5013–I–Q (v. 2) assessed ordinary building performance (Seligson and others, 2018), building code performance (Porter, 2018a), and tall-building performance (Almufti and others, 2018). Building codes are said to support “life safety,” but there is a common misconception that this means buildings will also be habitable and useable

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in the aftermath of a design-level earthquake (Porter, 2018a). The reality is that many people and businesses will likely be displaced (Applied Technology Council, 2012; Johnson and others, in prep. [planned to be published as part of this volume]). Building codes aim to preserve the lives of those inside them, but perhaps we can do better than that in the future (Porter, 2016). New engineering designs and risk mitigation measures put in place now can increase resiliency and recovery.

USGS and a coalition of State and university partners are developing and testing an earthquake early warning (EEW) system called ShakeAlert (https://www.shakealert.org) to provide a few seconds of earthquake early warning to reduce risk and increase resiliency, not just for utilities and infrastructure, but also for people and organizations. The ShakeAlert system continues to evolve, and pilot groups, technology enablers, licensed operators, and stakeholders in the transportation, utility, healthcare, education, and emergency management sectors have been engaged in developing hazard-mitigation best practices and strategies in response to alerts of shaking. In the spirit of HayWired's focus on interconnectivity, and the authors' work with ShakeAlert stakeholders, this chapter is meant to outline possibilities for uses and benefits of the ShakeAlert system based on data researched for the scenario and priority focus areas from stakeholders. It is not intended as a rigorous cost-benefit assessment; the numbers of affected people or systems discussed should not be taken as absolutes. The discussion in this chapter is best used as a planning tool to probe the extent of what is possible for ShakeAlert.

We live in a "wired," interconnected world. When the first thorough cost-benefit study of the impacts of EEW was done in California (Holden and others, 1989), automated controls were not an accepted part of daily life. Now, we cannot imagine a world without machines helping with ordinary, daily tasks. In 1989, planning for the unknown was often a part of life, and distribution of goods and services was handled differently. For example, before the constant presence of cell phones, many families had a plan of where to meet if, say, people went to different stores in a mall. Emergency-response groups historically had access to warehouses of supplies in case of dire need. Now, businesses rely on just-in-time delivery to fill stores, and on-site inventories have been reduced. An earthquake can temporarily interfere with our constant interconnectedness, so having a plan in place before an earthquake strikes is even more crucial in today's world. The hypothetical ShakeAlert responses discussed in this chapter do not cover the full range of what is possible but instead give a rational flavor of what we could expect to unfold during an earthquake like the HayWired scenario mainshock and provide a framework to engender discussion on new strategies and responses. (For other resources, also see Allen and others, 2009; Fujinawa and Noda, 2013; Gasparini and others, 2007; Goltz and Flores, 1997; Heaton and others, 1985; Strauss and Allen, 2016.)

ShakeAlert Time Estimation for the HayWired Scenario

EEW provides an alert that an earthquake has occurred and may forecast the final magnitude and severity of shaking at a location. EEW has been deployed in at least eight countries—China, Japan, Mexico, Romania, Switzerland, Taiwan, and Turkey (National Research Council, 2011) and the United States, South Korea and Israel. Mexico began providing limited public alerts to certain cities within the country in 1993. Japan's nationwide system has provided alerts for the safety of the general public since 2007. Taiwan implemented nationwide public alerting in 2016.

EEW has been in active development in the United States since 2006 (Allen, 2011; Burkett and others, 2014), in a collaborative group including the USGS, the California Institute of Technology, the University of California at Berkeley, the University of Oregon, and the University of Washington. This public EEW system is called ShakeAlert and operates on the West Coast of the United States. The ShakeAlert group also works with State, public, and private partners to assess dissemination, resiliency and hazard mitigation, and implementation strategies that can make use of the advanced warnings that EEW can provide.

The ShakeAlert system, as currently designed, will generate public alerts (in the future) for earthquakes greater than magnitude (*M*) 4.5 and will deliver alerts to regions estimated to experience expected Modified Mercalli Intensities (MMI) greater than or equal to II (that is, felt shaking). The estimated regions are octagonal contours and thus provide an average intensity estimate for the area, so actual felt shaking could vary on a more local scale. Technical users, which could include transportation and utility sectors, could receive more detailed and lower magnitude threshold alerts, as well as alerts for lower magnitude earthquakes. California public alerting was activated just prior to publication of this chapter. Public alert dissemination began earlier in the Los Angeles region through the use of a cell phone application, and will be tested in California by the end of 2019.

The ShakeAlert system uses a network approach, where the first seismic wave (the primary, or P-wave), which radiates from the earthquake hypocenter at speeds of 5–8 kilometers per second (km/s), is detected by nearby seismic sensors. Seismic sensors relay information about the P-wave to data centers, where algorithms compute the probable earthquake location and magnitude, and estimate the shaking intensities that will result. This information is used to generate an EEW alert for the impacted region that is sent to people and devices electronically. The goal is to distribute the alerts before the slower moving (3–5 km/s), yet generally stronger and more damaging, secondary wave (or S-wave) and following series of surface waves arrive at a given location. Because electronic communication travels much more rapidly than seismic energy, advanced warning can be possible even in regions where critical infrastructure and population centers are located close to the rupturing fault (as is the case in the HayWired scenario).

ShakeAlert (Cochran and others, 2017; Given and others, 2018; Kohler and others, 2017) relies on an array of sensors throughout the West Coast that relay information back to a central site for analysis and alert distribution. The amount of warning provided depends on many factors, including the time it takes for the fault rupture to grow (large ruptures can take several to tens of seconds to grow), the shaking intensity threshold used to issue an alert, how often alerts are updated, time to detect the growing rupture, and time to distribute an alert to an end user or to engage an automated control, as well as the user's distance from the earthquake hypocenter. The amount of shaking a user experiences is related to their distance from the part of the fault that ruptures and site conditions at their location, whereas the amount of warning a user receives is based on their distance from the epicenter.

It is important to note that these local variations in shaking intensity can be large, and estimated shaking intensities can have large uncertainties. In general, P-waves induce vertical shaking, which has minimal impact on the built environment, because buildings are constructed to withstand the vertical force of gravity and less so for lateral motions from S-waves. However, that does not mean that high shaking intensities will only be experienced during the S-wave and later phases of an earthquake. The reader is encouraged to keep this in mind, as the estimated ShakeAlert warning times below are in reference to S-wave arrival.

It is estimated that ShakeAlert would issue its first alert 5.1 seconds (s) after the HayWired scenario mainshock begins (for details, see appendix 2 of Porter and Jones, 2018). This estimate is based on the system's performance during the M_w 4.0 Piedmont, California, earthquake on August 17, 2015. The Piedmont earthquake epicenter lies only 6 km from the epicenter of the HayWired scenario mainshock, and thus it is a reasonable proxy for our purposes here because the initial alert latency should be comparable. Initial alert latency (the alert time minus earthquake origin time) depends on the local seismic station density and the speed with which data is delivered to ShakeAlert processing centers. The station density has remained relatively constant in this region but upgrades to sensors and telemetry have improved data delivery since 2015. In the future, ShakeAlert will also continue to refine the algorithms to improve alert speeds. Full station buildout is complete in the bay region as of this writing. Buildout for the State of California is funded and expected to be completed in the coming years. The full West Coast of the United States will be built out sometime after that. Once all stations are contributing to the system, alert speeds will improve in areas where coverage is currently lacking.

The time between an EEW alert and the S-wave arrival at a particular location is what we call the EEW time. Different alert distribution methods used by various pilot implementations, such as public announcement systems, cellular applications, or radio communications, will increase latencies and result in shorter EEW times for end users. For the HayWired scenario mainshock, the distance traveled by S-waves during the 5.1 s after the earthquake begins and the modeled distribution of the alert is approximately 15 km from the epicenter. This region defines a “no-warning zone,” where S-wave shaking would arrive before or at the time of the published ShakeAlert. At distances greater than 15 km, a user of an EEW system could receive an alert before the arrival of S-waves. It should be noted that for large ruptures, the initial shaking intensity estimates are likely to be low and increase as a fault continues to rupture. Automated responses, outlined below, should take this into account when setting thresholds (Minson and others, 2018).

Table 1 catalogs the warning times and shaking intensities that ShakeAlert could provide for major cities affected by the M_w 7.0 HayWired mainshock using the assumptions outlined above and described in appendix 2 of Porter and Jones (2018) (fig. 1). Nearby regions situated about 0–65 km

Table 1. Estimates for earthquake early warning times, relative to secondary-wave (S-wave) arrival, and peak shaking intensities at select locations for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario in the San Francisco Bay region, California.

