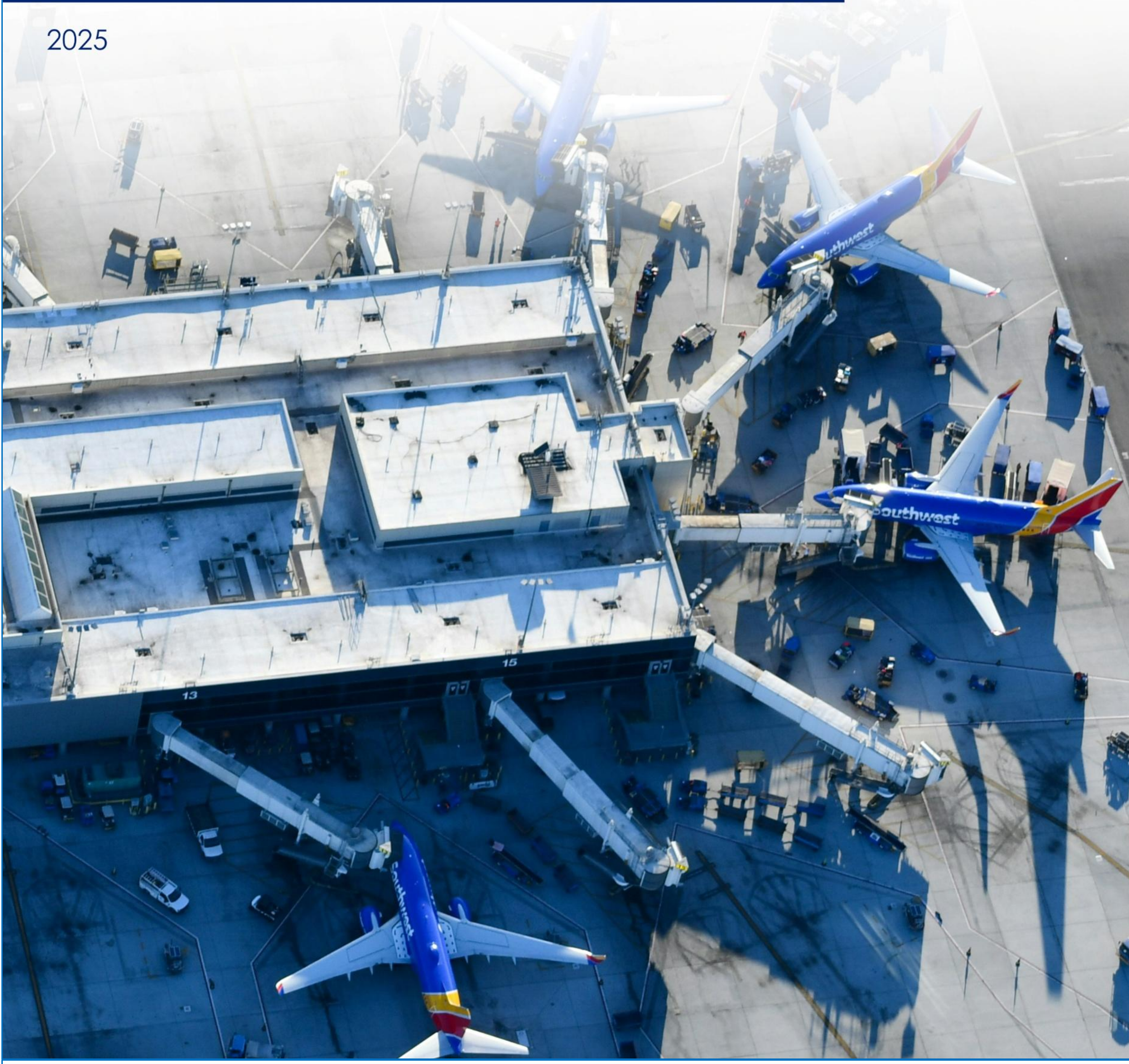
Enhancing Airport Resilience with Earthquake Early Warning

2025



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Executive Summary

Airports play a critical role in disaster response and recovery, yet they remain vulnerable to seismic events that can disrupt operations and jeopardize safety. Earthquake Early Warning (EEW) systems offer a potential strategy by providing critical seconds to minutes of advance notice, enabling proactive measures to mitigate damage, reduce injuries, and enhance resilience. This report examines the feasibility and potential benefits of EEW implementation at airports, focusing on historical earthquake impacts, current EEW technologies, and case studies at Palm Springs International Airport (PSP) and Los Angeles International Airport (LAX).

This study employs a multi-method approach to assess the potential benefits and challenges of EEW integration in airport operations. First, a historical analysis of past earthquakes and their impacts on airport infrastructure identifies key vulnerabilities. Second, a review of the California EEW System (CEEWS) and ShakeAlert, which will evaluate current capabilities and limitations. Additionally, to evaluate the economic feasibility of EEW at airports, this report includes a benefit-cost analysis (BCA) comparing implementation costs against potential savings from reduced damage, operational disruptions, and injuries. Costs considered include the EEW system installation, maintenance, staff training, integration with airport infrastructure, and specific costs associated with each application. Benefits are computed using a methodology that aggregates the seismic hazard and the fragility of various infrastructure systems and components at the airports and quantifies the consequent reductions in injuries, damage, downtime, and emergency response costs. By examining different implementation scenarios, this analysis helps determine whether EEW investments provide a net positive return for airport resilience and safety. PSP and LAX case studies provide insights into site-specific considerations for EEW implementation and report the benefit-cost ratios (BCRs) for different EEW applications. Applying a methodology that uses the fragility of relevant infrastructure as a function of ground shaking, shaking intensity thresholds are calculated for each EEW application at different risk levels that ensure safety and operational continuity. Finally, a qualitative assessment of stakeholder perspectives—including airport operators, emergency responders, and others—helps inform practical recommendations for integrating EEW into airport emergency management protocols.

Through this analysis, the report identifies strategies for integrating EEW into airport operations to improve emergency preparedness and response. These strategies include:

- **Enhanced Communication Protocols** – Establishing real-time alert distribution systems to notify air traffic controllers, ground personnel, and passengers via public announcement systems, mobile alerts, and operational dashboards.
- **Automated Response Systems** – Integrating EEW with critical airport infrastructure to trigger automated safety actions, such as stopping elevators at the nearest floor, shutting off fuel and gas lines, and opening fire station bay doors to prevent emergency vehicle entrapment.
- **Operational Planning and Training** – Developing emergency response procedures tailored to EEW, including staff training on immediate protective actions and coordination with local emergency services.
- **Infrastructure Resilience Measures** – Highlighting the obvious EEW limitations that cannot and should not replace seismic retrofitting and infrastructure improvements, particularly for airport structures that should remain operational after major earthquakes, such as control towers, terminal buildings, and fuel storage facilities.
- **Scalability and Regional Coordination** – Encouraging broader EEW adoption across multiple airports within a region to enhance collective response capabilities and minimize disruptions to California's air travel network.

By expanding EEW adoption across multiple airports within a region, California's regions can enhance collective resilience and ensure a more coordinated response to seismic events. A regional EEW approach could enable enhanced information sharing, standardized protocols, and improved resource allocation during seismic disruptions. By integrating EEW into California's airport network, the system could help mitigate cascading impacts on air travel, ensuring that even if one airport is affected, others in the region can adapt and support continued operations. This coordinated strategy has the potential to strengthen overall seismic preparedness and enhance passenger and staff safety.

1 Introduction

Airports play a critical role in disaster response and recovery, yet they remain vulnerable to seismic events that can disrupt operations and jeopardize safety. Earthquake Early Warning (EEW) systems offer a potential strategy by providing critical seconds of advance notice, enabling proactive measures to mitigate damage, reduce injuries, and enhance resilience. EEW provides advanced warning by detecting initial seismic waves and issuing alerts before the arrival of more damaging ground motion. This warning window allows for protective actions such as stopping elevators, securing critical infrastructure, and notifying staff and passengers. The feasibility and effectiveness of EEW depend on several factors, including technological capabilities, response protocols, and integration with airport emergency management systems.

This report examines these factors by analyzing historical earthquake impacts on airports, evaluating current EEW technology, and assessing case studies from Palm Springs International Airport (PSP) and Los Angeles International Airport (LAX).

The report is structured as follows:

- **Section 2: Earthquakes and Airports** – This section provides an overview of historical earthquake impacts on airports, including both international and California-specific case studies. It highlights structural vulnerabilities, operational disruptions, and the role that EEW could have played in mitigating damage. This section also introduces the case study airports, PSP and LAX, which serve as focal points for assessing EEW implementation.
- **Section 3: EEW Systems** – This section explores EEW development and functionality, focusing on the California EEW System (CEEWS) and ShakeAlert. It details EEW history, ShakeAlert technical capabilities, and current EEW implementations across different sectors and applications.
- **Section 4: Airport Uses for EEW** – This section examines specific EEW applications within the airport environment, including public and staff notifications, automated responses such as fuel shutoff and fire station door releases, and air traffic control (ATC) procedures. Case studies from PSP and LAX illustrate potential EEW integration benefits and challenges.

- **Section 5: Airport Acquisition and Implementation Considerations** – This section outlines the steps involved in adopting EEW at airports, including institutional goals, regulatory considerations, infrastructure integration, cybersecurity concerns, and phased implementation strategies. It discusses different pathways airports can take to implement EEW, along with potential adoption barriers.
- **Section 6: EEW Implementation Benefit-Cost Analysis (BCA)** – This section evaluates the financial viability of EEW in airport settings. It compares implementation costs, including equipment, installation, maintenance, and training, to potential benefits, such as reduced injuries, minimized infrastructure damage, and operational continuity. Using a methodology based on earthquake hazard quantification and structural responses that characterize the fragility of different infrastructure, this section provides an assessment of the monetary benefits and costs of different EEW applications and provides insights about whether EEW investments yield a net positive return for airport resilience and safety. Using a methodology that uses the fragility of relevant infrastructure as a function of ground shaking, shaking intensity thresholds are calculated for each EEW application at different risk levels that minimize the chances of false alarms, and ensure both safety and operational continuity.
- **Section 7: Conclusion and Recommendations** – The final section synthesizes key findings and provides actionable recommendations for integrating EEW into airport emergency management. It also emphasizes the importance of scalability and regional coordination, advocating for broader EEW adoption across multiple airports to enhance collective response capabilities and minimize disruptions to California's air travel networks.

By examining these topics, this report aims to provide a comprehensive understanding of how EEW can strengthen airport resilience, reduce earthquake-related risks, and improve emergency response. Through technical analysis, case studies, and BCA, it offers practical guidance for airport operators, policymakers, and emergency planners seeking to implement EEW as part of a broader seismic preparedness strategy.

2 Earthquakes and Airports

Earthquakes pose significant risks to critical infrastructure, including airports, which serve as vital hubs for emergency response and recovery operations. Seismic events can result in both structural and nonstructural damage, disrupting airport operations, limiting accessibility, and compounding the overall disaster impact. Understanding past earthquake events and their impact on airport facilities is crucial for enhancing resilience and developing effective mitigation strategies.

This section includes four subsections. The first examines international historical case studies and the role EEW could have played in reducing losses and enhancing emergency response. The second examines historical California case studies and the role EEW could have played. The third discusses the seismic vulnerability of California airports. The fourth introduces PSP and LAX, the case study airports examined as part of this research.

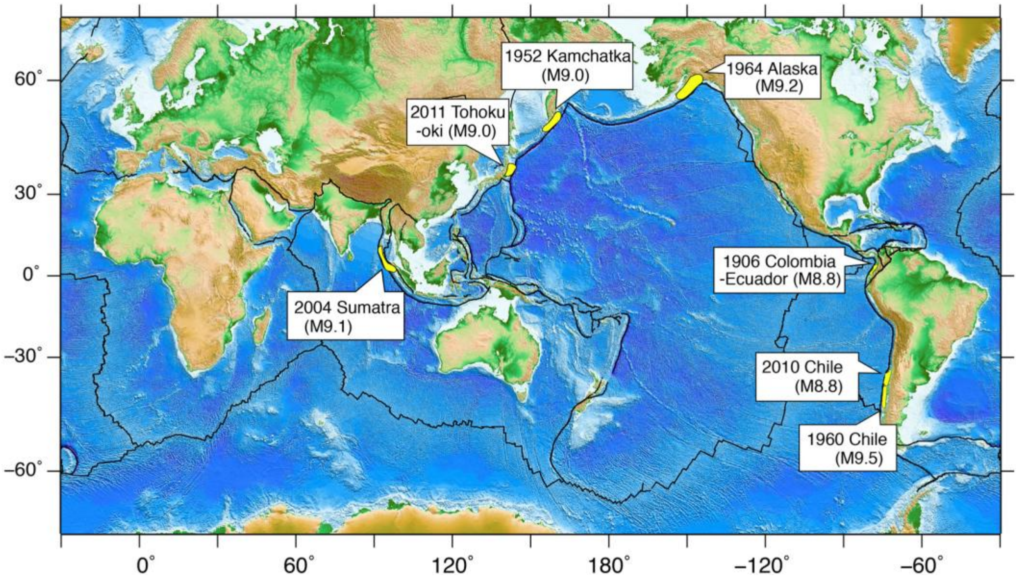
2.1 Historical Examples – International

This section provides an overview of three major earthquakes—2004 Sumatra, Indonesia; 2010 Chile; and 2011 Tohoku-oki, Japan—and their impacts on airport infrastructure. Each case study highlights the types of damage sustained, operational disruptions, and the role that EEW systems could have played in reducing losses and improving response efficiency.

2.1.1 2004 Sumatra, Indonesia, Earthquake

The magnitude 9.1 Sumatra earthquake occurred on December 26, 2004, at 7:58 a.m. local time, with a focal depth of 30 km and an epicenter located off the west coast of Aceh Province in northern Sumatra, Indonesia (United States Geological Survey [USGS], 2004). This event is one of the largest instrumentally recorded earthquakes (Kanamori, 2006). It ruptured the boundary between the Indo-Australian plate and the Eurasian plate along northwestern Sumatra (Figure 2.1). The earthquake and subsequent tsunami caused extensive damage and the death of 283,000 people (Lay et al., 2005).

Figure 2.1. Location of the 2004 Sumatra Earthquake and Global Distribution of Instrumentally Recorded M > 8.8 Earthquakes[1]



Scawthorn et al. (2006) conducted a survey of the earthquake and tsunami's impact on lifelines[2]. In Banda Aceh, the closest major city to the epicenter. The survey, conducted from March 1-6, 2005, included contacting lifeline operators for information, visiting key lifeline-related sites, and observing the effects of the earthquake and tsunami. The general finding was that airports suffered moderate earthquake-related damage to runways and terminal buildings (Scawthorn et al., 2006). Banda Aceh's largest airport, the Sultan Iskandar Muda International Airport, was not affected by the tsunami, and the earthquake damage was relatively light. Due to cracking in the ATC tower, air traffic services were provided from the old portable tower (Figure 2.2), and the airport managed traffic without notable disruptions. The damage cost at this airport was estimated at $0.2 million (The Ministry of National Development Planning of the Republic of Indonesia [BAPPENAS] 2005). The earthquake also affected other airports. Three airports in the region experienced runway settlement and cracking. There was damage to flight safety equipment and Very High Frequency and Single Sideband communications equipment in two of the airports. BAPPENAS (2005) categorized earthquake impacts on airports into four

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[1] Uchida & Bürgmann, 2021. The 2010 Chile and 2011 Tohoku-oki, Japan, earthquakes are discussed in following subsections. The yellow polygons schematically illustrate the surface projection of rupture areas.

[2] Lifelines provide the networks for delivering resources and services necessary for the economic well-being and security of modern communities. They are frequently grouped into six principal systems: electric power, gas and liquid fuels, telecommunications, transportation, waste disposal, and water supply (National Earthquake Hazards Reduction Program, 2010).

groups: (a) direct losses, encompassing costs of repairs of damaged airport infrastructure, (b) indirect losses from business interruption, (c) airport revenue losses, and (d) airport operating cost increases. A key benefit of EEW is defined as the reduction of losses. Therefore, this categorization is particularly helpful for BCA.

Figure 2.2. Cracking in the Control Tower and Portable Control Tower at Banda Aceh Airport[3]

2.1.2 2010 Chile Earthquake

On February 27, 2010, at 03:34 a.m. local time, a powerful earthquake with a magnitude of 8.8 struck central Chile (Figure 2.1). The epicenter was located approximately 8 km off the Chilean coast in the central region. The earthquake had an inclined rupture area spanning over 80,000 km^2, extending on shore and directly impacting the region of Maule. The intense shaking lasted for at least 100 seconds. According to the Ministry of Interior of Chile, the earthquake resulted in the death of 521 people, with nearly half of the fatalities caused by the subsequent tsunami. Fatalities, injuries, and displacement directly affected over 800,000 people. More than 300,000 buildings sustained damage, including several cases of total structural collapse (Elnashai et al., 2010).

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[3] Cracking in the control tower (red rectangle) and portable control tower (yellow rectangle) of the Banda Aceh Airport used for maintaining regular air traffic operations. Adopted from Scawthorn et al., 2006.