[MMI, Modified Mercalli Intensity]

City	Latitude (north)	Longitude (west)	Distance from epicenter, in miles	Distance from epicenter, in kilometers	Warning time, in seconds	Shaking intensity, MMI
Oakland	37.80	122.27	5	8	0.0	VIII
Berkeley	37.87	122.27	7	11	0.0	IX
Hayward	37.67	122.08	11	17	0.7	IX
San Francisco	37.78	122.42	13	21	1.8	VII
San Mateo	37.55	122.31	19	30	4.3	VII
Fremont	37.55	122.99	21	33	5.2	IX
Vallejo	38.11	122.24	21	35	5.8	VII
Redwood City	37.48	122.24	23	36	6.0	VII
San Rafael	37.97	122.53	23	36	6.0	VII
Livermore	37.68	122.77	24	39	6.9	VIII
San Jose	37.34	121.89	36	58	12.4	VIII

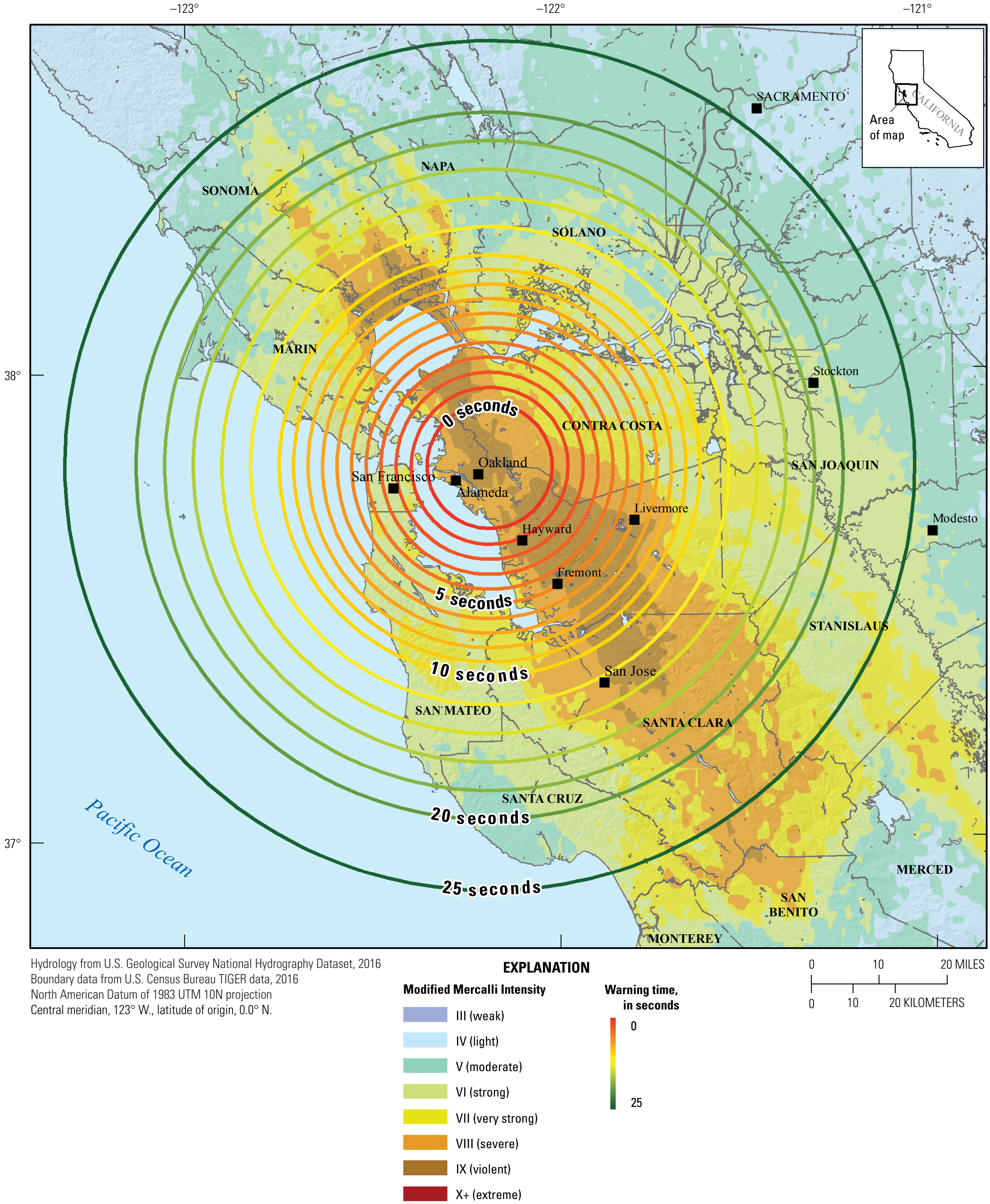


Figure 1. Map of the San Francisco Bay region, California, showing contours of earthquake early warning time estimates relative to secondary wave (S-wave) arrival for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault overlain on the instrumental intensity map for mainshock (intensity map modified from Aagaard and others, 2017a).

from the epicenter could receive advanced warnings ranging from 0 to 12.4 s and experience shaking intensities from VII to IX on the MMI scale. The MMI scale describes the very strong shaking level (MMI VII) as when people have difficulty standing during shaking. The next level up, severe shaking (MMI VIII), would not only prevent people from standing but could overturn heavy furniture, cause chimneys to collapse, and cause structural damage.

Discounting local site effects and amplification in basins and areas of liquefaction, which can locally increase shaking intensities, more intense shaking is usually experienced closer to the section of the fault that ruptures and falls off as a function of distance (Aagaard and others, 2017a). Inversely, greater early warning times are possible for locations farther from the epicenter of an earthquake. For large events (*M*7.0 and above), heavy shaking can be experienced far from the epicenter, because the rupture continues along the fault for some distance. Porter and Jones (2018, see appendix 2) suggest that MMI II or greater shaking would be felt as far as 250 km away from the epicenter of the HayWired mainshock. In such a case, people downstream of the event can receive larger warning times and still feel shaking.

For the HayWired scenario mainshock, many highly populated areas, such as San Jose, have warning times of more than 12 s and ground shaking intensities of MMI VIII (fig. 2), whereas San Francisco, which is closer to the epicenter, would only receive 1.8 s of warning time and experience lower shaking of MMI VII. People and businesses in Fremont could receive 5 s of warning of violent shaking. Further afield, people in the Central Valley could receive as much as 42 s of warning preceding severe shaking.

The HayWired mainshock rupture could be considered a worst-case scenario for the eastern part of the San Francisco Bay region, because the epicenter is right in the heart of an urban area, and the no-warning zone covers many affected people. Residents, businesses, and emergency responders in Oakland and Berkeley, less than 15 km from the epicenter, would be in this no-warning zone. That is, the S-wave would arrive before the warning did. The alert would not come in time for people in those cities to take advanced protective actions.

However, even in the no-warning zone, people who had been trained on how to use ShakeAlert warnings could have their minds and bodies “prompted” to remember their training to “drop, cover, and hold on” when an earthquake occurs, even if the warning came at the same time as or after the shaking. This is based on exemplification theory that tells us that:

> The use of exemplifying imagery, mostly as a complement to informative text, has emerged as a powerful means of creating risk consciousness and of motivating protective and corrective action (Zillmann, 2006).

The developers of ShakeAlert are working with social scientists to ensure that alerts can make use of this body of research to benefit the recipient by linking a situation with a response. This is why training in advance, like the annual ShakeOut drills (see https://www.shakeout.org), is important.

Of course, ShakeAlert warnings will not help with longer term decisions of constructing and retrofitting buildings for desired performance, nor can they prevent all impacts from heavy ground shaking. A few seconds of EEW is not enough time to take actions such as getting an earthquake kit together, contacting loved ones and deciding on a meeting place, securing heavy objects in a room, or stopping traffic over bridges. However, what a few seconds of EEW can do is allow people and organizations to implement mitigation and protective actions that were decided upon and put in place in advance of an earthquake. EEW is also a reminder that alerts and actions go hand in hand with preparedness (Allen and others, 2017). The process of planning strategies and actions for ShakeAlert can prompt people and organizations to also look at other protective actions in their environment that can be enacted well in advance of an earthquake. ShakeAlert is one tool in the resiliency toolbox, but one that requires prior planning to reach full potential. It should also be noted that the population affected by the no-warning zone for the HayWired scenario mainshock can, of course, benefit from warnings generated by earthquakes that occur in other parts of the San Francisco Bay region.

ShakeAlert Can Prompt Automated Controls

Automated controls are a key component for responding to the short warning times offered by ShakeAlert in the San Francisco Bay region. Automated responses eliminate the loss of precious time that a human would require to enact a process (such as opening fire station bay doors or slowing and stopping trains) that can aid in preventing cascading system failures. Cascading failures in this context are small failures that stack up together to have big impacts. Here, we outline some of the automated controls that ShakeAlert pilot users are working on, as well as those that were able to be directly investigated based on data provided as part of research for the HayWired scenario.

Many automated controls involve physical hardware and protocols to put specific equipment or systems into a safe mode. This is the case for elevator, door, and machinery type controls. There is also another approach that some groups are exploring to enable structural controls. These “smart civil structures” would be able to adapt building characteristics in real-time to more adequately brace a building for imminent earthquake shaking (Housner and Masri, 2000). A proof of concept using an EEW trigger to enact semiactive structural control capabilities was performed for a bridge in Southern California and shown to be effective at “reducing the response of the benchmark highway bridge for a wide variety of earthquake records” (Maddaloni and others, 2013). The analysis of structural controls is an interesting topic for further research but has not been integrated with EEW in the United States and is thus outside the scope of this chapter.