Arturo Merino Benítez International Airport (also known as Santiago Airport), located in Santiago, is Chile's primary airport. Although the airport suffered only minor structural damage, it experienced excessive nonstructural damage (Figure 2.3). This included damage to more than 80% of the ceilings throughout the airport, damage to light fixtures, collapse of most suspended air handling units, damage to air conditioning ducts, damage to cable trays, breakage of fire sprinkler piping with extensive water damage at retail spaces, collapse of hot water piping, damage to partition walls and glazing, damage to hydraulic elevators, and more (Miranda et al., 2012). Insured direct losses from physical damage at the airport were estimated at $40 million (Aon Benfield, 2010). In terms of indirect losses, the cost of the earthquake to LAN Airlines, the national airline in Chile, was approximately $25 million in lost passenger traffic alone (LAN Airlines, 2010). After a 4-day closure, the airport resumed partial operations.

Figure 2.3. Nonstructural Damage at the Santiago Airport[4]

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[4] First row: fallen pieces due to ceiling collapse; second row: damage to suspended ceilings; third row: damage to cable tray systems; fourth row: failure of anchorage in HVAC equipment suspended from ceiling (Miranda et al., 2012).

Carriel Sur International Airport (CCP) in Concepción, the second largest airport in Chile, also suffered major water damage, with 5 in. of water accumulated throughout the main terminal building, caused by damaged fire sprinkler heads. The hydraulic elevators, glazing, and ceiling were also damaged.

2.1.3 2011 Tohoku-oki, Japan, Earthquake

The Tohoku-oki earthquake occurred off the Pacific coast of the Tohoku region of Japan on March 11, 2011, with a magnitude of 9.0 and a rupture area of about 300 × 200 km (USGS, 2011, Figure 2.1). The strong shaking and resulting tsunami caused devastating damage, including the collapse of 121,996 houses and as many as 19,729 deaths (Fire and Disaster Management Agency, 2011). Earthquake early warning and tsunami warnings were issued by the Japan Meteorological Agency; however, the initial warnings underestimated the impending shaking and tsunami (Hoshiba & Iwakiri, 2011).

Hanaoka et al. (2013) interviewed several organizations in three airports in the earthquake-impacted region—Hanamaki, Yamagata, and Fukushima—to document damage, interruptions to operations, and lessons learned in these airports after the 2011 Tohoku-oki earthquake.

In Hanamaki Airport airside facilities, such as runways, aprons, and aviation lights, did not experience any damage; however, there was severe damage to the pavement of the maintenance road. Cracks were observed on the walls and floors of the passenger terminal building, and some parts of the equipment mounted on the ceiling fell (Hanoka et al., 2013). Two of the three transformers in the terminal building were completely damaged, and there was a power outage in the building for almost 2 days. Due to the power outage and structural inspections, the terminal building was closed for nearly 4.5 days, resulting in reduced airport operations. Backup power that immediately activated upon EEW notification could have possibly reduced the downtime of this terminal building.

At Yamagata Airport, no runway damage was observed. There was nonstructural damage in some airport facilities, such as broken mounts on the flight information service (FIS) terminal monitors, fallen light fixtures, and water leaks (Hanaoka et al., 2013). The Nippon Telegraph and Telephone (NTT) line dedicated to ATC authorities did not function for a few days after the earthquake, affecting some ATC operations. In addition, the FIS terminals were disconnected from the server for a day, disabling flight plan-related data entry.

There was a power outage after the earthquake, and the airport used a backup generator during this time. The NTT line malfunction and server issue might have occurred between the onset of the power outage and activation of the backup generator, although there is no direct evidence to confirm this.

In Fukushima Airport, almost all windows of the ATC tower were broken, although aircraft support operations continued using the emergency aircraft communication equipment. The water supply was suspended for almost 3 days. During this period, the water tank and water trucks supplied clean water. The commercial power supply experienced a 5-minute outage. A backup generator was activated and used during this time. There was difficulty with phone connections. Only one out of 10 calls was successful, even when using an emergency phone. During the earthquake, airport building staff waited for the shaking to stop and then directed passengers to go outside the building in accordance with the evacuation guidelines (Hanaoka et al., 2013). Like the EEW directives in California, which recommend the "Drop, Cover, and Hold On" protocol rather than evacuation during the earthquake (Earthquake Country Alliance, 2024), passengers were evacuated only after the earthquake ground shaking stopped. After passenger evacuation, airport operations were suspended to allow inspection of facilities. The inspection took approximately half an hour and reported that there was no damage that could cause interference with flight operations, allowing operations to resume.

2.2 Historical Examples – California

There have been several major earthquakes in California in the past century that both improved the understanding of seismic response of the built environment and the corresponding consequences and resulted in changes to the seismic provisions in building codes. The following subsections discuss airport earthquake performance during some of these earthquakes and the implications for EEW.

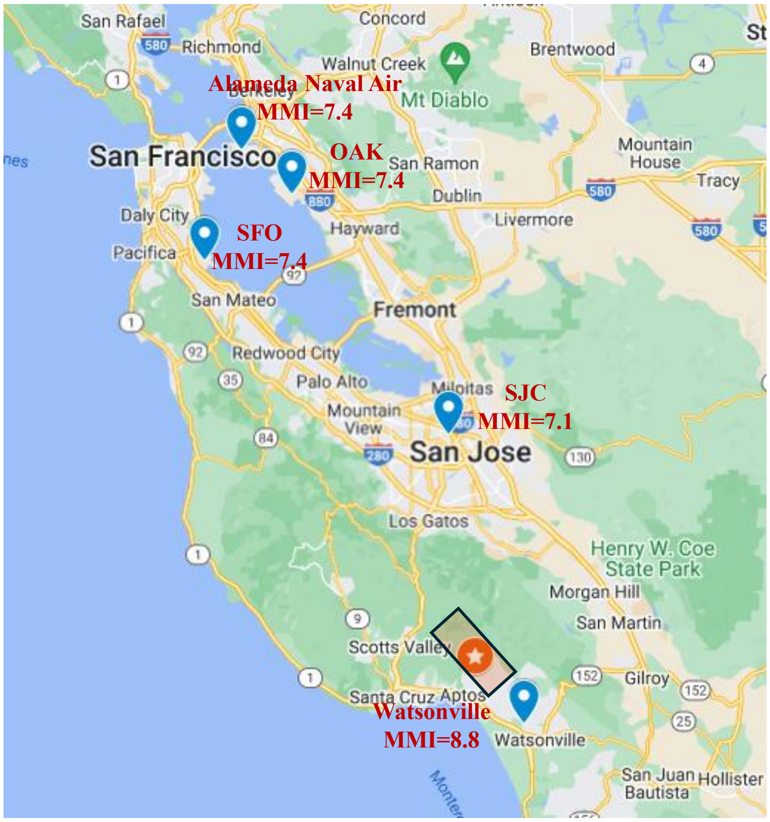
2.2.1 1989 Loma Prieta Earthquake

The October 17, 1989, Loma Prieta earthquake was a magnitude 6.9 earthquake with a focal depth of 17.2 km and epicentral coordinates of 37.036°N 121.880°W (USGS, 1989a). This earthquake occurred in the Loma Prieta area of the Santa Cruz mountains near the border of Santa Cruz and Santa Clara counties. The earthquake caused significant damage in nearby cities, such as Santa Cruz and Watsonville, and in major urban centers, like Oakland

and San Francisco (Kroll et al., 1991). The earthquake caused varying levels of damage and operational disruption to airports in the earthquake-impacted region.

Figure 2.4 shows the airports in the region impacted by the earthquake, the shaking intensity at these locations, the earthquake's epicenter, and the surface projection of the fault trace that caused the earthquake.

Figure 2.4. Airports Impacted by the Loma Prieta Earthquake[5]



San Francisco International Airport (SFO) is approximately 36.5 miles from the Loma Prieta earthquake fault rupture (Figure 2.4). The Pacific Earthquake Engineering Research (PEER) Center[6] has a well-established, web-based,

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[5] Airports impacted by the Loma Prieta Earthquake including shaking intensities (MMI), earthquake epicenter (star), and surface projection of the fault trace (rectangle).

[6] The Pacific Earthquake Engineering Research Center (PEER), https://peer.berkeley.edu, is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities, several consulting companies, plus researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering in disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, risk management, and public policy. The PEER mission is to develop, validate, and disseminate performance-based seismic design technologies for buildings and infrastructure to meet the diverse economic and safety needs of owners and society.

publicly available ground motion database (GMD) of worldwide and local strong ground motion data and supporting metadata (Chiou et al., 2008; Ancheta et al., 2014; PEER, 2024). As documented in the PEER GMD, the recorded Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) at SFO during the Loma Prieta earthquake were 0.29 g and 25.4 cm/s, respectively. Using the relationship between Modified Mercalli Intensity (MMI) and PGA&PGV (Worden et al., 2012), this corresponds to an MMI value of 7.4. At this distance from the earthquake source (36.5 miles), a lower level of shaking would typically be expected; however, the experienced shaking at SFO was intensified by local soil conditions. In saturated soils, increased groundwater pressure during an earthquake considerably reduces soil strength and stiffness by breaking the contact between the soil particles, a phenomenon known as liquefaction. Liquefaction caused some small support structures to shift. It is noted that EEW cannot reduce or eliminate such geotechnical and structural damage.

The runways, aviation lights, navigation equipment, fuel tanks, and piping at SFO were mostly unaffected. The control tower experienced window breakage and nonstructural damage, and some unanchored equipment was broken. There was also nonstructural damage in the terminals and an air cargo building. An issue occurred with a power transformer, and the power outage due to this issue was restored within 3 hours. EEW could reduce consequences caused by nonstructural damage and power loss. Air cargo buildings that include a baggage system could also benefit from EEW. Flights were suspended on the night of the earthquake primarily because there were not enough controllers to operate the tower safely (Earthquake Engineering Research Institute [EERI] 1990; Association of Bay Area Governments [ABAG] 2000).

Oakland International Airport (OAK) is located approximately 38.5 miles from the earthquake source (Figure 2.4), but OAK and the adjacent Port of Oakland experienced PGA of almost 0.3 g, PGV of 27.6 cm/s (USGS, 1989b), and corresponding MMI of 7.4 due to local soil conditions. The main OAK runway experienced major damage. The 10,000-ft runway, built on hydraulic fill over bay mud, was severely damaged due to settlement caused by liquefaction, and 3,000 ft of the runway experienced large cracks, with widths and depths up to a foot (ABAG, 2000). Lateral spreading of the adjacent unpaved ground resulted in cracks up to 3 ft wide. Large sand boils appeared on the runway and adjacent taxiway, with a few as wide as 40 ft (EERI, 1990). An adjacent taxiway was also damaged by liquefaction. As a result, OAK was immediately shut down to evaluate runway damage (ABAG, 2020). The main runway was reopened within a couple of hours with a usable length of 7,000 ft, which is 70% of its full length. This shorter length impacted cargo loads during takeoff. During this time, a shorter 6,212-ft general aviation runway was used to accommodate diverted air traffic. A 1,500-ft portion of the 3,000-ft damaged section of the main runway was repaired over the next month using an emergency repair order for resurfacing. Repairs of the damaged taxiway segment and the final 1,500 ft of the main runway were completed 6 months later (ABAG, 2000). Total repair cost due to earthquake damage was approximately $6.8 million, including $3.5 million for runway repairs, $2.2 million for taxiway repairs, and $1.1 million for other damage repairs (ABAG, 2000). EEW cannot prevent damage to runways or taxiways; however, in airports with liquefaction susceptibility, it could help reduce impacts by notifying relevant staff (e.g., those working in the taxiway) and delaying or diverting landings. The latter is more complicated due to external factors, such as Federal Aviation Administration (FAA) regulations, ATC coordination, and logistical constraints regarding passenger accommodation.

In the Loma Prieta earthquake, both telephone service and the usable radio frequency became quickly overloaded at OAK. Consequent challenges with post-earthquake communications affected both the cleanup crews and the public on site at the time of the earthquake. Since the Loma Prieta earthquake, extreme advancements in telecommunications combined with the development of new infrastructure are expected to provide superior performance and reliability. However, these new communication systems have not been tested in major earthquakes near urban centers in California. Other damage in OAK was limited; three windows were broken in the control tower, a walkway between terminals was damaged, and a water main ruptured, causing damage to a service road (EERI, 1990).

San José Mineta International Airport (SJC) is located approximately 15 miles from the Loma Prieta earthquake fault rupture (Figure 2.4) and experienced PGA, PGV, and MMI of 0.17 g, 30.9 cm/s, and 7.1. respectively (USGS, 1989b). The airport immediately closed for inspections of runways, the ATC tower, terminal buildings, and other structures (ABAG, 2000). It was observed that a window of the control tower was broken, along with other nonstructural damage. Minor nonstructural damage was observed at the terminal building. Utility power was lost for over 5 hours, but backup generators worked well. These issues were not considered major, and the airport reopened and was fully operational soon after the earthquake. The emergency plan for natural disasters, in place at the time of the earthquake, worked well based on information from the airport staff (ABAG, 2000). This plan spelled out procedures relating to duties, communications, and inspection procedures. In the case of EEW implementation, emergency plans at airports need to be updated to include EEW notifications and automated actions.

Naval Air Station Alameda is 44.1 miles from the Loma Prieta earthquake fault rupture (Figure 2.4). Recorded PGA, PGV, and corresponding MMI were 0.23 g, 32.4 cm/s (PEER, 2024), and 7.4, respectively. The terminal building was closed due to structural damage (ABAG, 2000). Substantial liquefaction led to the closure of both the 8,000-ft and 7,200-ft runways. The two runways were repaired and reopened in 4 months. The helicopter pads were not damaged and were used during emergency operation (EERI, 1990). Damage occurred to the water and gas distribution systems, but power was not disrupted (ABAG, 2000). This airport closed in 1995 and is not currently in operation (ABAG, 2000).

Watsonville Municipal Airport, at 6.5 miles, is the closest airport to the Loma Prieta earthquake fault rupture (Figure 2.4). Recorded PGA and corresponding MMI were 0.66 g (Center for Engineering Strong Motion Data, CESMD, 1989), and 8.8, respectively. This airport, with two 4,000-ft runways, experienced a power outage and lacked emergency generators. Nighttime flight departures were halted due to unlit runways. Additionally, hangar doors in one of the airport buildings fell from their support rails (ABAG, 2000). This is one type of hangar door damage; another type is racking of the door, which prevents it from opening. This is a concern for fire stations serving airports. EEW benefits include preventing fire trucks from being trapped by jammed doors. Despite these issues with the Watsonville airport, it played a crucial role in emergency relief efforts. On average, 25 military flights operated daily, and over 300,000 pounds of emergency supplies were delivered via more than 100 small aircraft landing at this airport (EERI, 1990; ABAG, 2000). These observations show that continued operation due to EEW could provide both the direct benefits discussed throughout the report and indirect benefits, such as contributing to emergency relief efforts.

Because of reduced operations at the airports discussed, flights were diverted outside of the Bay Area, namely to Sacramento International Airport (SMF). To manage the increased flight traffic at SMF, an emergency recall of fueling staff was ordered to assist with refueling aircraft, escorting vehicles, and handling flight plans and fueling paperwork. The airport accepted a total of 40 diversions in the first 5 hours after the earthquake (ABAG, 2020). The second runway and some taxiways were used to park incoming aircraft. Despite the additional traffic due to diverted flights, no domestic flights at SMF were canceled. Some international flights landed and refueled, but passengers were kept on board because no international facilities were available.

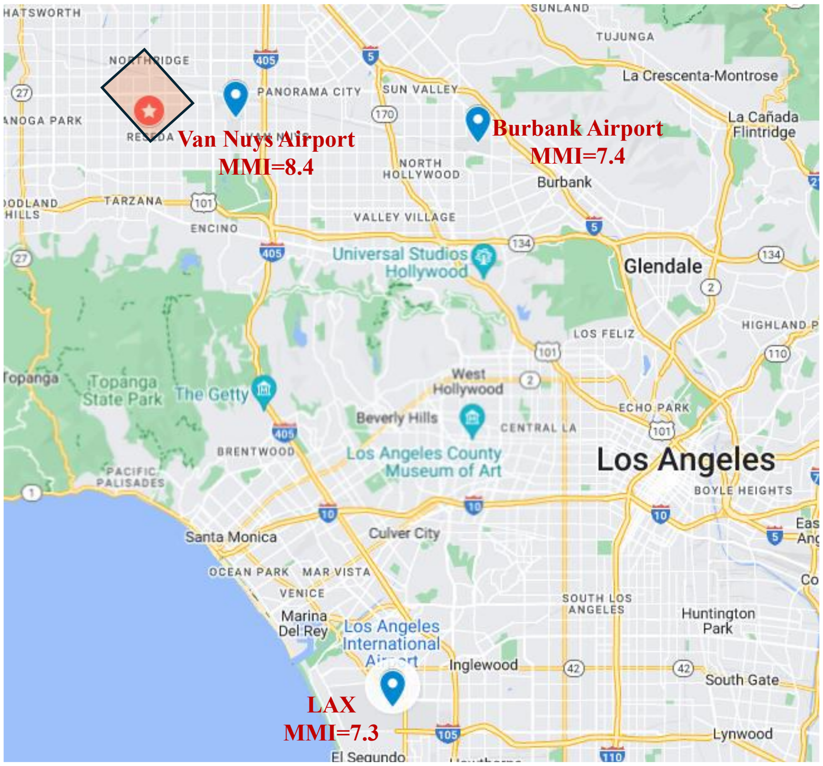
The Loma Prieta earthquake demonstrates the regional nature of airports and the interconnectedness of operations in the aftermath of earthquakes. Therefore, implementing EEW systems in one or two airports in the same geographical region may not be sufficient. Implementing EEW across multiple airports in a region could enhance their collective benefits.