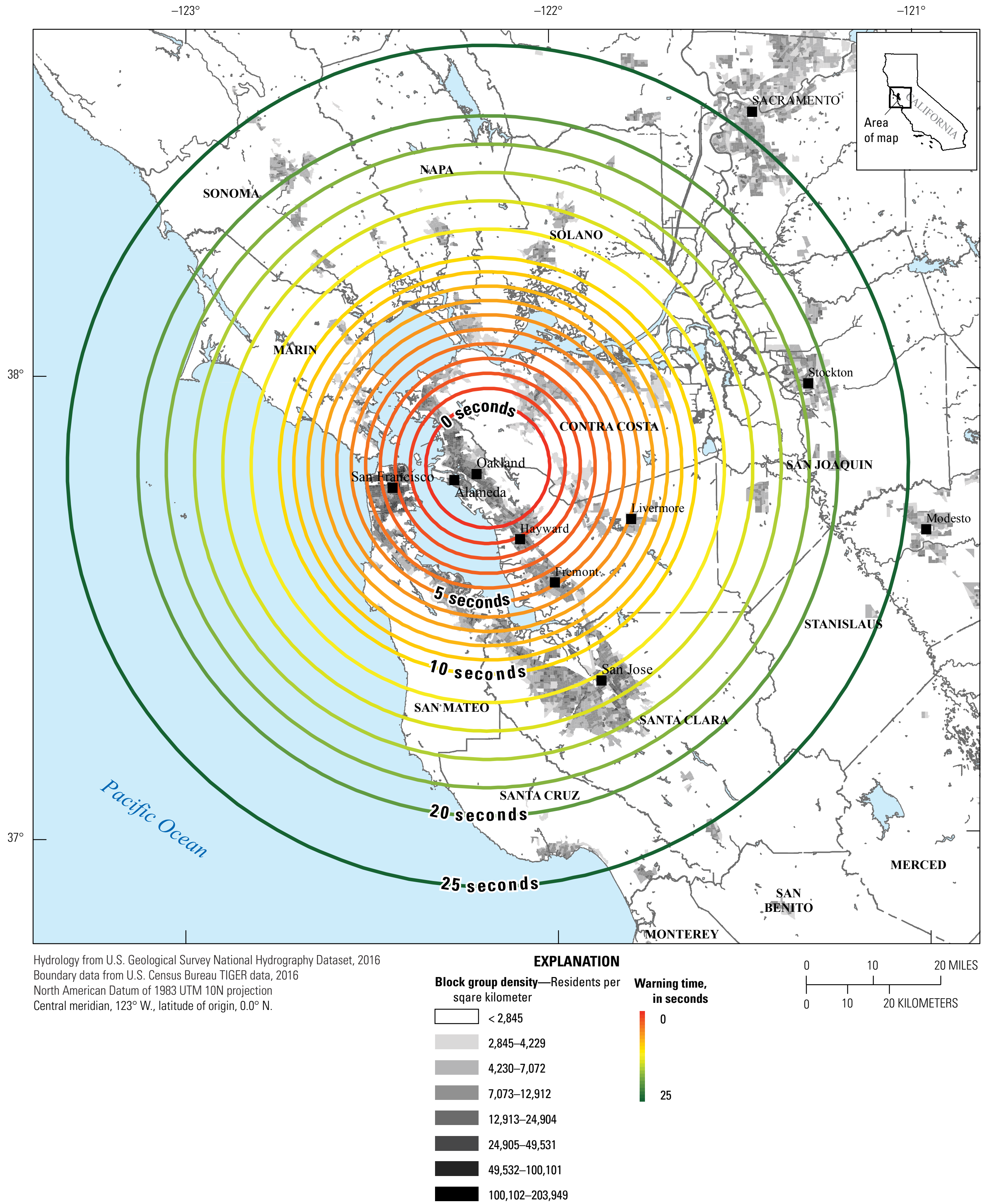


Figure 2. Map of the San Francisco Bay region, California, showing ShakeAlert (https://www.shakealert.org) earthquake early warning time estimates overlain with population density information for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault (also see fig. 2 in Porter and Jones, 2018). The geographically dispersed population experiences many different warning times in this scenario event.

Elevator Systems

Automated controls added to building elevator systems can prevent passengers from becoming trapped when an elevator car and its counterweight become misaligned during heavy earthquake shaking (in the absence of structural controls). Elevator systems with active response systems based on either EEW systems or threshold-crossing protocols for ground shaking held 16,700 occupants during the M_w 9.0 2011 Tohoku earthquake in Japan (Layne, 2011). All of these elevators were in the affected region and experienced shaking at a high enough level to cause the systems to trigger. Using such a system, elevators in the United States could be configured to send elevator cars to the ground floor or stop at the nearest floor and hold the doors open during a strong earthquake.

Currently, there are limitations on using EEW for elevator systems, because not all buildings are modern enough to permit retrofits with ShakeAlert EEW technology, and regulations affecting how ShakeAlert warnings can be transmitted to elevators would need to be modified. ShakeAlert pilot users have indicated that California regulations do not permit internet services to initiate an elevator stop. Recently, Pacific Gas and Electric Company installed on-site EEW in some of their elevators, which does not use the internet to initiate the stop as a workaround (BusinessWire, 2017). If State regulations were changed from a location-by-location strategy, this could result in a more realistic approach to building resiliency throughout the West Coast.

A detailed analysis of elevator entrapment owing to power outages can be found in Porter (2018b); we summarize the methodology and results here because we apply the same assumptions to show how ShakeAlert could reduce the risk of elevator entrapment in the region impacted by the HayWired scenario. Porter (2018b) assumed a national average of one elevator for every 334 people to estimate numbers of elevators. He removed an estimated proportion of elevators with emergency power and assumed 60 percent of the elevators are in use (for example, actually carrying people) at any instance during peak times, and of those elevators, 30 percent would be between floors when the HayWired mainshock occurred. On the basis of this approach, Porter (2018b) estimated 4,500 elevators in transit would be interrupted by power outages with the potential to trap as many as 22,000 people. This number is an upper limit estimation in that it assumes a widespread power outage occurs that affects all 10 million people living in the San Francisco Bay region and neighboring counties.

The following estimation of the number of people trapped in elevators represents ideal-world conditions where all elevators that could trap riders owing to shaking (that is, shaking that cuts power at the site or misaligns the elevator) have automated controls that do not add significant delay in response to a ShakeAlert. Also, we calculate percentages of elevators that could avoid entrapping riders where ShakeAlert conditions apply. Using the estimated ShakeAlert warning times for the HayWired mainshock that are a function of distance from the epicenter, we estimate the number of elevators in each warning-time band by invoking Porter's (2018b) assumption of one elevator for every 334 people. The numbers of people in each ShakeAlert warning-time band were calculated using population data (U.S. Census, 2016) and warning-time contours in a geographic information system (as shown in fig. 2). Similar to Porter (2018b), we removed percentages of elevators with emergency power, those not in use by riders, and those that would be at floors when the ShakeAlert is received.

We assume that given at least some ShakeAlert warning, elevators equipped with automated controls could be held at a floor and (or) stopped at the next floor with open doors for easy egress. For example, if elevators receive 2 s of warning of shaking that would trap riders, then those elevators that would have left a floor or would reach a floor in less than 2 s could be held before leaving a floor or stopped at the next floor, respectively. Hydraulic elevators, which according to Otis are "used extensively in buildings up to five or six stories high," have transit speeds of 150 feet per minute, requiring 3.2 s to get between floors (Otis, n.d.). Rounding the transit time to 4 s and assuming transit times are uniformly distributed at any one time, then elevators with approximately 1 s of warning (in the 1–2 s warning band) would allow one-quarter of riders to be held at a floor and one-quarter of riders to be stopped at the next floor. Similarly, half of riders might be held at a floor and the other half could be stopped at the next floor with about 2 s of warning (2–3 s warning band). If elevators can only be held or stopped, then three-quarters of riders might avoid entrapment with about 3 s of warning (3–4 s warning band). Beyond 4 s of warning, all riders would receive a warning in time to remain at a floor or stop at the next floor to avoid getting trapped.

With a ShakeAlert warning capable of only keeping elevators at a floor, about 9 percent of all riders receiving less than 2 s of warning could avoid entrapment (0 percent of elevator occupants in the area with less than 1 s of warning and 25 percent of elevator occupants in the area with 1 to 2 s of warning). About 40 percent of all riders receiving as much as 5 s of warning could avoid entrapment. This translates to about 1,600 elevators carrying about 8,000 riders and illustrates how a few seconds of warning could make a difference for elevator riders because elevators only take seconds to travel between floors. The hypothetical upper bound for ShakeAlert helping to avoid elevator entrapment in the HayWired scenario is 81 percent of elevator riders. If a ShakeAlert warning is able to stop elevators at the next floor, the results are the same because elevator transit is distributed uniformly. If a ShakeAlert warning can both hold departing elevators and stop elevators when they arrive at the next floor, then the numbers double for the first 1 s and 2 s of warning and cap at 87 percent of avoided entrapments or an upper bound of 19,600 riders in elevators in the region. See table 2 for the details of estimates of avoided entrapments. Elevators within the no-warning zone, within the 1-s warning zone, or in transit beyond the warning time could still benefit from existing mechanical earthquake sensor controls that are non-EEW-related.

Table 2. Number of elevators and percentage of riders in the San Francisco Bay region, California, that could use ShakeAlert to remain at a floor and (or) stop at the next floor to avoid entrapment of passengers in transit during power outage or damage at the site during the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario.

[Number of elevators is estimated using 2010 U.S. Census Bureau population data (U.S. Census Bureau, 2016) in the warning time areas. %, percent]

ShakeAlert warning-time bands	Estimate of the number of elevators in transit in warning-time band	Percent of riders avoiding entrapment with ShakeAlert capability to only hold elevators at a floor or only stop at the next floor	Percent of riders avoiding entrapment with ShakeAlert capabilities to both hold elevators at a floor and stop at the next floor
None	355	0	0
Less than 1 second	461	0	0
Less than 2 seconds	712	9	18
Less than 3 seconds	968	20	39
Less than 4 seconds	1,400	30	51
Less than 5 seconds	1,600	40	58
All warning-time bands in region, including areas receiving ≥5 seconds warning	4,500	81	87

Fewer people trapped in elevators would reduce the burden on 9-1-1 systems, which in turn could lessen the effects of cascading system and infrastructure failures. For example, in 2009, California experienced a 9-1-1 overload problem, which caused 26 percent of all wireless calls into the system to be "abandoned" (9-1-1 Industry Alliance, 2011). An example of how 9-1-1 overloads can lead to cascading failures involved a motorcycle accident on July 4, 2011, in Wichita, Kansas. Witnesses were unable to reach 9-1-1 to report the accident owing to the sheer volume of calls about fireworks clogging the lines (Finger, 2011). Paramedics were only reached after one witness bypassed 9-1-1 and directly contacted his father, who was an off-duty police officer. In light of this ongoing nationwide concern, California Governor's Office of Emergency Services created the Routing on Empirical Data (RED) project, to use locations from wireless devices to help reduce the number of busy signals—"shaving time and saving lives" (California Governor's Office of Emergency Services, 2014). This method involves "using historical empirical call data [to] determine the most efficient routing for wireless 9-1-1 calls" (California Governor's Office of Emergency Services, 2014).