2.2.2 1994 Northridge Earthquake

The magnitude 6.7 Northridge earthquake occurred at 4:31 a.m. local time on January 17, 1994, in the San Fernando Valley. The death toll was 57, and property damage was estimated to be as high as nearly $100 billion (in 2024 dollars), making it the costliest natural disaster in U.S. history. The greater Los Angeles area suffered widespread disruptions in the weeks and months following the earthquake. The three airports in the area with the most severe shaking were closed for runway and structural inspections. There was no significant damage to any of the airports, and they reopened quickly after inspections. Figure 2.5 shows the airports in the region impacted by the earthquake, including the shaking intensity at each location, the earthquake epicenter, and the surface projection of the fault trace that caused the earthquake.

Van Nuys Airport, which is a general aviation airport, is the closest airport to the earthquake source at approximately 8 miles. Closest ground motion recording to this airport recorded PGA and PGV of 0.45 g and 63.2 cm/s (CESMD, 1994), with a corresponding MMI of 8.4 (Figure 2.5). There was broken window glass in the control tower, and some equipment in the tower slid up to 4 inches (EERI, 1995). It is important to emphasize that the Northridge earthquake was pivotal in earthquake engineering, revealing that, while casualties were relatively low, significant economic losses arose from damage to nonstructural components and business disruptions. Before this event, there was minimal emphasis on the performance of nonstructural elements in structural design. Focus on this aspect increased afterward. In current engineering practice, there is more emphasis on nonstructural component damage and performance, but it is still secondary compared to structural component design. Therefore, EEW notifications to staff may help avoid issues with important equipment in the control tower and control rooms in terminal buildings. Damage to FAA facilities at the Van Nuys Airport control tower totaled about $160,000 (Schiff, 1995), which EEW could have reduced. However, to justify this statement, more detailed information on the specific sources of this economic damage is needed.

Figure 2.5. Airports Impacted by the 1994 Northridge Earthquake[7]



Hollywood Burbank Airport, which is a commercial airport, is located around 11 miles east of the Northridge earthquake source (Figure 2.5). This airport experienced PGA, PGV, and MMI of 0.18 g, 38.5 cm/s, and 7.4, respectively (CESMD, 1994). The airport closed for approximately 5 minutes while the runways and taxiways were inspected (ABAG, 2000). The terminal building was closed for approximately 2 hours for inspection and to clean up fallen ceiling tiles (EERI, 1995). After this cleanup, inspections revealed there was no damage that could impact operations, and airport operations resumed.

LAX, one of the case study airports in this study, is located approximately 22 miles south of the fault source zone (Figure 2.5). Recorded PGA and PGV at a nearby ground motion recording station, and the corresponding MMI were 0.18

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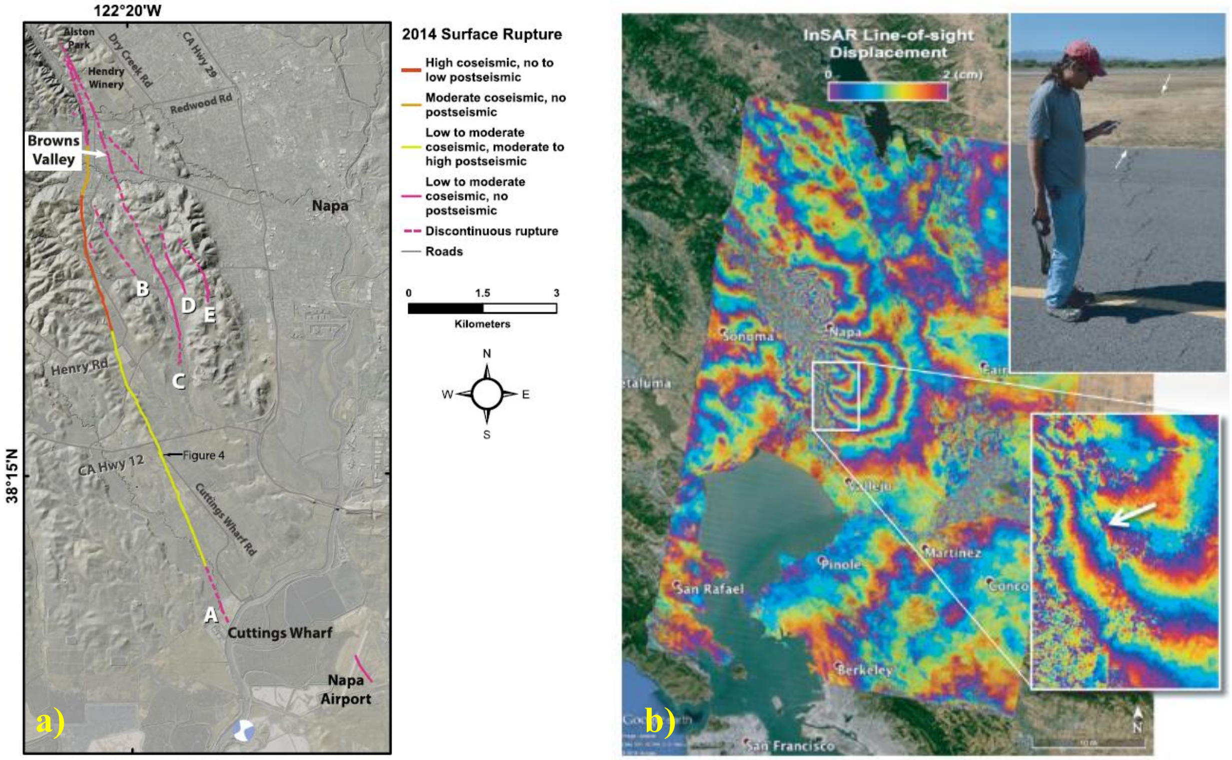
[7] Airports impacted by the Northridge earthquake including shaking intensities (MMI), earthquake epicenter (star), and surface projection of the fault trace (rectangle).

g, 38.5 cm/s, and 7.3. LAX closed for several hours for inspection. Due to a power loss for approximately 1 hour, emergency backup generator power was used, which functioned properly. Some ceiling tiles fell, and there were some water leaks at pipe joints (EERI, 1995). Fallen ceiling tiles are frequently cited as a commonly observed damage type in earthquakes.

2.2.3 2014 South Napa Earthquake

The magnitude 6.0 South Napa earthquake struck at 3:20 a.m. local time on August 24, 2014. The earthquake produced significant damage resulting from shaking, fault rupture, and ground deformation in the cities of Napa, American Canyon, and Vallejo (EERI, 2014; Hudnut et al., 2014; DeLong et al., 2016). Napa County Airport is located very close to the earthquake source (< 1 mile) and experienced minor cracking due to surface rupture on a taxiway (Figure 2.6). Because the airport is so close to the fault rupture, EEW may not have been beneficial for this airport because of insufficient warning time.

Figure 2.6. Surface Rupture Map of 2014 South Napa Earthquake and Airport Location Relative to the Fault Rupture, Satellite Imagery of Ground Displacement Discontinuity, and Photo of Cracking Due to Rupture[8]



Despite being so close to the earthquake source, the airport reported no damage to its facilities, except for the mentioned minor cracking on one taxiway. Operations were halted for 30 minutes for inspection, starting at the usual airport opening time of 7:00 a.m. Operations resumed after the inspection was completed. Although the airport lost commercial power, the backup power operated effectively (EERI, 2014). Most of the airports discussed so far experienced power outages after earthquakes, followed by backup power use. Therefore, the following sections discuss the EEW benefits obtained by eliminating the gap between loss of commercial power and activation of backup power.

The ATC tower sustained no structural damage; however, there was glass breakage in its main control room windows. There were no reports of injuries due

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[8] Figure 2.**Error! Main Document Only.** shows a map of surface rupture from field observation associated with 2014 South Napa earthquake and the location of the airport relative to the fault rupture (DeLong et al., 2016), satellite imagery showing ground displacement discontinuity at the airport, and a photo showing cracking due to rupture (EERI, 2014).

to this glass breakage. ATC was not available for 4 days until a temporary tower was brought in. It was used for several weeks until the broken glass was replaced (EERI, 2014). Operations continued without ATC and pilots. The air traffic controllers communicated directly via radio, which is the normal procedure at airports that do not have ATC. Most airports discussed experienced window glass breakage problems in the control tower. This likely results from amplified accelerations at the top of the tower, generating inertia forces that create external pressure on the window glass, leading to its breakage. While EEW cannot prevent this breakage, these observations highlight the need to improve window design for control towers to withstand earthquake shaking.

2.2.4 2019 Ridgecrest and 2022 Ferndale Earthquakes

Other recent notable earthquakes in California are the 2019 Ridgecrest sequence and the 2022 magnitude 6.4 Ferndale earthquake. No damage to airports was reported in these earthquakes. During the Ridgecrest earthquake, the accelerometer at the control tower of the General William J. Fox Airfield (commonly known as the Lancaster airport), located 79 miles from the earthquake source, recorded 0.24 g acceleration (Mosalam et al., 2019). This is a considerable vibration level for that distance. Airport control towers closer to the earthquake source, which experienced window breakage, likely recorded even higher accelerations; however, these were not recorded due to a lack of instrumentation. Such data could be beneficial for designing tower windows to withstand earthquakes without breaking and underscore the need for enhanced seismic instrumentation in airport facilities to improve their seismic response and inform EEW implementations.

2.3 Seismic Vulnerability of California Airports

Common types of damage observed at airports during earthquakes include: (a) liquefaction damage to runways, (b) structural damage to control tower and terminal buildings, (c) nonstructural damage in control tower and terminal buildings, (d) power and communications disruptions, and (e) disruptions to airport transportation and fuel systems. Table 2.1 provides a qualitative description of EEW benefits for each seismic vulnerability. The following subsections describe the vulnerability of California airports by category.

Table 2.1. Qualitative Description of EEW Benefits for Seismic Vulnerabilities in California Airports

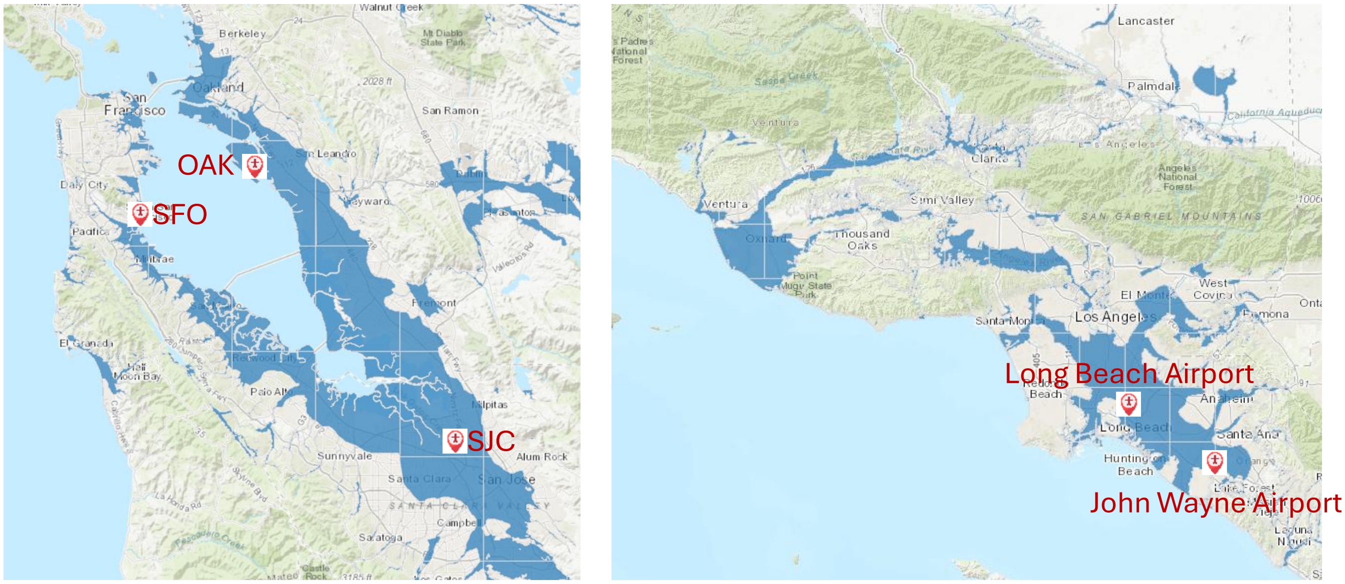
Potential Seismic Vulnerabilities in California Airports	EEW Benefits
Liquefaction damage to airport runways	Limited effectiveness
Structural damage to the control tower and terminal buildings	Ineffective
Nonstructural damage to the control tower and terminal buildings	Effective
Power and communications disruptions	Effective
Fuel and transportation system disruptions	Limited effectiveness

2.3.1 Liquefaction

Groundwater pressure increases during an earthquake, breaking the contact between the particles of saturated soils, resulting in a considerable reduction of soil strength and stiffness (Kramer, 1996). Liquefaction typically occurs in cohesionless soils, such as sand and silt, or in artificial fills. When liquefaction occurs, saturated sandy materials can behave like a liquid rather than a solid. This phenomenon can cause the ground to sink or separate and sand boils can emerge. These ground failures can damage paved areas, pipelines, and building foundations (ABAG, 2000). These failures manifest as: (a) flows and lateral spreads in the form of landslides on flat or nearly flat ground near rivers, harbors, or drainage channels; (b) ground oscillations or movement of the liquefied ground layer separately from surrounding layers; (c) loss of bearing strength and reduced ability to support buildings or hold underground tanks; and (d) settlement and differential settlement that can lead to tilting of buildings and downward movement of pavement surfaces.

Liquefaction can affect airports in the form of settlement to runways and loss of bearing strength of airport buildings, although runway damage is more common. Several airports in California are in regions susceptible to liquefaction (Figure 2.7). SFO is built on artificial fill that is potentially susceptible to liquefaction, which can lead to a settlement of 0.5 ft across the entire runway in an earthquake like the 1906 San Francisco earthquake (ABAG, 2000). OAK is susceptible to liquefaction due to its sandy artificial fill overlying bay mud. Liquefaction does not occur in all earthquakes, and its occurrence depends on the level of shaking. Using published and unpublished data, the likelihood of different sizes of earthquakes in quaternary faults in the San Francisco Bay Area, the levels of shaking at airports of interest during these earthquakes, and the relationship between the level of shaking and severity of liquefaction, the approximate probability of at least one airport closure due to liquefaction in a 30-year time frame is calculated as 61% at OAK, 33% at SJC, and 18% at SFO (ABAG, 2000). Although EEW cannot prevent such closure, it could potentially reduce the consequences of liquefaction and runway damage by notifying outdoor airport staff and delaying landings or diverting aircraft to other airports. However, realization of these actions is not as clear and straightforward as some of those related to other benefits; therefore, this benefit is labeled as "Limited effectiveness" in Table 2.1.

Figure 2.7. Examples of Airports in Liquefaction Susceptible Regions in the San Francisco Bay Area and Los Angeles.[9]



2.3.2 Structural Damage

Airports are categorized as essential structures that should remain functional after earthquakes, classified as Risk Category IV in ASCE 7-22[10] (American

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[9] Liquefaction susceptible regions are shown in blue on California Geological Survey (CGS) Liquefaction Maps, (2019).

[10] ASCE 7, formally known as "Minimum Design Loads and Associated Criteria for Buildings and Other Structures," is a standard developed by the American Society of Civil Engineers (ASCE). This standard provides guidelines for determining the loads (such as dead, live, snow, wind, and earthquake loads) that structures in the United States must be designed to withstand, along with related criteria. ASCE 7-22 is the 2022 version of the standard.

Society of Civil Engineers, ASCE, 2022). Structures in this category are designed to withstand higher demands, using earthquake loading that is 1.5 times that of regular structures in Risk Category II. Despite these more stringent requirements, structural damage to airport facilities could still occur, especially in older buildings. For example, Naval Air Station Alameda sustained structural damage during the 1989 Loma Prieta earthquake. Although most older airport buildings in California have been or are being retrofitted, these retrofits may not achieve the complete structural performance of a new design.