Although the number of calls to 9-1-1 reporting trapped high-rise elevator occupants is not likely to ever reach the upper limit value of 3,900 calls represented by the number of elevators that could be held at a floor using ShakeAlert—in the HayWired scenario (87 percent of 4,500 elevators)—removing even some of these calls from the queue can have an impact on the volume of calls routed by 9-1-1 call centers.

Fire following earthquake is a major cause of postearthquake destruction (Scawthorn, 2018), so ShakeAlert's ability to reduce 9-1-1 calls from low-level injuries through drop, cover, and hold on (outlined later in this chapter) and by stopping elevators (and the use of other automated controls) in combination with the RED project, may enable more calls, like those for fire, to get through.

Transportation Systems

Bay Area Rapid Transit (BART) trains are a crucial transportation system for the San Francisco Bay region. BART has invested in structural retrofits, an earthquake safety program, and in using the ShakeAlert system to limit system vulnerabilities in the case of an earthquake. BART is a crucial lifeline in the San Francisco Bay area, and these actions work together to increase resiliency for the train network.

In the HayWired scenario, trains arriving and departing from the Fruitvale, Coliseum, San Leandro, Bay Fair, Hayward, and South Hayward stations intersect locations of high estimated shaking damage and areas with low to moderate liquefaction and (or) landslide probability (fig. 3). BART works with the ShakeAlert team and has implemented ShakeAlert warnings and their own local sensors, to slow and (or) stop the trains.

The BART system carries individual riders on more than 127 million trips annually (2015 data; Bay Area Rapid Transit, 2015). On Wednesdays at 4:18 p.m., there are on average 10,482 persons in motion on 40 trains and 2,021 patrons on 6 berthed trains (Kevin Copley, BART, written commun., 2015). Using timetables for each BART line passing through these six stations, we can construct a snapshot of train locations and directions along the track lines at 4:18 p.m. on a Wednesday afternoon (fig. 4) and envision how ShakeAlerts could impact the system. The following scenario is based on BART's late 2017 schedule.

Three trains (the Oakland International Airport and both Richmond line trains at Bay Fair) are berthed at the station platforms at 4:18 p.m. when the ShakeAlert alarm is received. Thus, approximately 1,011 passengers on the platforms and within the three trains would receive the command to hold position. Two trains on the Fremont-Daly City lines (both northbound and southbound) would be enroute between the South Hayward and Hayward stations at the time of the alarm.

Each train should receive 2 s of ShakeAlert warning in this scenario. BART receives alerts directly from ShakeAlert that do not pass through a third-party redistributor, so latency times are minimal from alert generation to alert receipt at BART. Two seconds is not enough time to slow and completely stop trains in motion; BART trains only can reduce speed 3 miles per hour per second. However, for the two trains in motion, which receive 2 s of warning before shaking, and the five trains in transit through the affected area, which would not receive an early enough warning, the automated controls still protect the system by not requiring slower human interventions to make decisions to begin slowing or stopping the trains. The trains would automatically begin slowing as a result of either the networked ShakeAlert warning or BART's own wayside track monitors. We should note that currently BART's Oakland International Airport to Coliseum leg does not yet have the benefit of automated reaction.

Other transportation systems, such as metered entrances to highways and toll bridges, could benefit from ShakeAlert. There are thousands of commuters on the road during rush

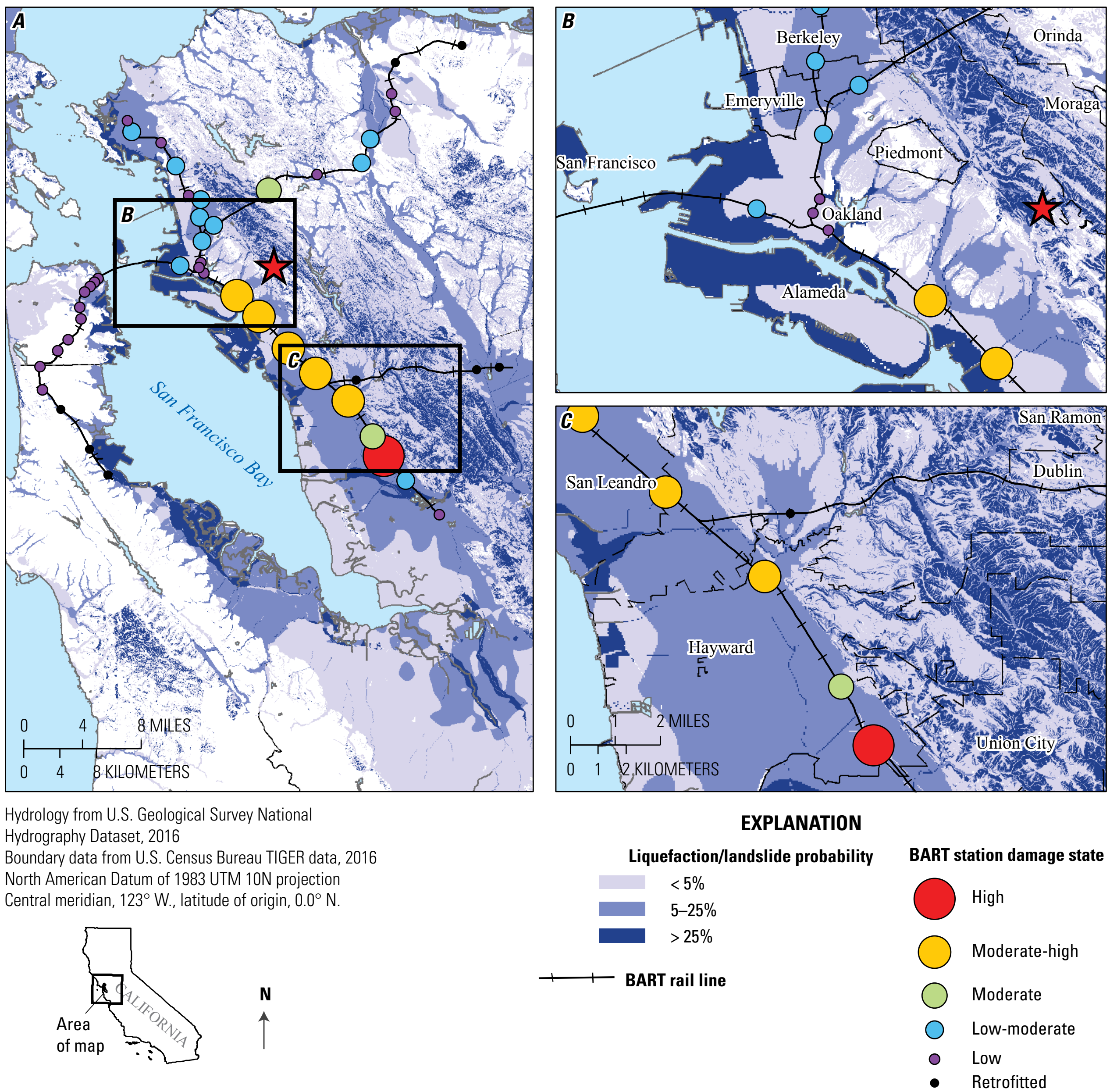


Figure 3. Maps of the San Francisco Bay region California, showing U.S. Geological Survey ShakeCast (see https://earthquake.usgs.gov/research/software/shakecast.php) shaking damage estimate for the Bay Area Rapid Transit (BART) system at the time of the hypothetical April 18, 2018, moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault. *A*, Map showing the entire BART system; *B*, map showing BART stations near the mainshock epicenter (star) that are forecast to sustain moderate-high shaking damage, and *C*, map showing BART stations further south of the mainshock epicenter that are forecast to sustain moderate-high to high shaking damage.

hour in the San Francisco Bay region, with many crossing over the Richmond Bridge, Golden Gate Bridge, San Francisco-Oakland Bay Bridge, San Mateo-Hayward Bridge, Dumbarton Bridge, and other smaller spans to return home. During the M_w 6.9 1989 Loma Prieta earthquake, more than 80 bridges in the region sustained minor damage, 10 required temporary supports, and 10 were closed owing to major structural damage—including most notably, the San Francisco-Oakland Bay Bridge, whose upper level collapsed, causing one fatality. The Cypress Viaduct in the east bay catastrophically collapsed owing to amplified shaking of the underlying soft soils and was the locus of the vast majority of fatalities for the earthquake (Yashinsky, 1998). Today, the Bay Bridge has been retrofitted and a new eastern span has been put in place. The Cypress Viaduct was demolished, and a new connector between I–880 and I–80 was built nearby. Bridges in the region should now be safer to cross during heavy shaking, owing to the retrofitting and relocation, but halting traffic at freeway entrance metering lights and bridge toll booths in response to a ShakeAlert warning could lessen the number of cars entering these areas during peak shaking and further reduce potential risk.