Although EEW cannot prevent structural damage, it could potentially reduce its consequences by reducing injuries. However, historical earthquake data show that the major cause of injuries is nonstructural damage, while injuries from structural damage are comparatively rare. For example, less than 1% of injuries in the Northridge earthquake and no injuries following the Whittier Narrows or Loma Prieta earthquakes were caused by structural elements falling or building collapse (Shoaf et al., 1998; Porter et al., 2006). Therefore, EEW is considered ineffective in preventing structural damage or reducing its consequences.

2.3.3 Nonstructural Damage

As previously stated, airport facilities are designed to withstand higher demands compared to other structures. However, this enhances the seismic performance of the structural system, placing further demand on nonstructural components. Although the importance factor for nonstructural components in Risk Category IV is the highest (ASCE 7-22), nonstructural component damage is still commonly observed in California airports, particularly the older ones.

EEW is effective in reducing the consequences of nonstructural damage. These reductions can be categorized into two groups: safety benefits and operational benefits.

Benefits in the first group are related to safety, such as the reduction of injuries due to fallen ceiling tiles or fallen equipment attached to the ceiling. Benefits in the second group are related to reducing operational disruptions and recovery time, such as damage to water piping, the consequences of which could be reduced by automated water shutoff.

Some nonstructural damage impacts both safety and operations. For example, elevator damage could trap people inside, potentially leading to post-traumatic stress disorder (PTSD), and hinder post-earthquake operations, increasing recovery time. Preventing fire trucks from being trapped in fire stations by jammed bay doors ensures faster response times for medical emergencies (safety) and helps contain any fires (safety and operation), though fire following historical earthquakes is rare in airports.

ATC towers at airports have experienced nonstructural damage, particularly window breakage, in almost all major California earthquakes. However, this was not an issue for operations, which continued with alternative means, such as deploying temporary towers or direct communication via radio. It is noted that any costs due to temporary tower deployment were not documented in the relevant documents.

2.3.4 Power and Communications Disruptions

Disruptions to power and communications systems are a potential risk to airport operations. Problems with these systems were among the most common in past earthquakes, and operations continued with backup power. For the backup power to provide the most benefit, the gap between the onset of a power outage and the backup generator's activation should be eliminated, which is possible with EEW.

2.3.5 Fuel and Transportation Systems Disruptions

Major airports, such as SFO, LAX, and OAK, receive jet fuel via dedicated pipelines. Notably, SFO and OAK share the same jet fuel pipeline (ABAG, 2000). These pipelines are susceptible to damage from ground shaking, liquefaction, or fault rupture during earthquakes. Implementing fuel shutoff mechanisms triggered by EEW could prevent fuel leakage and potential fires. Although not near airports, fires caused by gas and fuel pipeline breakage occurred after the 1994 Northridge earthquake (Lund, 1996). This fire destroyed five houses (Bain et al., 2024).

In contrast, smaller commercial airports such as PSP and general aviation airports receive fuel delivered by trucks. Damage to transportation networks, including roads and bridges, could disrupt these truck-based refueling operations, posing significant logistical challenges. EEW is less effective in mitigating disruptions for trucked fuel deliveries. Although bridges in California have undergone major improvements since the 1989 Loma Prieta earthquake, potential issues with transportation systems could still occur. Therefore, maintaining emergency fuel reserves is essential for these airports to ensure operational continuity in the event of such disruptions.

2.4 Introduction to PSP and LAX

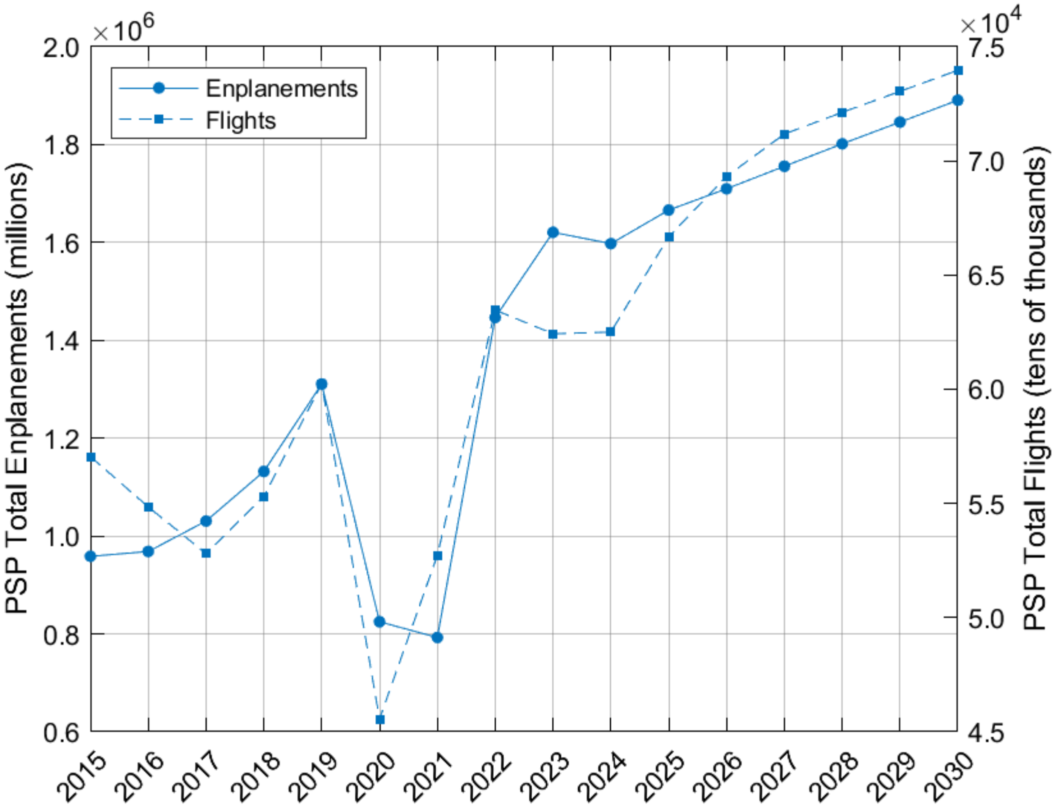
As part of this research, we examine two case study airports—PSP and LAX (Figure 2.8)—to assess the implications of EEW systems in airport operations. These airports were selected for their distinct operational contexts, with PSP representing a regional airport with unique seismic preparedness needs and LAX serving as a major international hub. The case studies explore how EEW could enhance resilience, mitigate disruptions, and support early response decision-making in the event of an earthquake.

Figure 2.8. Locations of PSP and LAX

2.4.1 PSP

PSP is a mid-sized airport in Southern California owned by the City of Palm Springs. It is located roughly 2 miles from the city's downtown. The FAA classified it as a small hub in the 2023 financial year.[11]. In the 2023 calendar year, PSP saw 62,400 flights and 3.2 million passengers going through the airport (Figure 2.9) (FAA, 2024). These flights come from a range of airlines, with the largest by volume being Southwest, SkyWest, American, Alaska, and United. In total, 12 airlines provide flights to more than 30 different destinations (PSP, 2025).

Figure 2.9. Historical and Projected Trends in PSP Total Enplanements and Flights (2015-2030)



Terminal Facilities

Figure 2.10 provides a general map of PSP. The terminals are made up of three primary structures (Figure 2.11).

- The iconic main terminal building was completed in 1966, designed by influential mid-century architect Donald Wexler. It currently houses a

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[11] https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger

variety of facilities, including ticketing, rental car facilities, administrative offices, and airport security.

- The Sonny Bono Concourse was added in 1999. It has eight contact gates and eating establishments.
- The Regional Concourse was added in 2009 to the southeast side of the terminal facilities. It includes an additional eight ground-boarded gates.

Between the main terminal facilities and the concourses is an outdoor space. This includes grassy areas, a children's play area, and various shops and eateries.

Figure 2.10. General Map of PSP

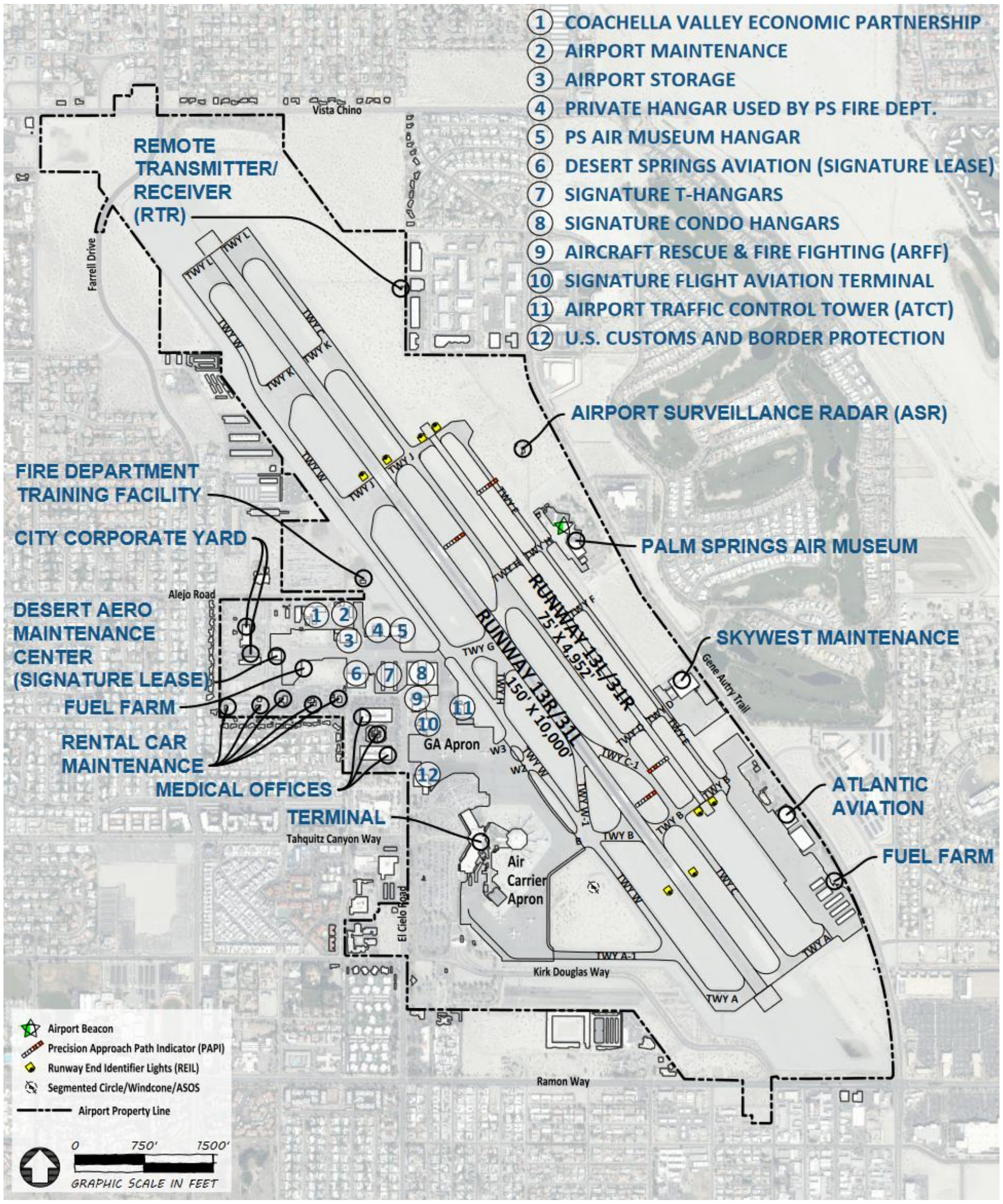
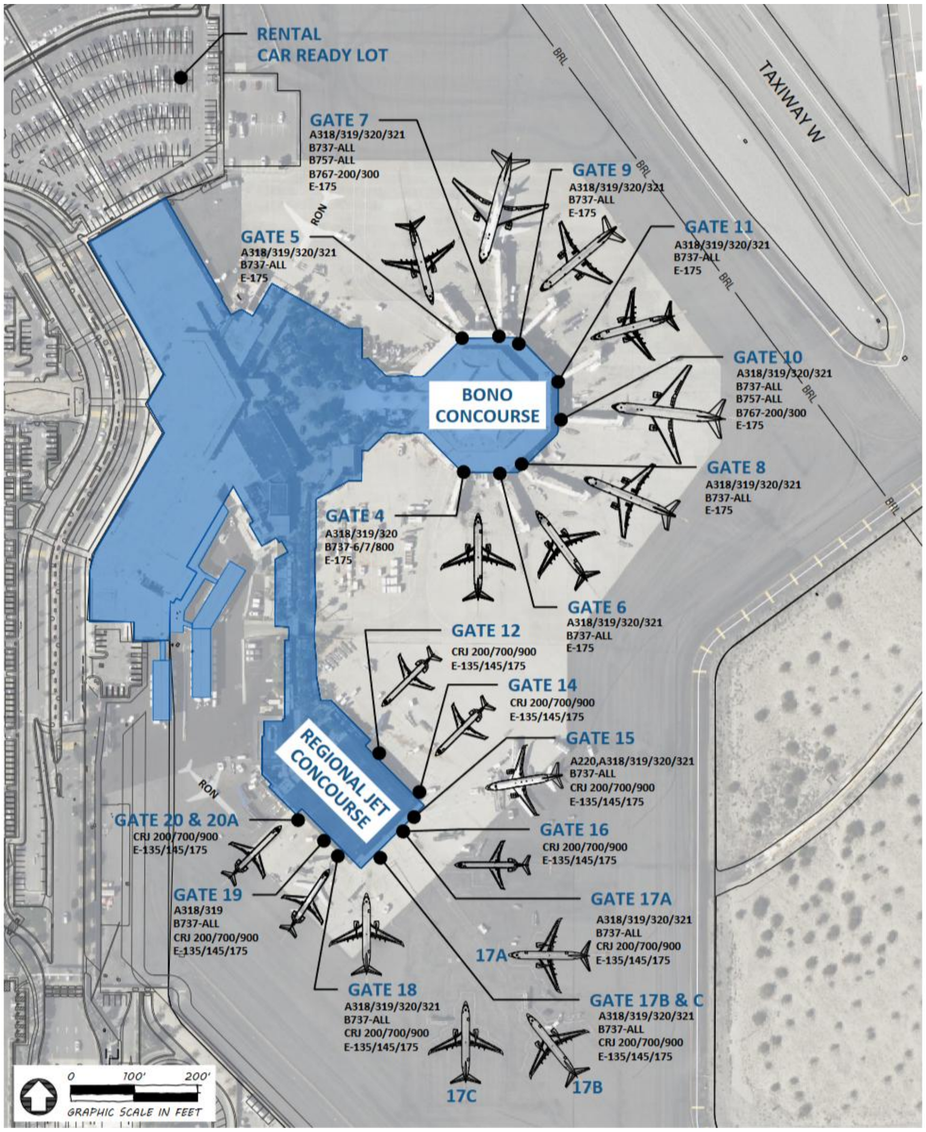


Figure 2.11. PSP Terminal Buildings



Runways

PSP has two runways, which run parallel to one another in a northwest/southeast direction. The larger, 13R/31L, is 10,000 ft long and 150 ft wide. The other, 13L/31R, is 4,952 ft long and 75 ft wide (PSP, 2025).

The current ATC tower opened in 2013. It is positioned to the north of the terminal facilities, on the west side of the runways, and is 150 ft tall[12].

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[12] https://calpilots.org/2013/09/new-palm-springs-ca-control-tower/

Fuel Services

Signature Aviation and Atlantic Aviation manage PSP's fuel[13]. No pipeline serves the PSP fuel farm; fuel supplies are trucked in throughout the day to keep the tanks filled. Trucks also disperse the fuel from the tanks to the aircraft.

Fire Emergency Services

PSP has the Palm Springs Fire Department Station 2 on site. The facilities include Aircraft Rescue and Fire Fighting (ARFF) index C, indicating an average (by departure) aircraft size between 126 and 159 ft that the ARFF facilities serve[13].

Ground Transportation Access

PSP is connected to the City of Palm Springs by a local roadway. East Tahquitz Canyon Way runs east-west and connects the airport parking and terminal area to downtown Palm Springs. El Cielo Road runs north-south along the front of the airport facilities. No interstate or rail facilities directly serve the airport, although I-10 runs to the north of the airport, connecting the airport to the broader Coachella Valley. A variety of rideshare and carshare services, such as Uber and Lyft, serve the airport. Several local bus lines and an Amtrak bus line serve the airport as well. Car rental services are on site, connecting directly to the north to the main terminal building.

Capital Improvements

PSP is undergoing significant capital improvement projects. This includes updates and improvements to the Sonny Bono Concourse, including new service desks, improved visibility within the concourse, new flooring, and more. Additionally, the airport is engaged in updates to eating establishments, including the addition of three new dining options and two coffee shops in the terminal facilities (Palm Springs Tribune, 2023).

Broader plans for a larger airport expansion are underway (Figure 2.12). PSP has seen record numbers of passengers in recent years and these numbers are expected to double by the 2040s. While the planning process is ongoing, preferred alternatives for facility updates have already been selected. These updates will make maximum use of existing facilities but include significant expansion of surface parking, the addition of new terminal buildings and gates, and an expanded rental car facility.