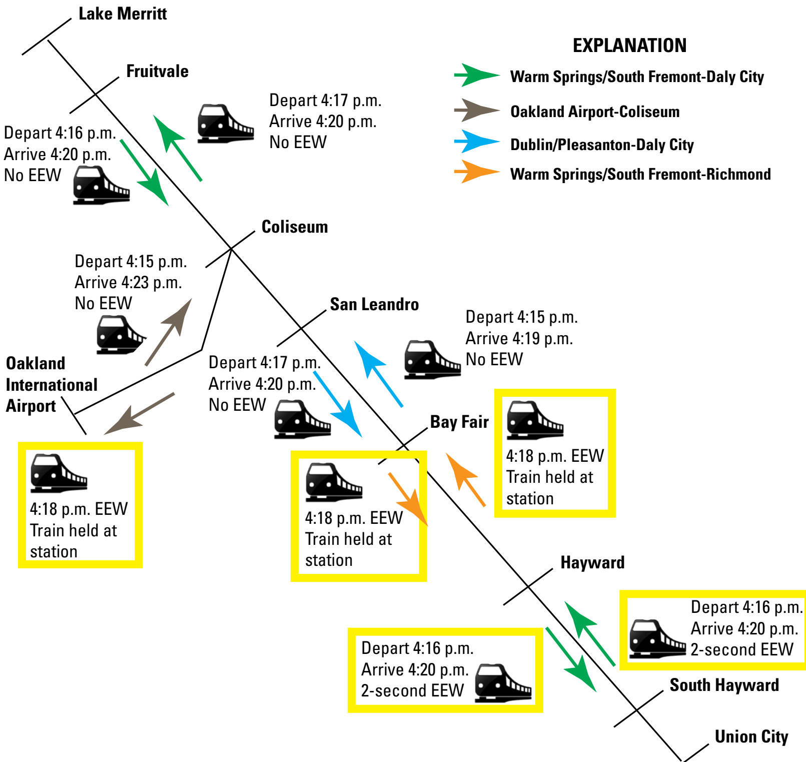


Figure 4. Schematic illustration of Bay Area Rapid Transit (BART) train locations along the systems tracks at the time of the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault in the San Francisco Bay region, California. Colored arrows represent the train direction of motion in the area of interest and yellow boxes indicate trains that receive earthquake early warning (EEW).

ShakeAlert Can Prompt Protective Actions

Hospitals and Injuries

Hospitals play a crucial role for society after an earthquake—responding not only to patients currently in their care, but also triaging incoming patients with injuries resulting from shaking. Horiuchi (2009) researched EEW capabilities in a hospital setting in Japan and found that within the hospital, EEW can play a role in securing patients during surgery to prevent errors, protecting equipment so it may be useable after shaking, and protecting staff so that they may be physically able to carry on their duties. Horiuchi (2009) found possible protective applications for EEW such as securing radiation sources (turning off X-rays) and detaching tubing that could become forcibly removed during shaking. Each hospital will need to identify their own best practices for EEW based on their own facility and seismic risk.

In discussions with hospital groups in the San Francisco Bay region, one theme that is often brought up is the impact that ShakeAlert could have on reducing a large influx of patients in the aftermath of an earthquake. As was seen when Hurricane Katrina struck the Gulf Coast in 2005, medical personnel were overwhelmed by the number of patients coming in and could only triage and provide basic first aid, leaving many critical patients unassisted owing to lack of supplies and resources (Franco and others, 2006). Reducing the sheer number of people who need to be triaged, in an earthquake's aftermath, could speed the triage process and allow hospitals to more nimbly respond to any severe trauma cases.

For the HayWired mainshock, this could be especially crucial in the east bay, where critical-care facilities are concentrated in a few city centers (fig. 5). This is in contrast to the San Francisco Peninsula side of the bay, from San Francisco to San Jose. There, warning times are larger, shaking is lower, and critical-care facilities are more evenly distributed geographically. If the roads and bridges are passable, facilities along the peninsula could perhaps help by providing extra medical services to east bay residents. However, roads and bridges may be difficult to navigate after a powerful earthquake on the Hayward Fault, so east bay residents could have difficulty reaching these other hospitals on their own. This could put stress on ambulances and other first responders. ShakeAlert could be used to reduce the number of injuries in an earthquake like the HayWired mainshock (see next section) and thus may be a helpful tool to reduce the demands on medical services.

Two hospitals in the Los Angeles region were running pilots of the ShakeAlert system during the 2019 Ridgecrest earthquake sequence. Alerts were received but no actions were taken at the facilities, even though people there experienced shaking, because the shaking at those locations did not reach pre-set thresholds for action. The hospitals are now considering lowering the thresholds, since people in the

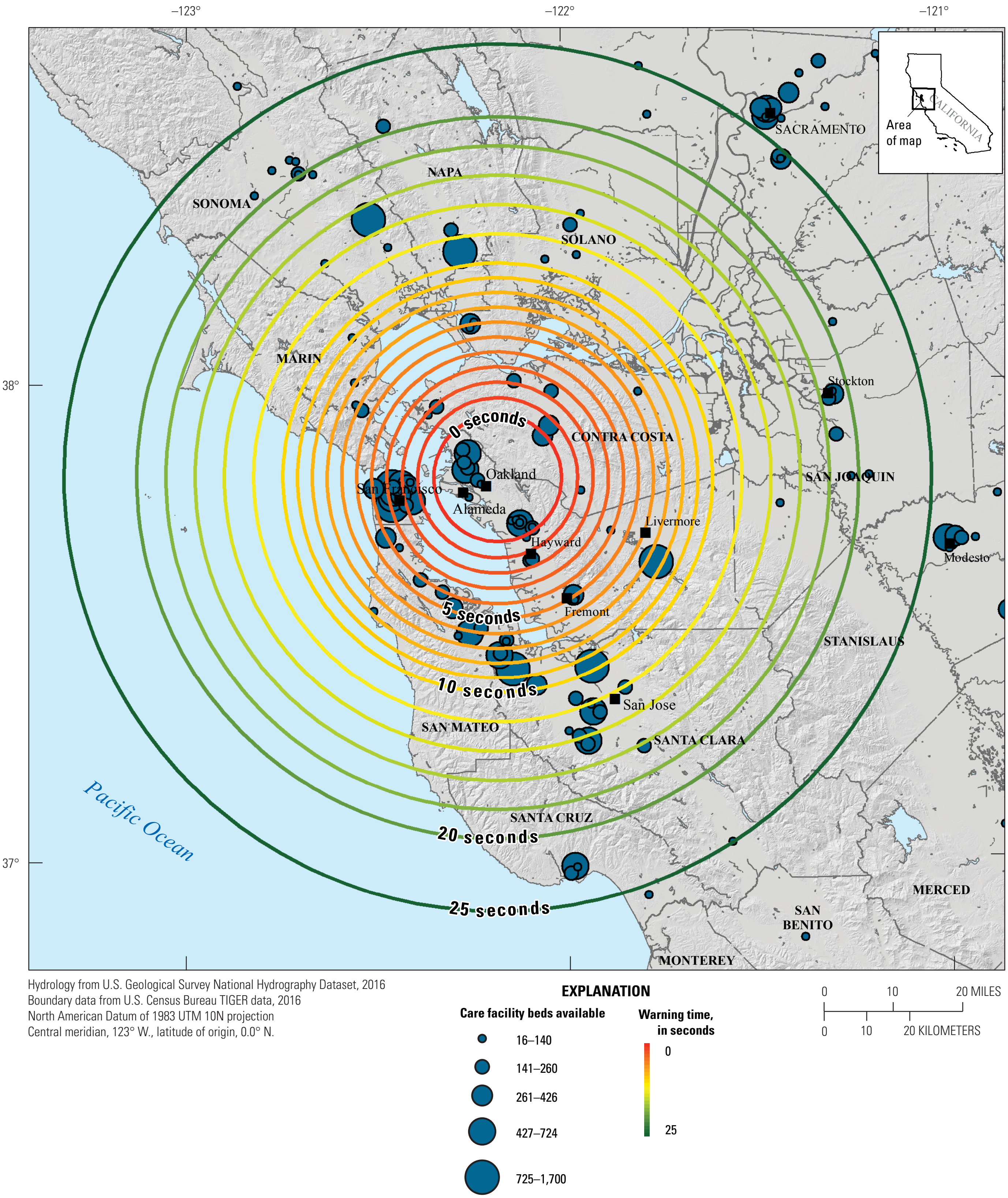


Figure 5. Map of the San Francisco Bay region, California, showing the location of critical-care facilities and the number of beds that they can accommodate (Doug Bausch, Federal Emergency Management Agency, written commun., 2014), overlain with earthquake early warning time estimates for the hypothetical moment-magnitude-7.0 mainshock of the HayWired earthquake scenario on the Hayward Fault.

building felt the earthquake and expected an alert (Margaret Vinci, California Institute of Technology, oral commun., 2019). Before considering the impact to injuries, it is important to keep in mind that giving people information about what they are experiencing is considered useful and desired.

Looking at past events, we can obtain a better picture of the prevalence of injuries. After the 1989 Loma Prieta earthquake, it was determined that more than 50 percent of the nonfatal incidents were caused by falls and falling hazards (Shoaf and others, 1998). This includes those caused by collapses of chimneys and porches, which were the most common structural collapse hazards. In the M_w 6.2 2011 Christchurch, New Zealand, earthquake, 70.4 percent of soft-tissue injuries were from trip or fall hazards (Lambie and others, 2017). Lambie and others (2017) used closed-circuit television footage to code responses during the earthquake and found that only a small number took self-protective actions—1.3 percent of people dropped and 26 percent held on to something. This is similar to the findings of Lindell and others (2016), where only 7.2 percent of people in Christchurch and 13.9 percent of people Hitachi, Japan, took cover during the 2011 Christchurch and Tohoku earthquakes, respectively. However, more than 30 percent of people froze in place (Lindell and others, 2016). Lindell also found that "lower levels of earthquake preparedness . . . produced higher levels of freezing in place." Getting a warning out to people is important, but so is educating people on what to do if they receive such an alert.

Drop, Cover, and Hold On

Training and education are crucial for populations to perform the most effective self-protective actions during an earthquake. The messages received from ShakeAlert can serve to improve and increase performance of protective actions by communicating the proper response to take (Drabek, 1986; Mileti and Fitzpatrick, 1991; Mileti and Sorensen, 1990; Sorensen, 2000). "Drop, cover, and hold on" (DCHO) is the recommended action to take when shaking is felt (provided it is safe to do so). EEW serves to augment the efficacy of this self-protective action by providing the person with advanced notice to be aware of the coming situation, remember their training, and take action.