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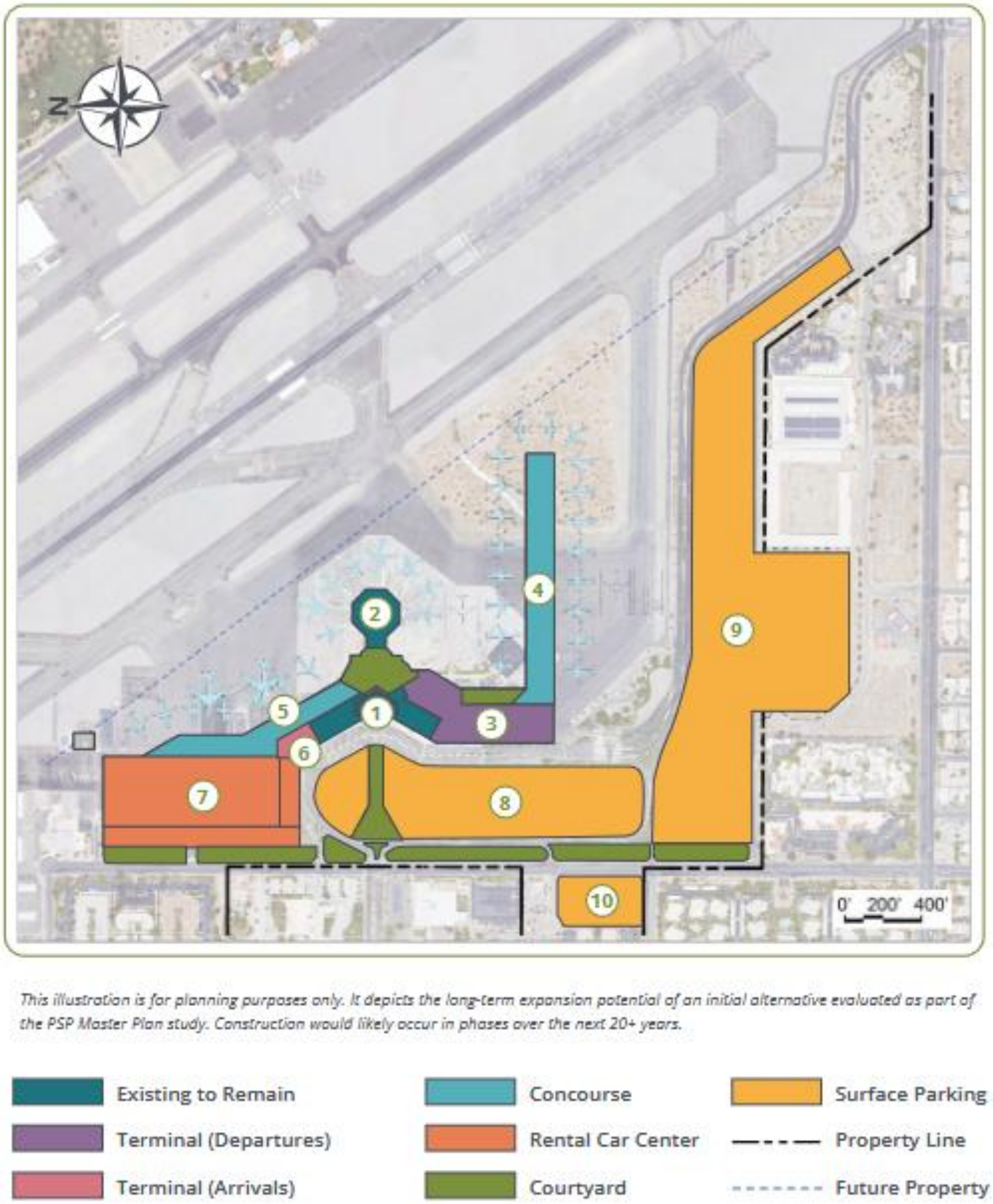
[13] https://www.airnav.com/airport/KPSP

Figure 2.12. Visual Illustration of PSP Expansion Plans

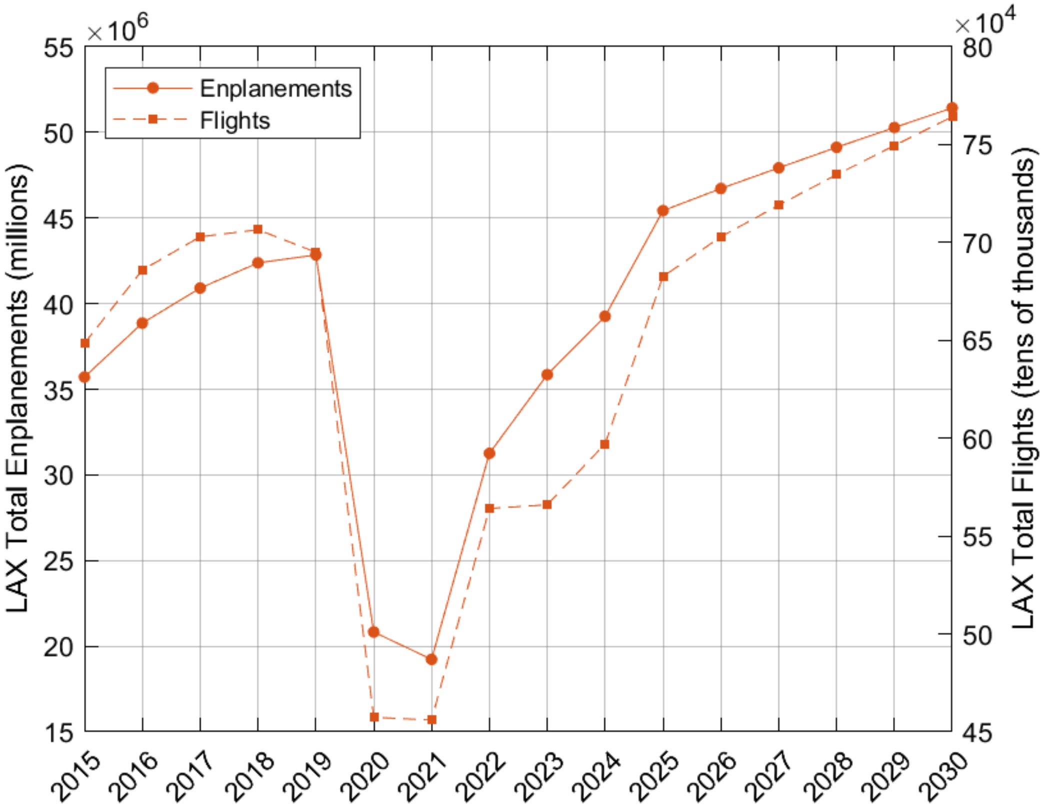


This illustration is for planning purposes only. It depicts the long-term expansion potential of an initial alternative evaluated as part of the PSP Master Plan study. Construction would likely occur in phases over the next 20+ years.

2.4.2 LAX

LAX is located west of Los Angeles in Inglewood, adjacent to the Pacific Ocean. LAX is the largest airport on the West Coast of the United States and was one of the 10 busiest airports in the world in 2023, with a 75 million passenger throughput (Figure 2.13; Los Angeles World Airports, LAWA, 2024).

Figure 2.13. Historical and Projected Trends in LAX Total Enplanements and Flights (2015-2030)

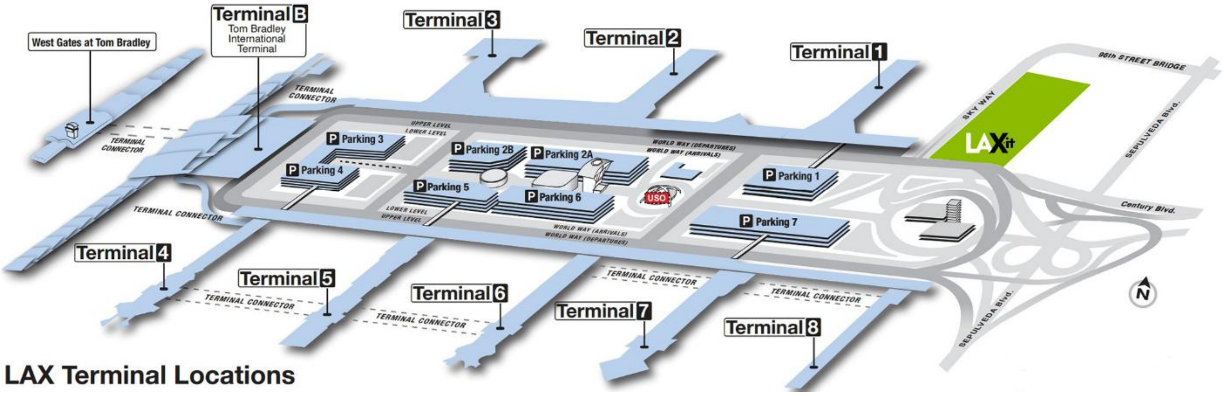


Terminal Facilities

LAX covers 3,500 acres and includes many aviation facilities, administrative buildings, and tenant structures. At its heart are 10 terminal buildings (Figure 2.14).

- Terminals 2 through 8 were designed and constructed in the early 1960s as part of a master plan that saw the creation of the iconic buildings.
- Terminal 1 and the Tom Bradley International Terminal were constructed before the 1984 Olympic Games, along with a series of other additions and modernizations to the airport infrastructure. This included the addition of an elevated roadway and building connecting each of the original satellite terminals.

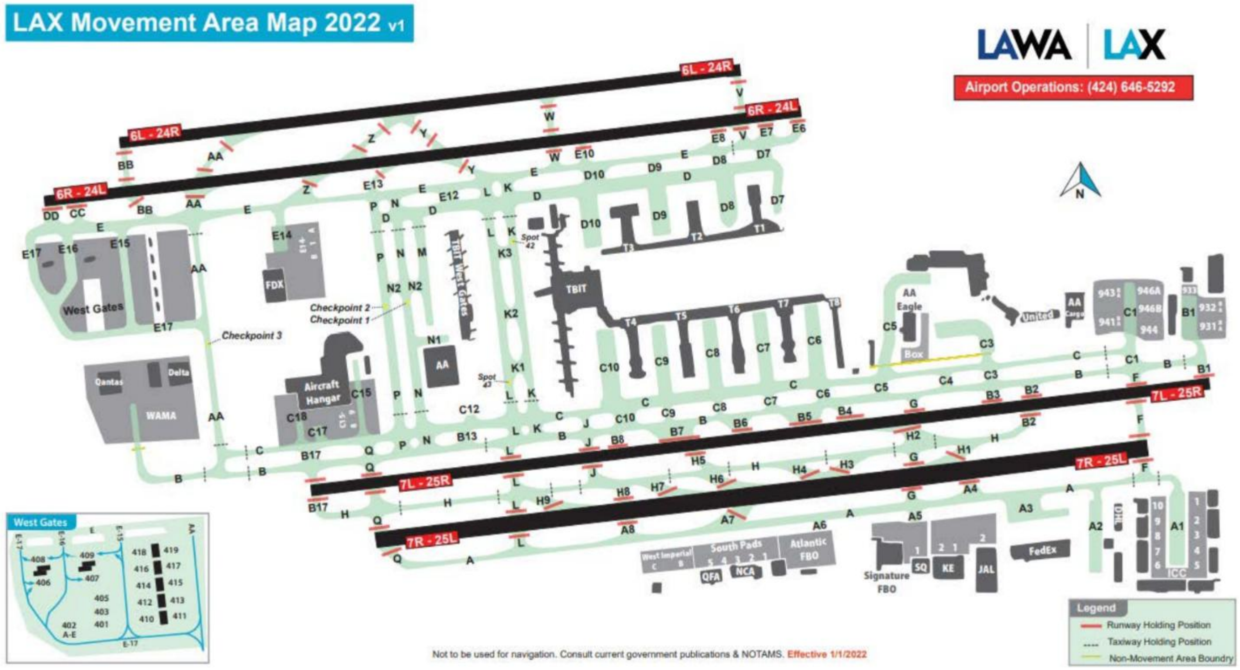
Figure 2.14. LAX Terminal Buildings[14]



Runways

LAX has four runways, two on each side of the terminal area (Figure 2.15). These include 24R/6L (8,926 ft), 24L/6R (10285 ft), 25L/7R (12091 ft), and 25R/7L (11095 ft). The first three runways are 150 ft wide, while 25R/7L is 200 ft wide. All runways run parallel in an east-west orientation. A previous north-south crosswind runway was converted into a taxiway.

Figure 2.15. LAX Runways[15]



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[14] https://www.flylax.com/-/media/flylax/pdfs/getting-around-lax/lax-airline-location-map.ashx

[15] https://www.flylax.com/-/media/flylax/media-center/pdfs/fs---airfield-feb_2021.ashx

ATC Tower

The current ATC tower replaced the original 1961 tower, built along with the original satellite terminals. The current tower, at 277 ft tall, was completed in 1996[16].

Capital Improvements

To prepare for the 2028 Olympic Games, LAX is undergoing substantial capital improvement worth roughly $30 billion. This includes the addition of the Automated People Mover to allow for movement between terminals, parking, and rental car facilities[17]. The expansive set of projects also includes infrastructure improvements across Terminals 2, 3, 4, 5, 6, and Tom Bradley International, new concourses, a new Terminal 0, and a consolidated rental car facility.

Fuel Facilities

The LAX fuel farm (LAXFUEL) is the largest consortium for jet fuel in the United States[18]. Aircraft Service International Group has managed LAXFUEL since 1986, following the centralization of fuel services at LAX. Approximately 75-80 airlines use the facility, which has 15 tanks capable of storing around 600,000 barrels on site. Three additional off-site locations provide pipelines with a further 1.5 million barrels of fuel. Combined, these facilities provide roughly 20 days of fuel. Four pipelines supply the fuel farm directly from various refineries and fuel sources. As with the rest of the airport, LAXFUEL operations are 24 hours a day[19].

Emergency Services

Los Angeles Fire Department Station 80 serves the LAX area. The station is positioned across from the Tom Bradley International Terminal on the west side of the airport grounds[20].

Ground Transportation

LAX is connected on the landside via several significant interstates and thoroughfares. Access to the terminals comes from Century Boulevard in the east-west direction and from Lincoln Boulevard in the north-south direction. The

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[16] https://flightpathlax.com/lax-history/

[17] https://spectrumnews1.com/ca/southern-california/transportation/2023/02/28/lax-is-getting-so-many-upgrades--it-s-almost-an-entirely-different-airport

[18] https://www.aviationpros.com/home/news/10378452/asig-marks-25-years-with-laxfuel

[19] https://www.aviationpros.com/gse/fueling-equipment-accessories/article/10246019/centralized-fuel-delivery-improves-logistics-and-profits

[20] https://lafd.org/fire-stations/station-80

west side of the airport, which includes administrative buildings, the fuel farm, the fire department, tenant hangars, and other facilities, is accessed by World Way and Pershing Drive. These large local arterials connect to Highway 1, Interstate 105, and Interstate 405, providing access from around Los Angeles County.

A variety of public transportation options serve LAX, including LAX FlyAway Shuttles that connect LAX with Union Station and Van Nuys Airport[21]. LA Metro, Culver City Bus Line, Santa Monica Big Blue Bus, Torrance Transit, and Beach Cities Transit all provide services at LAX as well. Currently, no rail transit directly serves LAX, though this will change with the addition of the Automated People Mover an electric train will connect guests and employees to terminals and parking, and LA Metro's new LAX/Inglewood Station.

In addition to public transit, rideshare applications, rental cars, and taxis are also available as means of ingress and egress to the terminal facilities. Substantial parking facilities are located around the airport grounds. Hotel shuttles also provide services directly to the airport[22].

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[21] https://www.flylax.com/lax-traffic-and-ground-transportation#one

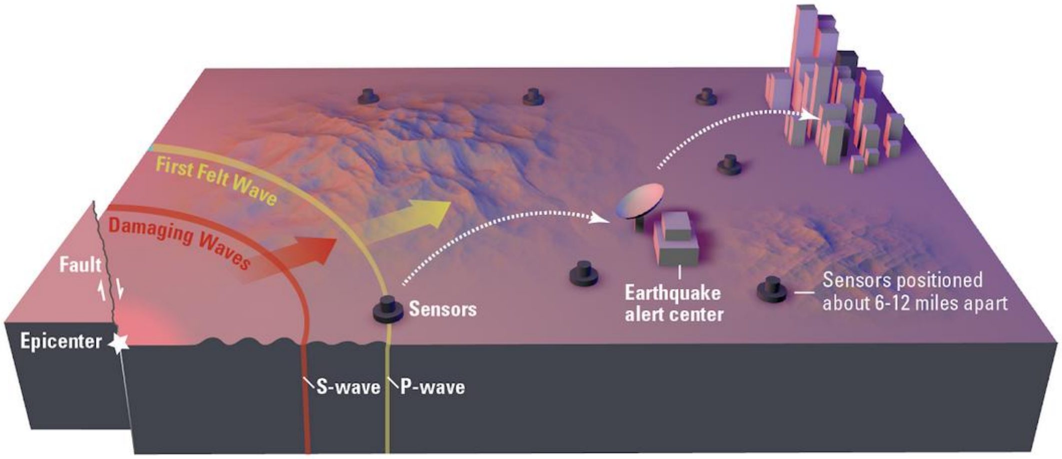
[22] https://www.flylax.com/lax-traffic-and-ground-transportation#one

3 Earthquake Early Warning

EEW is a system that rapidly detects seismic waves from an earthquake to deliver warning messages to the affected areas before strong shaking occurs. This information is distributed to users to warn them of the impending shaking. Warning time may range from no warning (late alerts) to up to tens of seconds. This early warning gives users the opportunity to take protective actions to mitigate the damage and harm caused by the earthquake. It is important to note that EEW does not involve earthquake prediction.