As part of the HayWired scenario, Porter and Jones (2018) conducted a survey of people to assess response times to DCHO after a simulated earthquake alert. The survey results indicated a median time to complete DCHO at 8.8 seconds. The Federal Emergency Management Agency's Hazus-MH damage-estimation tool calculates 800 deaths and 18,000 nonfatal injuries from building and structural damage caused by ground shaking and liquefaction hazards from the HayWired mainshock in the San Francisco Bay region. They combined these data with the ShakeAlert warning-time contours for the HayWired mainshock to assess the number of people that could conceivably complete DCHO before heavy shaking began (S-wave arrival). Porter and Jones (2018) found that the population of the bay region that lives in areas receiving more than 8.8 seconds of EEW represents 8 percent of the total nonfatally injured population, or about 1,500 people, and they estimated that "The U.S. Government would value mitigation measures to avoid that number of nonfatal injuries at approximately $300 million (in 2015 [U.S. dollars])."

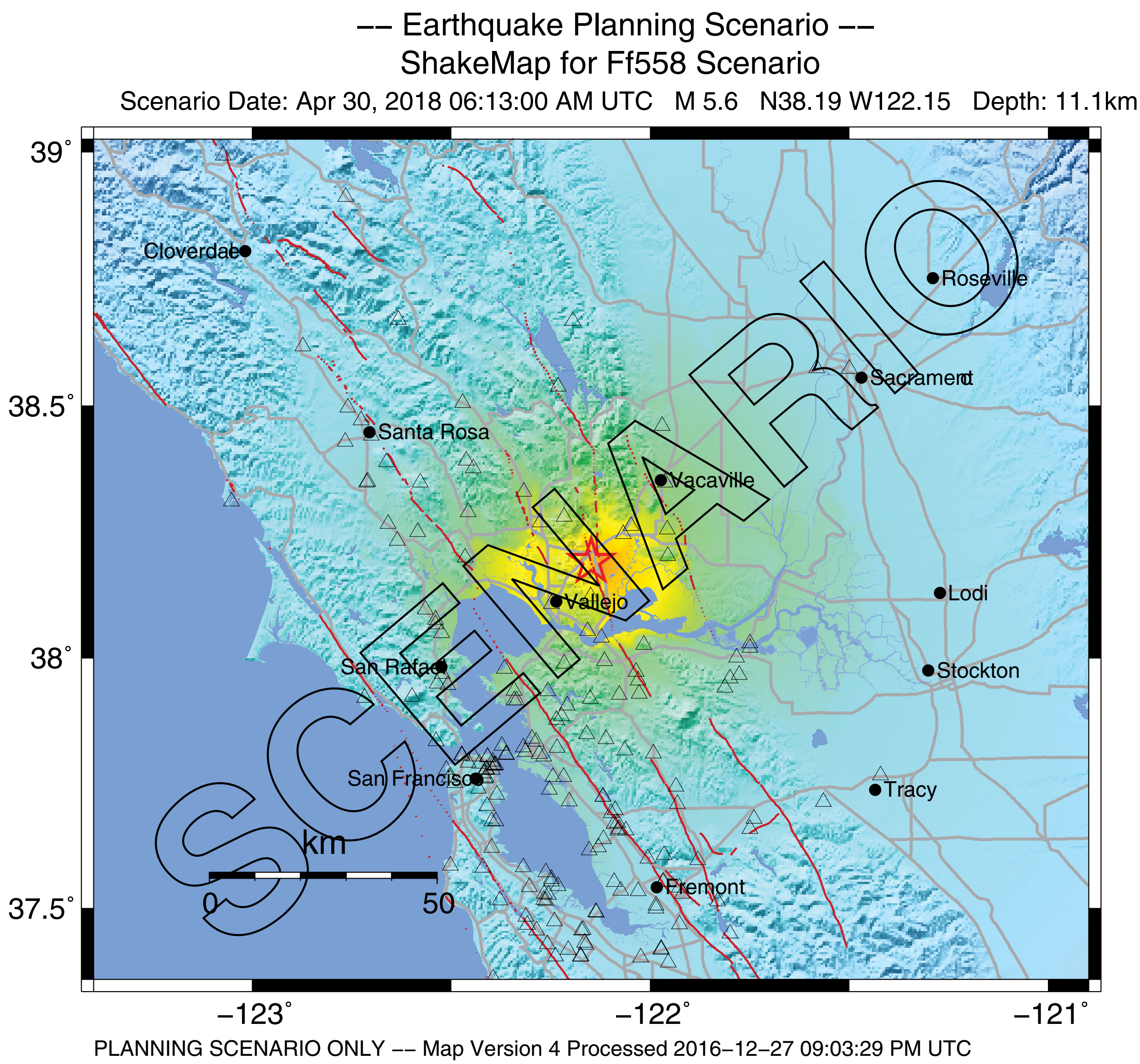
One should note that this number only represents subjects that fully completed DCHO before shaking began. Not every person may be able to fully complete DCHO in the population average time used for this study, but it is likely that DCHO may not need to be fully completed before the arrival of heavy shaking to have a benefit. As noted above, Lindell and others' (2016) Christchurch and Tohoku earthquake studies indicated that many injuries are trip and fall hazards. It therefore stands to reason that the "drop" part of DCHO is the most important step to prevent fall and trip injuries. Further studies could assess the benefits of "drop" or "hold" and the time required to complete these actions. DCHO is thought to be an effective strategy even in the absence of EEW, and a ShakeAlert warning message augments this strategy by providing the cognitive link between imminent earthquake shaking and the prescribed action to take. ShakeAlert messages could help increase the probability that DCHO will be performed.

Effective training should not be overlooked. A survey on EEW responses, outlined by Nakayachi and others (2019), suggests that "respondents seemed to place more value on mental preparation rather than reducing their chance of injury or death." People want an alert, but more social science research needs to be done to improve the incidence of DCHO responses within the short time frames provided by EEW and to reduce the time spent milling, that is, seeking confirmation and deciding what to do (Wood and others, 2017). This is supported by Nakayachi and others' (2019) observation that "the connection between receiving an EEW and swiftly moving through key psychological processes to undertake quick, deliberate protective actions has not yet been established."

ShakeAlert and Aftershocks

Aftershocks can occur following any earthquake. It should be noted that smaller aftershocks can vary in magnitude and can be more impactful than a mainshock in some areas, and a larger earthquake could also occur and become the new mainshock—as was the case in Japan in 2011, where a M_w 7.2 occurred offshore and was followed 2 days later by the M_w 9 Tohoku event. In the HayWired scenario, the M_w 7.0 mainshock is the beginning of an earthquake sequence in the San Francisco Bay region with aftershocks large enough to cause or aggravate damage and complicate emergency response and recovery (Wein and others, 2017).

Many aftershock sequences were generated by scientists for the Hayward fault rupture. We use a few earthquakes from the aftershock sequence selected for the HayWired scenario (Wein and others, 2017). The modeled HayWired aftershock sequence has 175 earthquakes of M_w 4 or larger that occur in



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<0.1***	***0.5***	***2.4***	***6.7***	***13***	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	***11***	***22***	***43***	***83***	***>160***
INSTRUMENTAL INTENSITY	**I**	**II–III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X+**

Scale based on Wald and others, 1999

Figure 6. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-5.6 Fairfield aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on April 29, 2018, at 11:13 p.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earthquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.

the 2 years following the mainshock, the largest of which is a M_w 6.4 event. We examine three of the larger aftershocks in this sequence and how recovery and ShakeAlert could work together (figs. 6–8). The selected aftershocks were chosen based on size, area of impact, and time of day, as well as elapsed time after the mainshock to assess a broad range of situations where EEW could be notable.

The analysis assumes that the ShakeAlert system continues to function and alerts are received by the public and organizations after the HayWired mainshock. ShakeAlert has redundant servers in three locations throughout the West Coast to ensure that even if one location experiences loss owing to shaking, other locations will still be able to push out alerts. Alerts would also be provided using multiple pathways (cellular, broadcast, and internet methods), which provide redundancy to increase the chances that alerts will get out. Physical damage to stations, communication lapses, or other effects could slow down alert delivery and result in shorter EEW times.

The first aftershock we consider is centered in Solano County near Fairfield, a M_w 5.6 event occurring 12 days after the mainshock on April 29, 2018, at 11:13 p.m. (fig. 6). For this event, the maximum expected shaking intensity is MMI VII. The area of strong shaking in this event does not overlap with the area of strong shaking during the mainshock, so there is an expectation that critical infrastructure in this area was likely not heavily damaged in the mainshock. We can also surmise that at 11:13 p.m. most people are at home and not working or commuting, so injuries sustained are likely to be fewer. We specifically highlight this aftershock to show that aftershocks can occur at some distance from the mainshock, especially to encourage organizations that use the HayWired scenario to construct or test resiliency plans to include contingencies for ShakeAlerts from such events. This also serves to remind readers that the no-warning zone of the mainshock will not always be the same for subsequent aftershocks. The EEW system is designed to help people in a broad region, not just those near the epicenter, so lifelines, businesses, and people could take this into consideration with their planning. The HayWired scenario mainshock is not likely to be the exact location of the next actual major earthquake on the HayWard Fault, so the covered populations could vary greatly.

The second aftershock we consider here is a M_w 5.4 event modeled to occur in Alameda County near Oakland on May 20, 2018, at 8:37 a.m. (fig. 7). At that time, 32 days would have passed since the mainshock. Infrastructure repairs would likely be ongoing in some areas because afterslip (fault movement after an earthquake) on the Hayward Fault of ~0.5–1.5 m (see Aagaard and others, 2017b) could continue to shift pipelines, roads, and utility conduits as the ground continues to move over time.