The science behind EEW is simple in concept, though sophisticated to execute. When a fault ruptures, two distinct kinds of waves emanate from the epicenter. The first wave, the primary or P-wave, is faster and typically causes less damage. The secondary or S-wave is slower and typically causes stronger shaking and more damage. A network of seismic sensors constantly monitors for these waves. Because P-waves are faster, they reach the seismic sensors first. Sensors record ground motions and send the data to ShakeAlert servers. Licensed operators then use that data to send alerts to areas expected to experience shaking. Figure 3.1 illustrates this system.

Figure 3.1. Representative Diagram of the ShakeAlert EEW System in the Western United States[23]



The expected warning time provided by an EEW system can range from a few seconds to tens of seconds, depending on the distance of the affected area

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[23] California Earthquake Authority, 2024.

from the earthquake's epicenter. Because it takes time for seismic stations to detect an earthquake, those very close to the epicenter are unlikely to receive much, if any, alert before strong shaking. However, in many cases, this brief warning can make a significant difference in mitigating the earthquake's impact, allowing people to take immediate protective actions such as moving to safer locations, stopping machinery, or taking cover. Critical infrastructure and systems could also be automated to shut down or secure sensitive operations, minimizing the risk of accidents and damage. Additionally, emergency services could be mobilized promptly, enhancing overall preparedness and earthquake response. Consequently, even a short warning could save lives, reduce injuries, and limit property damage.

This section is organized into three subsections. The first section discusses the history and origins of EEW. The second section discusses early applications of EEW in California. The third section discusses EEW implementation and emerging lessons from several contexts, such as airports, rail and transit systems, medical and research facilities, fire and emergency services, and utilities.

3.1 History

EEW was conceptualized as early as the 19th century. Following the 1868 earthquake on the Hayward Fault in Northern California, J.D. Cooper, a doctor in the San Francisco Bay Area, suggested using telegraph wires to send warning messages to surrounding areas ahead of shaking in a local newspaper article. It was not until roughly a century later that technology and scientific understanding allowed for an actual implementation of this concept, when Japan deployed a system to mechanically detect shaking caused by S-waves and send warnings across its Shinkansen high-speed rail lines. The first P-wave detection occurred in 1984, when Japan deployed its Urgent Earthquake Detection and Alarm System (UrEDAS), issuing an alert before shaking was felt. This was applied to automatically slow and stop Shinkansen trains and metro trains in the early 1990s. Further applications, including automated stopping of metro trains and public alerts, were rolled out around the same time (Nakamura & Saita, 2007).

Mainly in response to the devastating magnitude 8.0 earthquake in Mexico City in 1985, the Sistema de Alerta Sísmica Mexicano was created and operates similarly to UrEDAS. Between 2005 and 2019, other countries began implementing various levels of alerting, including China, Turkey, Italy, South

Korea, and Taiwan. Other countries, including Chile and Israel, have since implemented systems, though they are still in the testing and development phase. (McBride et al., 2022).

The United States Geological Survey (USGS) began developing the first EEW system in the United States in 2006. The first limited use sent warnings to select users in California in 2012. This resulted in the first completed prototype of ShakeAlert in 2016 in California, expanding to Oregon and Washington in 2017. ShakeAlert entered its phase 1 rollout in 2018 along with its technical release 2.0. This phase has seen significant adoption among technical partners and end users, driven by dedicated initiatives to bring on new users (Kohler et al., 2018).

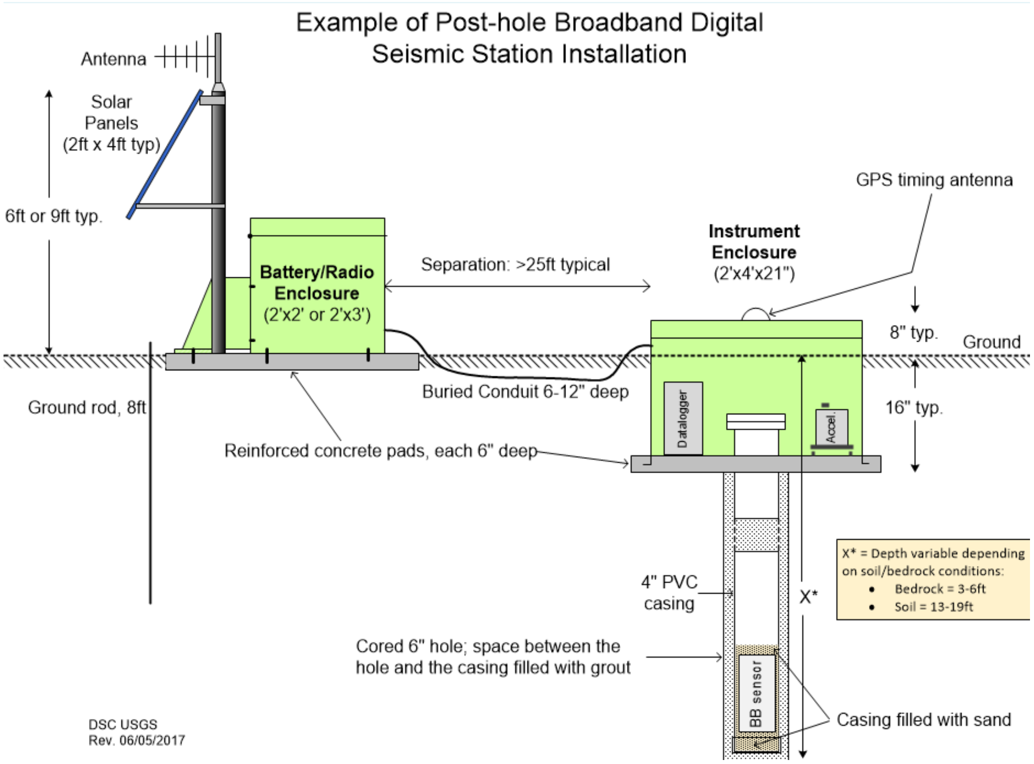
3.2 CEEWS and ShakeAlert

CEEWS powered by ShakeAlert was established in 2016 when Governor Jerry Brown signed House Bill 438 (California Governor's Office of Emergency Services [Cal OES], 2016). California Integrated Seismic Network (CISN), the network of seismic sensors around the state that monitors seismic activity, forms the system's backbone. This network connects to centers that process the signals and send warnings. A number of partners, including USGS, UC Berkeley Seismology Lab (BSL), California Institute of Technology Seismology Lab, University of Washington, University of Oregon, and California Geological Survey (CGS), are integrally involved in these projects. This section describes the nature of this system's structure, technology, performance, and value proposition.

3.2.1 Technology

ShakeAlert is a network-based EEW system that ingests data from seismic networks from Mexico to Canada. The system detects earthquakes shortly after they begin by triggering on P-wave arrivals at stations in the network (Figure 3.2). ShakeAlert uses triggers from at least four stations to rapidly locate and estimate earthquake magnitude. ShakeAlert then publishes alert messages to subscribed users. The time between when a user receives a warning and when shaking is experienced at their location varies depending on the user's proximity to the earthquake epicenter, the density of stations near the earthquake, and the alert delivery mechanism. One EEW limitation is that users close to the epicenter may receive little or no warning before strong shaking is observed. Warning time increases with distance from the epicenter as the time between the fast-moving P-waves and the slower but more damaging S-waves increases. While warning times could be improved by network densification and improvements to the ShakeAlert algorithms, a late-alert zone near the epicenter is unavoidable and expected. Current ShakeAlert technology allows for at most tens of seconds of warning to affected regions in the United States (McGuire et al., 2021).

Figure 3.2. Representative Diagram of a Seismic Station Used by CISN and ShakeAlert[24]



As of 2022, ShakeAlert ingests data from 1,300 sensors across the West Coast, with efforts continuing to increase the sensor density for improved accuracy and speed in delivering warnings. This includes an additional 366 sensors planned in the near future, as shown in Figure 3.3 (Rowan, 2022). Increasing sensor density adds both speed and accuracy to calculating the earthquake's location and magnitude. The P-wave arrives at seismic stations more quickly in a dense network, and the additional data from multiple sensors improve the output of the algorithms used for this estimation (McGuire et al., 2021).

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[24] California Earthquake Authority, 2024.

Figure 3.3. Location of Seismic Sensors in the ShakeAlert System (2022)[25]

ShakeAlert employs two seismic algorithms, the Earthquake Point-source Integrated Code (EPIC; Chung et al., 2019) and the Finite Fault Rupture Detector (FinDer; Böse et al., 2012). EPIC is a point-source code that detects earthquakes using a minimum of four stations. EPIC alerts tend to be the faster algorithm, but magnitude estimates saturate at approximately 7.5 as the rupture is estimated as a point. FinDer tends to be slightly slower to alert. However, because it estimates the fault rupture as a line source, it does not suffer from the same magnitude saturation problem as EPIC. ShakeAlert recently added the

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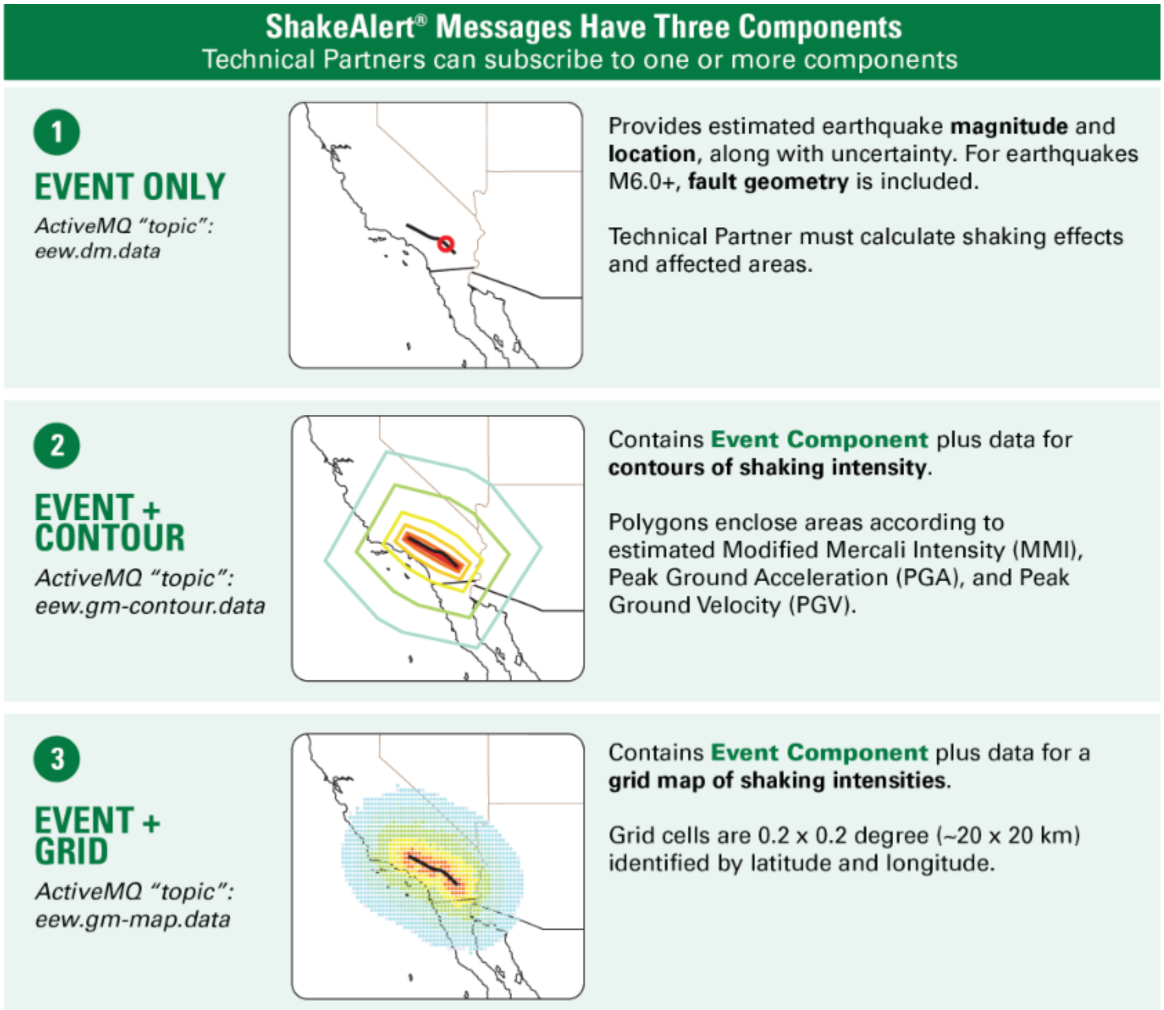
[25] Blue represents current sensors and yellow represent sensors slated for addition in the near future (Rowan, 2022).

Geodetic First Approximation of Size and Timing (GFAST-PGD) algorithm (Crowell et al., 2016; Add et al., 2023), which uses data recorded by Global Navigation Satellite System sensors. Due to the noisy nature of geodetic data, GFAST-PGD is most useful for earthquakes of magnitude 6 or greater.

ShakeAlert messages carry information about both the magnitude and the intensity of an earthquake. Magnitude quantifies the energy released at the earthquake's source, with larger numbers indicating greater energy release during the fault rupture. Intensity describes the effect of the earthquake on the earth's surface, people, buildings, and natural features. This is measured using the MMI scale, which is based on observed effects and ranges from I (not felt) to XII (total destruction). Appendix 9.1 gives a complete description of the scale. While magnitude provides a single, objective measure of an earthquake's size, intensity varies based on location and local geological conditions. EEW notifications are based on both criteria, so users are warned only if the magnitude and the expected MMI exceed the identified thresholds. For example, if a moderate earthquake occurs in Northern California, users in Southern California may not receive a warning, as the shaking there will not be significant enough to warrant an alert because of the large distance from the epicenter.

Expected shaking is calculated and transmitted in two ways. The location of the epicenter may be accompanied by either concentric polygons of expected shaking expanding from the estimated epicenter (called the “contour product”) or spatial grids of resolution of roughly 20 km^2 (“grid product”) (Figure 3.4). After the initial signal is sent, updated information may be sent as the system receives additional data, including magnitude and location estimates over time. These messages are published in XML format to technical partners and applications that are connected to the ShakeAlert system.

Figure 3.4. ShakeAlert Message Components[26]



ShakeAlert® Messages Have Three Components

Technical Partners can subscribe to one or more components

1 **EVENT ONLY**

ActiveMQ "topic": eew.dm.data

Provides estimated earthquake **magnitude** and **location**, along with uncertainty. For earthquakes M6.0+, **fault geometry** is included.

Technical Partner must calculate shaking effects and affected areas.

2 **EVENT + CONTOUR**

ActiveMQ "topic": eew.gm-contour.data

Contains **Event Component** plus data for **contours of shaking intensity**.

Polygons enclose areas according to estimated Modified Mercali Intensity (MMI), Peak Ground Acceleration (PGA), and Peak Ground Velocity (PGV).

3 **EVENT + GRID**

ActiveMQ "topic": eew.gm-map.data

Contains **Event Component** plus data for a **grid map of shaking intensities**.

Grid cells are 0.2 x 0.2 degree (~20 x 20 km) identified by latitude and longitude.

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[26] ShakeAlert, 2022, adapted from Given et al., 2018.

3.2.2 Public Warnings System Components

The CEEWS, powered by ShakeAlert, is tied directly to a variety of public warning systems. As airports plan for their own EEW implementation, they should be aware of these services.

Licensed Technical Partners

A variety of technical partners use the ShakeAlert signal. This legal partnership with USGS allows institutions to use the ShakeAlert signal within their own systems for warnings and automated actions. Companies may obtain a license to provide EEW services by acting as a vendor for EEW systems.

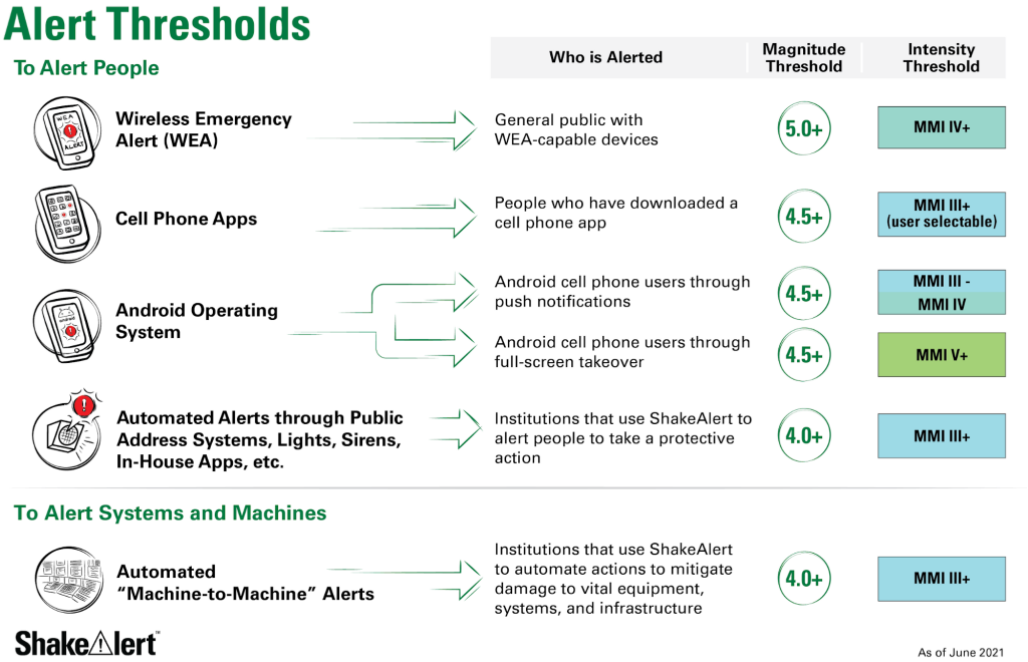
The following are examples of technical partners that deliver messages to the public via personal devices. Airports should be aware that passengers and staff may already have access to and receive alerts from these sources.

- **Wireless Emergency Alerts (WEA):** WEA are short emergency alerts delivered by governments or local authorities to a particular region, using cell towers, to any WEA-enabled devices in that region. They do not require an application to be downloaded; they are pushed directly to cellular devices. This system is used to alert the public to a variety of emergency scenarios, such as AMBER or SILVER alerts. It could also be used for natural or man-made disasters to warn people of incoming danger, as is the case for EEW.
- **MyShake:** MyShake is a free application created by Berkeley Seismology Laboratory in partnership with Cal OES. It uses ShakeAlert data to deliver alerts directly to individuals' phones in areas expected to experience shaking. The mobile application also captures data from devices in the region that experienced an earthquake to better understand the ground motion and further scientific causes, including improvements to ShakeAlert. MyShake may also be an option for institutional use by airports that only require notification/warning on non-proprietary systems.
- **Android Alerts:** The Android mobile operating system warns users of expected ground shaking directly to Android-powered cellular phones without the need for an application. The alerts are applied in various regions around the world, but utilize ShakeAlert in regions where ShakeAlert operates. Messaging about the earthquake depends on the expected intensity of the shaking, with more intense expected shaking resulting in a more disruptive warning on the device.

Warning Thresholds by System

As previously stated, a combination of magnitude and intensity determines which end users are at risk of experiencing dangerous shaking, triggering alerts. These thresholds are relatively higher for the public, with a magnitude of 4.5 required to send an alert (Figure 3.5). Technical partners receive ShakeAlert messages at magnitude 4 and MMI III and higher; however, they are not necessarily required to enact automatic warnings and actions at that level. The institution with the partnership could designate thresholds for specific warnings.

Figure 3.5. Thresholds for Warning Systems Connected to ShakeAlert[27]



Alert Thresholds

	Who is Alerted	Magnitude Threshold	Intensity Threshold
To Alert People			
Wireless Emergency Alert (WEA)	General public with WEA-capable devices	5.0+	MMI IV+
Cell Phone Apps	People who have downloaded a cell phone app	4.5+	MMI III+ (user selectable)
Android Operating System	Android cell phone users through push notifications	4.5+	MMI III - MMI IV
	Android cell phone users through full-screen takeover	4.5+	MMI V+
Automated Alerts through Public Address Systems, Lights, Sirens, In-House Apps, etc.	Institutions that use ShakeAlert to alert people to take a protective action	4.0+	MMI III+
To Alert Systems and Machines			
Automated "Machine-to-Machine" Alerts	Institutions that use ShakeAlert to automate actions to mitigate damage to vital equipment, systems, and infrastructure	4.0+	MMI III+

ShakeAlert

As of June 2021

3.2.3 Performance

The ShakeAlert system automatically generates Post ShakeAlert Message Summaries (PSMS) for earthquakes with an estimated magnitude larger than 3.5 (USGS, 2024c). These summaries provide information on detected earthquakes and ShakeAlert's performance, including the accuracy of the estimated earthquake location and magnitude, the number of seismic stations contributing data, and the warning time received by nearby cities. For earthquakes of magnitude 4.0 or larger, humans review ShakeAlert messages and forward them to the National Earthquake Information Center to be posted at www.earthquake.usgs.gov. PSMS dates back to June 18, 2019, and is

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[27] ShakeAlert, 2024.

available at: https://www.shakealert.org/system-information/post-shakealert-message-summaries.

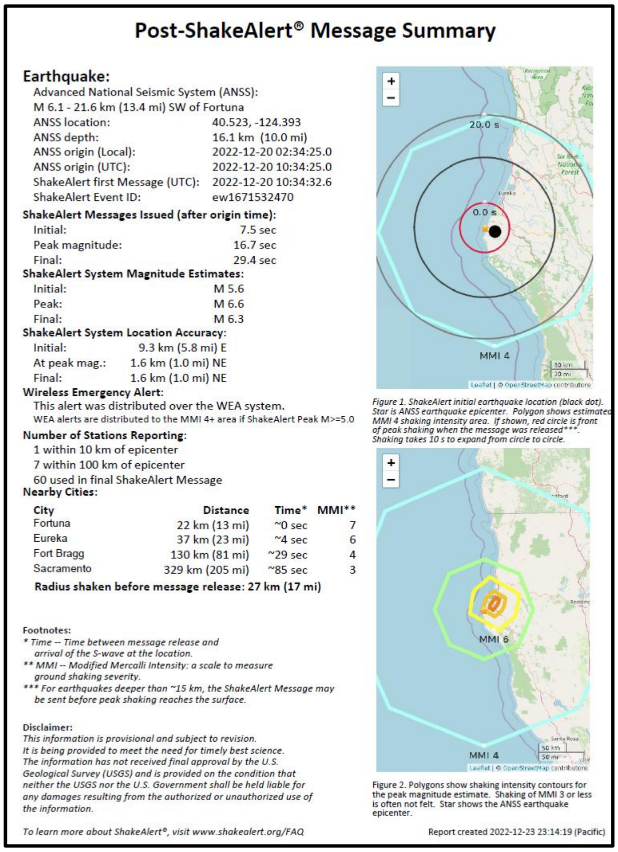
Although statewide public alerting in California began in October 2019, ShakeAlert was operational in July 2019 and provided limited public alerts within Los Angeles County during the Ridgecrest earthquake sequence. Alerts were provided both for the magnitude 6.4 foreshock on July 4th and the magnitude 7.1 mainshock on July 5th (Chung et al., 2020). ShakeAlert issued alerts for these large earthquakes and many aftershocks, detecting and characterizing both the magnitude 6.4 and 7.1 earthquakes within 6.9 seconds of their origin times (Chung et al., 2020). Messages were sent to pilot users, but the ShakeAlertLA cell phone application did not issue public alerts because the predicted shaking for Los Angeles County was below the alerting threshold of MMI 4. While this was accurate for the magnitude 6.4 earthquake, ShakeAlert underestimated the shaking levels for the magnitude 7.1 earthquake due to underestimating the magnitude by 0.8 units. Despite overall reasonable performance, this sequence revealed several software and hardware issues that contributed to the magnitude underestimation, which needed to be addressed in future ShakeAlert releases (Chung et al., 2020).

Between October 2019 and December 2021, 51 ShakeAlert messages resulted in public warnings for earthquakes that caused low-level shaking and minimal damage, according to the Congressional Research Service (CRS) (2022). Warnings sent through the Federal Emergency Management Agency's (FEMA) WEA system often did not arrive before significant shaking began. These failures were the result of transmission delays that often exceeded 5 seconds or non-delivery due to technical issues. In contrast, warnings sent via cell phone applications over wireless or cellular networks were more prompt, typically with delivery delays of less than 5 seconds.

Since 2022, several notable earthquakes detected by the ShakeAlert system are: the October 25, 2022, magnitude 5.1 Alum Rock earthquake; the December 20, 2022, magnitude 6.4 Ferndale earthquake; the January 1, 2023, magnitude 5.4 Rio Dell earthquake (aftershock of the Ferndale earthquake); the May 21, 2023, magnitude 5.6 Offshore Petrolia earthquake; and the May 11, 2023, magnitude 5.5 Lake Almanor earthquake and its magnitude 5.2 aftershock on May 12, 2023 (Saunders et al., 2024).

ShakeAlert detected the October 25, 2022, magnitude 5.1 Alum Rock earthquake 5.1 seconds after the origin time, with accurate magnitude and epicenter estimates. The ShakeAlert system performed well during both the magnitude 6.4 Ferndale and magnitude 5.4 Rio Dell earthquakes (Figure 3.6). These events were detected 8.5 and 13 seconds after their origin times, respectively. Several seconds of warning were available to some locations that experienced strong (MMI > 7) shaking during the magnitude 6.4 mainshock. Due to the deep hypocenter of the magnitude 5.4 aftershock (30.6 km depth), it is possible that ShakeAlert detected this event and issued its first alert before the S-waves reached the surface (Saunders et al., 2024). The May 21, 2023, magnitude 5.6 Offshore Petrolia earthquake occurred approximately 100 km from the coast along the Mendocino Transform Fault. ShakeAlert had a magnitude overestimate for this event (estimated 6.0, actual 5.6) because the epicenter was estimated 50 km west of the actual epicenter (Saunders et al., 2024; Figure 3.7). It is noted that inaccurate magnitude and/or location estimates are common for offshore earthquakes in this region (Chung et al., 2019; Williamson et al., 2023).

Figure 3.6. ShakeAlert Message Summaries for the Magnitude 6.4 Ferndale and Magnitude 5.4 Rio Dell Earthquakes[28]



Post-ShakeAlert® Message Summary

Earthquake:

Advanced National Seismic System (ANSS):
M 6.1 - 21.6 km (13.4 mi) SW of Fortuna
ANSS location: 40.523, -124.393
ANSS depth: 16.1 km (10.0 mi)
ANSS origin (Local): 2022-12-20 02:34:25.0
ANSS origin (UTC): 2022-12-20 10:34:25.0
ShakeAlert first Message (UTC): 2022-12-20 10:34:32.6
ShakeAlert Event ID: ew1671532470

ShakeAlert Messages Issued (after origin time):

Initial: 7.5 sec
Peak magnitude: 16.7 sec
Final: 29.4 sec

ShakeAlert System Magnitude Estimates:

Initial: M 5.6
Peak: M 6.6
Final: M 6.3

ShakeAlert System Location Accuracy:

Initial: 9.3 km (5.8 mi) E
At peak mag.: 1.6 km (1.0 mi) NE
Final: 1.6 km (1.0 mi) NE

Wireless Emergency Alert:

This alert was distributed over the WEA system.
WEA alerts are distributed to the MMI 4+ area if ShakeAlert Peak M>=5.0

Number of Stations Reporting:

1 within 10 km of epicenter
7 within 100 km of epicenter
60 used in final ShakeAlert Message

Nearby Cities:

City	Distance	Time*	MMI**
Fortuna	22 km (13 mi)	~0 sec	7
Eureka	37 km (23 mi)	~4 sec	6
Fort Bragg	130 km (81 mi)	~29 sec	4
Sacramento	329 km (205 mi)	~85 sec	3

Radius shaken before message release: 27 km (17 mi)

Footnotes:
** Time -- Time between message release and arrival of the S-wave at the location.*
*** MMI -- Modified Mercalli Intensity: a scale to measure ground shaking severity.*
**** For earthquakes deeper than ~15 km, the ShakeAlert Message may be sent before peak shaking reaches the surface.*

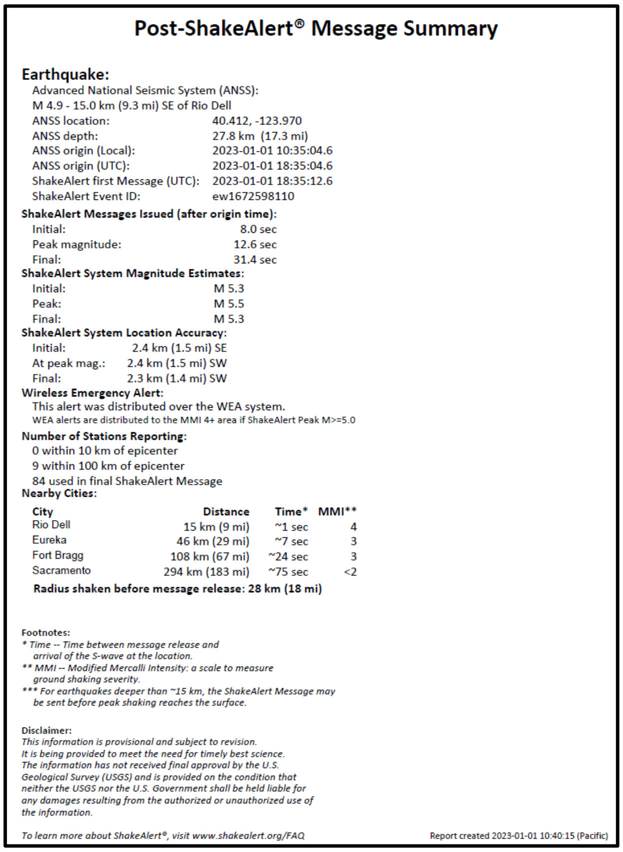
Disclaimer:
This information is provisional and subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

*Figure 1. ShakeAlert initial earthquake location (black dot). Star is ANSS earthquake epicenter. Polygon shows estimated MMI 4 shaking intensity area. If shown, red circle is front of peak shaking when the message was released***. Shaking takes 10 s to expand from circle to circle.*

Figure 2. Polygons show shaking intensity contours for the peak magnitude estimate. Shaking of MMI 3 or less is often not felt. Star shows the ANSS earthquake epicenter.

To learn more about ShakeAlert®, visit www.shakealert.org/FAQ

Report created 2022-12-23 23:14:19 (Pacific)



Post-ShakeAlert® Message Summary

Earthquake:

Advanced National Seismic System (ANSS):
M 4.9 - 15.0 km (9.3 mi) SE of Rio Dell
ANSS location: 40.412, -123.970
ANSS depth: 27.8 km (17.3 mi)
ANSS origin (Local): 2023-01-01 10:35:04.6
ANSS origin (UTC): 2023-01-01 18:35:04.6
ShakeAlert first Message (UTC): 2023-01-01 18:35:12.6
ShakeAlert Event ID: ew1672598110

ShakeAlert Messages Issued (after origin time):

Initial: 8.0 sec
Peak magnitude: 12.6 sec
Final: 31.4 sec

ShakeAlert System Magnitude Estimates:

Initial: M 5.3
Peak: M 5.5
Final: M 5.3

ShakeAlert System Location Accuracy:

Initial: 2.4 km (1.5 mi) SE
At peak mag.: 2.4 km (1.5 mi) SW
Final: 2.3 km (1.4 mi) SW

Wireless Emergency Alert:

This alert was distributed over the WEA system.
WEA alerts are distributed to the MMI 4+ area if ShakeAlert Peak M>=5.0

Number of Stations Reporting:

0 within 10 km of epicenter
9 within 100 km of epicenter
84 used in final ShakeAlert Message

Nearby Cities:

City	Distance	Time*	MMI**
Rio Dell	15 km (9 mi)	~1 sec	4
Eureka	46 km (29 mi)	~7 sec	3
Fort Bragg	108 km (67 mi)	~24 sec	3
Sacramento	294 km (183 mi)	~75 sec	<2

Radius shaken before message release: 28 km (18 mi)

Footnotes:
** Time -- Time between message release and arrival of the S-wave at the location.*
*** MMI -- Modified Mercalli Intensity: a scale to measure ground shaking severity.*
**** For earthquakes deeper than ~15 km, the ShakeAlert Message may be sent before peak shaking reaches the surface.*

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To learn more about ShakeAlert®, visit www.shakealert.org/FAQ

Report created 2023-01-01 10:40:15 (Pacific)