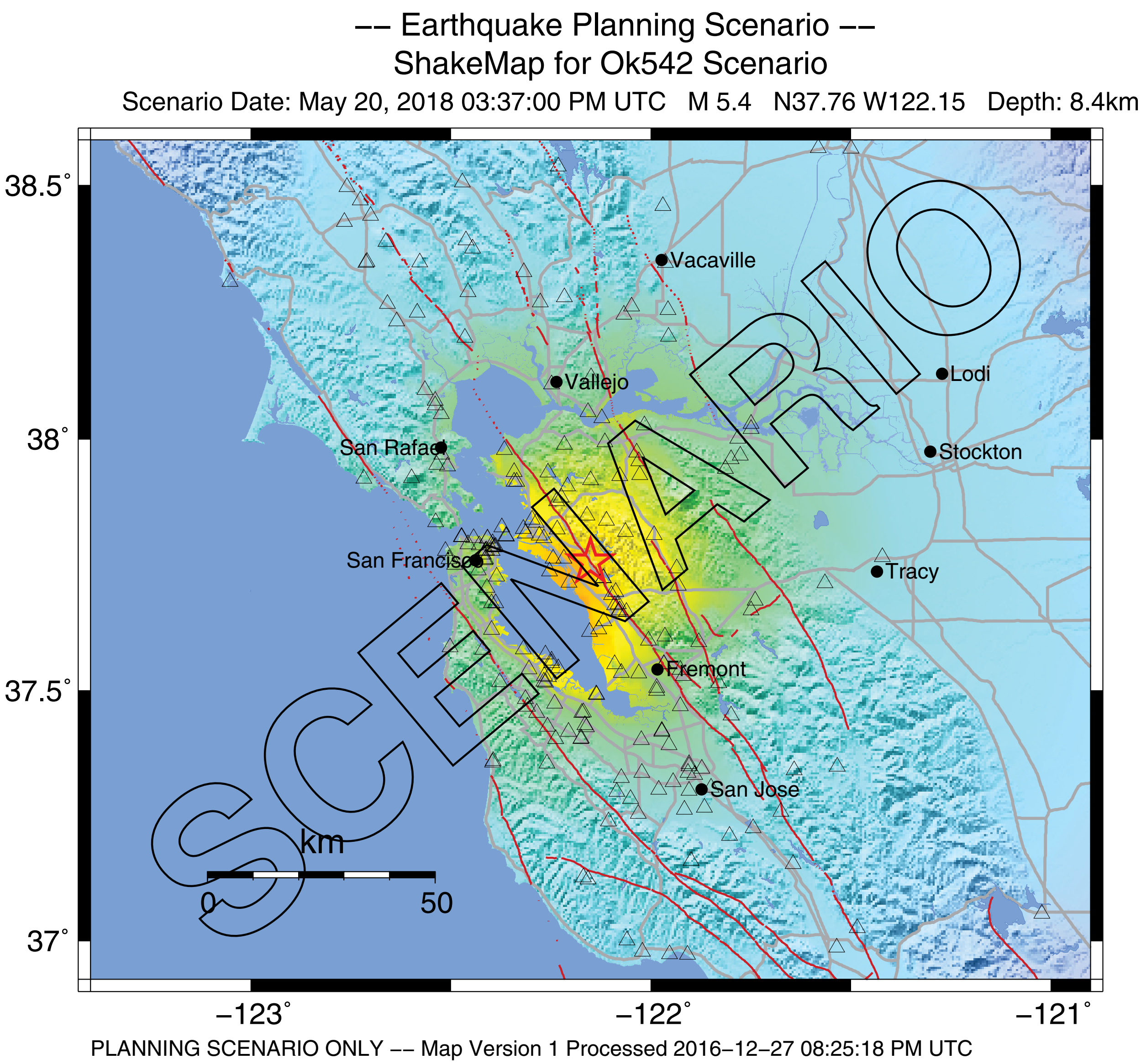
Land on the margins of the east bay side of San Francisco Bay that was already compromised by the mainshock and other aftershocks would be impacted by the strong shaking of this aftershock. In the Oakland area, those people at or heading to work, who were able to return to work since the mainshock, would be especially impacted by the shaking, as 8:37 a.m. is in the middle of morning rush hour. However, owing to the location and the less widespread heavy shaking, ShakeAlert may not be as effective for this area. Most of the heavily impacted locations with ongoing road repairs and unstable debris might be in the no-warning zone and may not receive sufficient warning for actions to be taken. This emphasizes the importance of restricting entry to dangerous areas. Repairs that were completed in the early weeks after the mainshock may now have to be redone.

Several of the larger HayWired aftershocks cluster in Silicon Valley (in the southern part of the San Francisco Bay region), hitting the area multiple times in the 2 years following the mainshock. This is a situation where (1) people will be continually rattled (as in Fairfield) and (2) multiple damaging earthquakes will wreak havoc on the recovery efforts. A M_w 6.4 aftershock in Santa Clara County near Cupertino on October 1, 2018, at 12:33 a.m. (fig. 8) follows close on the heels of a M_w 6.0 aftershock near Mountain View (also in Santa Clara County) 4 hours earlier. Although many repairs may not be underway during the night, response to the 8:16 p.m. M_w 6.0 event will have begun, and unstable debris and any repair work will likely be heavily shaken. In the M_w 6.4 aftershock, strong and very strong shaking would be felt over a large area of the south bay, so many people would receive a ShakeAlert warning. First responders activated in response to the earlier M_w 6.0 aftershock using ShakeAlert would know that another larger aftershock was on its way and might be more prepared to take self-protective actions. ShakeAlert could also help prioritize response to the aftershock before more detailed information is available.

The ShakeAlert warning could also help protect repair workers outside of the no-warning zone from unstable debris and other hazards caused by the M_w 6.0 aftershock. Bakun and others (1994) note that:

> Structures damaged in strong shaking are weakened and susceptible to additional damage and possible failure in subsequent shaking from aftershocks. More than 20 magnitude 4 and larger Loma Prieta aftershocks occurred in the month following the mainshock, each large enough to be widely felt in San Francisco and Oakland. Weeks after the shock, crews were still working in and near damaged structures in the Marina district of San Francisco and at the collapsed Cypress Street section of the 1-880 freeway in Oakland. The certainty of aftershocks in the weeks following the Loma Prieta earthquake posed a constant threat to the rescue and reconstruction crews working near weakened structures. Clearly the few tens-of-seconds warning of incoming strong shaking achievable in an early warning system provides a means to reduce this risk.

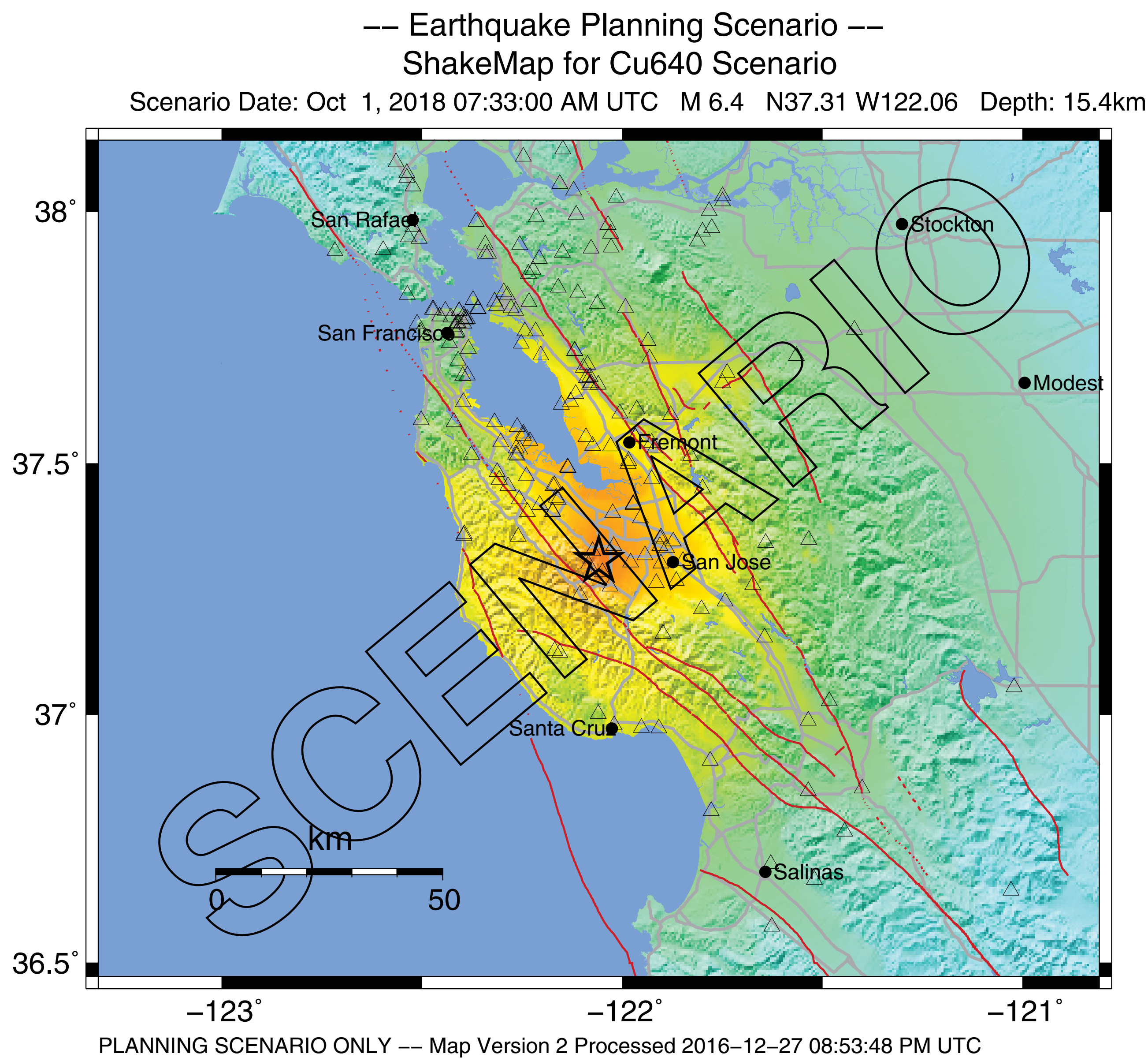
The damage done by continual aftershocks is not just to the built environment. A longitudinal study assessed the mental-health impact of the continuing aftershocks following the M_w 7.1 2010 Canterbury, New Zealand, earthquake



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<0.1***	***0.5***	***2.4***	***6.7***	***13***	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	***11***	***22***	***43***	***83***	***>160***
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based on Wald and others, 1999

Figure 7. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-5.4 Oakland aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on May 20, 2018, at 8:37 a.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earhquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	***<0.1***	***0.5***	***2.4***	***6.7***	***13***	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	***11***	***22***	***43***	***83***	***>160***
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based on Wald and others, 1999

Figure 8. U.S. Geological Survey ShakeMap (see https://earthquake.usgs.gov/data/shakemap/) of the San Francisco Bay region, California, for the moment-magnitude-6.4 Cupertino aftershock of the hypothetical HayWired scenario earthquake sequence on the Hayward Fault on October 1, 2018, at 12:33 a.m. For details of the HayWired aftershock sequence see Wein and others (2017). km, kilometer; peak acc., peak acceleration; peak vel., peak velocity; %g, amount of ground acceleration caused by the earthquake, expressed in terms of the percentage of gravity's acceleration at the Earth's surface; cm/s, centimeter per second.

(Spittlehouse and others, 2014). The researchers found that there was an increased prevalence of major depressive disorder and bipolar disorder in the study cohort in the 18 months after the earthquake. They also found “scores significantly lower than the population norms in the mental health, vitality, social functioning and role-emotional subscales” (Spittlehouse and others, 2014). ShakeAlert would not be able to prevent the psychological repercussions of major earthquakes, as described by Mooney and others (2011) after the 2010 Canterbury earthquake. Although there is evidence that more people opt to use EEW than not (Ohara and others, 2012), and the benefits include increasing their awareness and preparedness to take protective actions (Allen and others, 2017; Ohara and others, 2012), psychological benefits from using ShakeAlert (for a damaging earthquake or during an aftershock sequence) is an open research question.

Actions Discussed Elsewhere in the Literature

EEW is in use in several countries worldwide, including Japan and Mexico, and is a proven technology for hazard mitigation (Fujinawa and Noda, 2013; Lee and Espinosa-Aranda, 2003; Shimamura and others, 2001; Allen and Melgar, 2019). An exhaustive list of self-protective actions to take in response to EEW was not attempted for this chapter and only a few are highlighted, and automated controls in response to ShakeAlert warnings are still under development. To encourage discussion of ShakeAlert among those who may use the HayWired scenario to inform hazard mitigation strategies, several overviews of EEW in the literature are worth noting. However, not all EEW actions performed in other countries will be applicable or practical to enact in the United States.

Heaton and others (1985) pioneered the idea of using computer-based automated controls in conjunction with EEW to increase resiliency. This idea took hold, and now many EEW systems are in place worldwide that are aided by automated technology. A summary of these systems and EEW use cases can be found in Allen (2011). A more specific demonstration of capabilities for both the prototypic U.S. ShakeAlert system and the Japan Meteorological Agency’s approach to EEW are outlined by Burkett and others (2018), Fujinawa and Noda (2013), and Given and others (2014). Specific actions that can be taken to enhance the benefits of EEW include development of risk scenarios (for example, planned response protocols) in advance of an earthquake, such as described by Pittore and others (2014) and general-use case studies that include recovery and economic benefits as described by Strauss and Allen (2016).

Transportation systems can use EEW alerts to hold trains at station platforms and slow and stop trains that are enroute to reduce the chance of derailment and allow patrons and workers at stations to take protective actions, as discussed for the BART system in this chapter. Edwards and others (2015) extend this discussion beyond the San Francisco Bay region to look at transportation systems in Japan as well. Bridge and tunnel metering lights could be turned on to reduce the number of entering cars. Airports could make use of EEW alerts both inside and outside of terminals—baggage handlers can protect themselves before items fall, moving baggage carousels can be stopped to prevent damage, and alerts to patrons inside terminals could allow them to take self-protective actions.

Schools and hospitals both house vulnerable populations. EEW alerts in schools allow teachers and staff advanced warning to help their students to take DCHO actions and get to a safe space after shaking stops (Motosaka and Homma, 2009). Frequent drills help reinforce this training. In hospitals, surgeons can secure patients during surgery, delicate machinery like magnetic resonance imaging (MRI) machines can be put into a safe mode, and staff can take (as well as help patients take) self-protective action to ensure they are ready to respond once shaking ends (Horiuchi, 2009).

Fire following earthquake can be a large contributor to the postearthquake damage and is examined for the HayWired scenario by Scawthorn (2018). During the Northridge earthquake in 1994, many fire stations were seriously affected (Schneider, 1994). ShakeAlert triggers could be used to open firehouse doors before heavy shaking or loss of power occurs, enabling firefighters to exit with their equipment in a faster manner and more quickly respond to fires.

Work with ShakeAlert pilot groups in the water, gas, and electric distribution sectors, has shown that protecting both personnel and infrastructure with ShakeAlert will be a key to resiliency for a powerful earthquake. ShakeAlert warnings for utility workers in “cherry picker” lifts, out in the field, or in small tunnels are being assessed to ensure that these personnel are protected and services can get restored in a timely manner. Both water and gas systems could use ShakeAlert to trigger safety interlock systems for hazardous chemicals to reduce spills, fires, and explosions. Some groups are also exploring redirecting or securing certain sections of the utility grids.

Emergency responders help coordinate their disaster response and recovery efforts through incident command centers. Many in the San Francisco Bay region subscribe to the California Integrated Seismic Network Display to get accurate up-to-date information on earthquakes that have recently occurred. Groups in major cities and counties of the San Francisco Bay region are also piloting the ShakeAlert system through its UserDisplay (see https://www.shakealert.org/eew-research/caltech/shakealert-user-display/), which provides information on local shaking intensity, epicenter location, and event magnitude. ShakeAlert provides situational awareness to emergency responders so that they can more quickly and safely mobilize their teams and choose the best plan of action. Knowing right away where an earthquake epicenter is located and which areas likely experienced the most significant shaking can help the incident command team marshal resources to the correct areas for damage assessment and provide information on likely mutual aid from outside areas that were not as affected. The importance of this was seen in the M_w 6.0 2014 South Napa, California, earthquake, when many local first responders initially assumed that the epicenter was near San Francisco. Had they been using ShakeAlert at the time, they would have known right away that mutual aid was likely coming their way and to prepare for that fact.

Conclusion

The HayWired earthquake scenario presents a framework to envision ShakeAlert's contribution to protecting local populations and infrastructure and reduce cascading failures in the aftermath of a major urban earthquake in the San Francisco Bay region. The most recent major earthquakes in this region—the M_w 6.0 2014 South Napa and M_w 6.9 1989 Loma Prieta earthquakes—are often reference points for people when they imagine what a Hayward Fault event could look like. Unfortunately for planning purposes, the South Napa earthquake was much smaller than the M_w 7.0 mainshock modeled in the HayWired scenario, and the epicenter of the Loma Prieta earthquake, although of similar magnitude, was not directly under a densely built urban environment. Thus, "tabletop" exercises using the HayWired scenario can better support proper planning and forecasting of risk reduction benefits, including those derived from ShakeAlert.

In closing, we would like to outline some limitations of ShakeAlert and the assumptions we made, as well as areas for future analysis. ShakeAlert is a tool for improving resiliency; however, building retrofits, improvements to building codes, and lifeline coordination will continue to be crucially important, even when a full public ShakeAlert system is in place. Fire following earthquake is a major source of loss in the HayWired scenario. Therefore, end users who use ShakeAlert in their critical facilities might consider assessing whether automated controls can be put in place that use the alerts to reduce ignition sources. As mentioned earlier, current regulations in California prohibit internet-distributed ShakeAlert warnings to trigger switches on elevators to cause them to remain open at the nearest floor. Changes to these regulations would need to be undertaken to permit these automated controls to be put into practice.

The ShakeAlert system will also need to explore a varied landscape of alert redistribution methods to ensure broad coverage and uptake of the system. Working with groups such as the Alliance for Telecommunications Industry Solutions will likely be needed to develop longer term alert delivery solutions so that future technologies can better serve the end user. As part of the 2018 limited public rollout of ShakeAlert, pilot users and technology enablers are exploring the landscape of options. Any policies on alert distribution need to also consider that notifications should be equitable and cover a number of different groups, including those with access and functional needs, people without access to cellular networks, and technical users who require more detailed information. The public will need to be made aware that broad alert distribution channels may cause them to be alerted when they may not personally feel shaking at their location. More technical users will also need to be made aware that the design of automated controls need to take this into consideration and not be precisely dependent on strict shaking values. A full public ShakeAlert system can have many benefits for people, including the possibility to begin the drop, cover, and hold on recommended action before shaking onset. However, public use of ShakeAlert will require an ongoing education and training campaign to be effective. The U.S. Geological Survey's Joint Committee for Communication, Education, and Outreach will need to work with State and local officials to develop a long-term strategy to engage the public. This will be especially necessary during times of low earthquake activity, so that preparedness remains fresh in the public's memory.

The HayWired scenario provides the first glimpse of ShakeAlert's role in resiliency and postearthquake recovery in the San Francisco Bay region. We envision a future where a broader landscape of automated responses and uses for ShakeAlert are identified and implemented. Organizations who use the information in this chapter should be aware that the solutions outlined here have not been fully developed or tested in the United States. Also, the epicenter for an actual large earthquake on the Hayward Fault may be in a different location with a different magnitude, so ShakeAlert times could geographically vary significantly from what is outlined here. Policymakers and end users would be best served by using this chapter about the potential immediate responses to ShakeAlert warnings in concert with longer term earthquake mitigation actions and planning.

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