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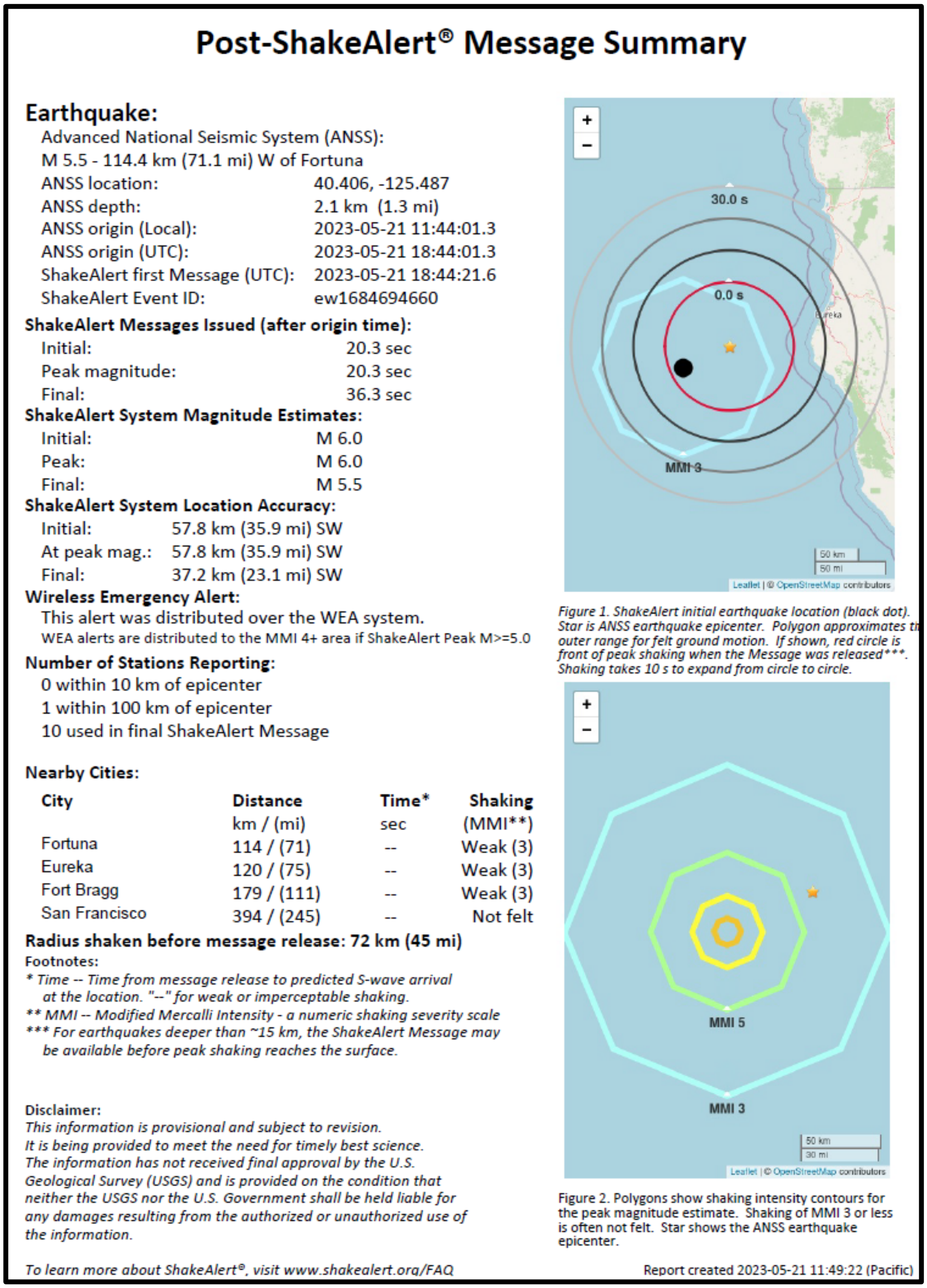
[28] USGS, 2024c.

Figure 3.7. ShakeAlert Message Summary for the Magnitude 5.6 Offshore Petrolia Earthquake Highlighting Errors in the Magnitude and Epicenter Estimates[29]



Post-ShakeAlert® Message Summary

Earthquake:

Advanced National Seismic System (ANSS):
M 5.5 - 114.4 km (71.1 mi) W of Fortuna
ANSS location: 40.406, -125.487
ANSS depth: 2.1 km (1.3 mi)
ANSS origin (Local): 2023-05-21 11:44:01.3
ANSS origin (UTC): 2023-05-21 18:44:01.3
ShakeAlert first Message (UTC): 2023-05-21 18:44:21.6
ShakeAlert Event ID: ew1684694660

ShakeAlert Messages Issued (after origin time):

Initial: 20.3 sec
Peak magnitude: 20.3 sec
Final: 36.3 sec

ShakeAlert System Magnitude Estimates:

Initial: M 6.0
Peak: M 6.0
Final: M 5.5

ShakeAlert System Location Accuracy:

Initial: 57.8 km (35.9 mi) SW
At peak mag.: 57.8 km (35.9 mi) SW
Final: 37.2 km (23.1 mi) SW

Wireless Emergency Alert:

This alert was distributed over the WEA system.
WEA alerts are distributed to the MMI 4+ area if ShakeAlert Peak M>=5.0

Number of Stations Reporting:

0 within 10 km of epicenter
1 within 100 km of epicenter
10 used in final ShakeAlert Message

Nearby Cities:

City	Distance km / (mi)	Time* sec	Shaking (MMI**)
Fortuna	114 / (71)	--	Weak (3)
Eureka	120 / (75)	--	Weak (3)
Fort Bragg	179 / (111)	--	Weak (3)
San Francisco	394 / (245)	--	Not felt

Radius shaken before message release: 72 km (45 mi)

Footnotes:

** Time -- Time from message release to predicted S-wave arrival at the location. "--" for weak or imperceptable shaking.*

*** MMI -- Modified Mercalli Intensity - a numeric shaking severity scale*

**** For earthquakes deeper than ~15 km, the ShakeAlert Message may be available before peak shaking reaches the surface.*

Disclaimer:

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*Figure 1. ShakeAlert initial earthquake location (black dot). Star is ANSS earthquake epicenter. Polygon approximates th outer range for felt ground motion. If shown, red circle is front of peak shaking when the Message was released***. Shaking takes 10 s to expand from circle to circle.*

Figure 2. Polygons show shaking intensity contours for the peak magnitude estimate. Shaking of MMI 3 or less is often not felt. Star shows the ANSS earthquake epicenter.

To learn more about ShakeAlert®, visit www.shakealert.org/FAQ

Report created 2023-05-21 11:49:22 (Pacific)

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[29] USGS, 2024c.

3.2.4 Past Usage of BCA Studies in Earthquake Engineering

BCA is a systematic methodology for evaluating decisions that affect society (Smyth et al., 2024). BCA is widely used in the engineering decision-making process for risk reduction, assessing future risk reduction benefits against investment costs (Zhang et al., 2024). When exploring the BCR for implementation, if the total benefit exceeds the total cost, the investment is considered cost-effective (FEMA, 2009; Fung et al., 2022). BCR could also be used to rank different alternatives. BCA has been employed in earthquake risk-reduction studies, particularly to characterize the benefits and costs of building code adoption, above-code seismic design, and seismic retrofits for older buildings with various structural systems across different risk categories (Zhang et al., 2024).

Catalyst et al. (2020) conducted a comprehensive study of BCA for EEW systems in California. Typical benefits of EEW for airports include reduced injury rates, decreased property damage, reduced operational disruption, faster recovery, and improved emergency response. Typical costs include EEW equipment and installation, training, operations, maintenance, testing, replacement, public education campaign, and the consequences of false alarms.

3.3 Current Implementations

The following section details examples of domestic and international institutions that have already implemented EEW. While in no way a comprehensive list of potential and actual EEW uses, they offer insight into the technology's potential. Some are relatively simple, with warnings sent out to staff or the public, while others employ more sophisticated automated mechanical operations over large geographic areas.

3.3.1 Japanese Airports

Two of Japan's major airports, Haneda and Narita, have already implemented EEW at their facilities. Both advise passengers of the warning system through their websites. Magnitude 5.0 or higher earthquakes trigger public announcements, warning passengers of the upcoming shaking so they may take protective actions.

3.3.2 Metro and Train Systems

As mentioned in Section 3.1, using EEW to automatically slow and stop the high-speed rail in Japan was the first use of EEW for automated protective actions to reduce the damage and harm caused by an earthquake. It continues its status as a frontrunning application in the United States, as both the Bay Area Rapid Transit (BART) and Los Angeles' Metrolink systems have brought on ShakeAlert as a technical partner.

BART was an early adopter of the ShakeAlert system, bringing it online to automatically slow and/or stop trains in the event of earthquake-induced strong ground shaking in its service area. BART uses EEW across its service range to detect and determine the best action. For example, underground trains may surface before stopping at a safe location (Bay Area Rapid Transit, BART, 2020).

3.3.3 Medical and Research Facilities

EEW integration in hospitals is a critical advancement in safeguarding both patients and medical staff during seismic events. When an EEW alert is received, hospitals could initiate a series of automated and manual actions designed to minimize harm and maintain operational capabilities. For example, automated systems could secure and protect sensitive medical equipment, shut down hazardous processes, and ensure backup power systems are ready to engage. Additionally, hospital staff could take protective actions, such as securing vulnerable patients, suspending surgeries in progress, and preparing for potential mass-casualty scenarios, immediately after the shaking ceases.

The Allen Institute, a biomedical research center in Seattle, Washington, was an early adopter of the ShakeAlert system. They chose to design and build their warning system in-house, sending the EEW to computers and public address (PA) systems on-site to ensure staff could move away from dangerous areas in labs and take protective action to drop, cover, and hold on (Allen Institute, 2022).

3.3.4 Fire Stations and Emergency Services Facilities

EEW system integration at fire stations has become an integral component of emergency preparedness and response strategies, allowing emergency personnel to take immediate protective actions. For example, fire stations could automatically open garage doors to prevent them from jamming during an earthquake, ensuring that emergency vehicles could be dispatched quickly after the shaking stops. Additionally, firefighters could secure equipment, brace themselves, and prepare for the rapid mobilization of rescue operations post-earthquake.

The Menlo Park Fire Protection District in Northern California brought EEW into its emergency preparedness systems. This includes seven stations over a 30-square-mile area to detect the initiation of ground shaking. Menlo Park contracted with SkyAlert, a company licensed to install ShakeAlert-powered EEW at their stations. The system provides staff notifications, automatically opens bay doors to prevent emergency vehicles from becoming trapped inside buildings, and shuts off gas valves serving ranges to prevent leaks from damaged lines (USGS, 2024d).

3.3.5 Utility Companies

Water utility companies have adopted the EEW system to automatically close valves, protecting valuable water supplies in the event of an earthquake. Over 60 water supply reservoirs across the state of Washington currently use this technology (Porter, 2020). Grants Pass in Oregon instituted a similar system, estimating that valve shut-off could save enough water to provide residents with 10 gallons of water per day for a month (USGS, 2024e).

4 Airport Uses for EEW

This section examines potential use cases for EEW at airports, such as (a) notifications and warnings, (b) automated responses, (c) ATC responses, and (d) specific applications for the PSP and LAX case study locations.

4.1 Notifications/Warnings

EEW notifications and warnings are alerts issued before strong earthquake shaking starts at a given location. They are based on real-time seismic data and could provide seconds to minutes of advance warning, allowing individuals, businesses, and infrastructure systems to take protective measures. Broadly speaking, these notifications and warnings could be public notifications and institutional or internal-facing alerts used to prepare employees and trigger automated responses.

4.1.1 General Public

Public announcements powered by ShakeAlert could provide an auditory warning to the public. This EEW application is used both inside and outside the United States in places such as hospitals, large residential buildings, and schools (Kohler et al., 2018; Wu et al., 2017). Tokyo's two major international airports, Narita and Haneda, have PA warning systems in their terminals. Reducing injuries due to falling and being hit by loose objects during an earthquake by warning individuals is one of the largest quantified benefits of EEW (Strauss & Allen, 2016). While the concept is straightforward, details of how to provide these warnings must be considered carefully.

Best Practice

ShakeAlert EEW messages are designed by the USGS ShakeAlert Committee for Communication, Education, and Outreach. While most applications, for example, WEA, are for text alerting through mobile devices, the messaging may be relevant to PA announcements as well. These messages include the following components (Sutton et al., 2020):

- **"EARTHQUAKE, EARTHQUAKE":** A header to quickly grab attention and designate the nature of the alert.

- **“Drop, Cover, Hold On”:** Current best practice in messaging for the United States is to evoke these three protective actions to prevent injury.
- **“Protect Yourself Now”:** An imperative to provoke action by the person receiving the warning.

Cal OES and ShakeAlert offer a variety of resources, including recommendations for messaging and protective actions (https://earthquake.ca.gov/get-prepared/ & https://www.shakealert.org/education-and-outreach/messaging_toolkit/). Organizations could use these for both announcement messages and outreach efforts designed to warn and inform the public.

Additionally, there are general best practices for airport emergency public announcements. These include:

- **Repetition:** For warnings given to the traveling public in the terminal, repetition is critical, as it could take several iterations before passengers pay attention to the message. Passengers are inclined to tune out messages, and repetition is the best way to combat this.
- **Languages:** Airports need to consider which languages to use for public announcements and/or visual warnings. City government or other local regulations may play a role in these decisions. Which languages are most appropriate and relevant to the airport will depend largely on local demographics and common origins of travelers from abroad.
- **Visual Paging:** In an airport, passengers may have difficulty hearing spoken announcements. In addition to audio announcements, visual paging systems and warning tones similar to the FEMA Emergency Broadcast System may be used to improve all passengers' ability to receive the message (Price & Forrest, 2016).

Airports should carefully plan and manage public announcement messaging to provide the most appropriate context for each event. Because ShakeAlert-powered messages are likely to be delivered to mobile phones in various ways, including WEA and MyShake, measures should be taken to ensure consistency across these messages to avoid conflicts and confusion.

It is a common concern that the public may panic upon receiving the warning, ultimately creating a more chaotic situation. However, studies do not generally find this to be the case. A more common observed behavior is “milling,” where people are inclined not to act and wait for more information or confirmation from others (McBride et al., 2022). This behavior is not optimal in an EEW scenario where the warning time could be very short.

Prior outreach on what protective actions to take in the event of an earthquake, such as informational signage or literature, decreases milling behavior and generally increases the effectiveness of public warnings. Airport personnel should also be trained to model appropriate responses to the alert, should they be in public areas when the alert is triggered.

Some specific examples of public announcements used by EEW adopters include:

- **Standwood-Camano School District (US):** “Earthquake! Earthquake! Expect shaking soon. Drop, Cover, and Hold On. Protect yourself now.”
- **Narita Airport (Tokyo, Japan):** “It is an emergency earthquake bulletin, please be aware of strong shakes.” This message is broadcast across the terminals twice in each of four languages: Japanese, English, Chinese, and Korean.
- **Regatta Seaside Condominiums (US):** “Earthquake. Earthquake. Earthquake. Drop, Cover, and Hold On. Protect yourself now.”

Key Implementation Considerations

Airports should be aware that local regulations or policies may impact public announcements, such as dictating required languages for the warning.

Additionally, airports have various terminal ownership and management arrangements, with airline terminal management being a common model. This could add to the organizational implementation complexity, as a single airport could include different terminals with different management. Airport stakeholder involvement in the process is necessary to ensure an appropriate response.

Limitations and Challenges

Airports have some unique challenges when implementing public announcements that are worthy of note:

- **Language:** Large commercial airports may have a travelling public with a large variety of geographic backgrounds and thus a larger number of people with first languages other than English.
- **Earthquake Familiarity:** Because of the geographic dispersion of the travelling public, airport patrons may not be familiar with typical earthquake safety protocol, making them less likely to take correct

protective actions in an earthquake and less prepared to respond quickly to earthquake warnings.

- **Security:** Airports have many restricted areas for security and safety reasons. It is important to ensure that these areas are kept secure as the public takes protective action during an earthquake warning. Instructions to remain in place, as opposed to leaving the terminal, are consistent with "the drop, cover, and hold-on" messaging and may deter terminal users from entering secure areas.
- **Diverse Infrastructure:** Airports have a variety of physical features, such as broad panes of glass, hanging panels or art installations, conveyances, people movers, and automated baggage systems. These features could lead to a diverse set of appropriate actions for individuals to best protect themselves, which may be difficult to incorporate into messaging. Designating safe zones in the terminal, where hazards from falling objects during an earthquake are low, should be considered.

This context requires careful consideration of messaging, training, and outreach to best protect people. Each airport should be cognizant of its own context and make necessary assessments and adjustments in these areas.

Benefits and Costs

Many ShakeAlert systems are compatible with a wide range of PA systems, and if this connection is straightforward, the costs involved are generally relatively low. If the entire PA system needs to be upgraded, costs could be greater, but many systems could be compatible with older systems; therefore, it is unlikely that this would be strictly necessary.

Public announcement benefits are substantial because of the reduction in personal injury and death. Studies show that location and population-specific messages from credible sources about the threat and appropriate actions are more likely to induce protective behaviors (Sutton et al., 2020).

4.1.2 Employee Facing Alerts

Airports rely on a diverse group of people for their operations. With seconds of advance warning about an earthquake, staff could manually initiate measures to protect passengers, other staff, infrastructure, and themselves. They could also decide the best way to communicate with passengers about the earthquake and guide them on how to best protect themselves from injury.

Operational Best Practice

ShakeAlert message data is processed, and automated information alerts are sent to the different airport staff. These alerts are customized to contain information relevant to each staff category.

The communications could be delivered to staff through the following channels (USGS, 2021):

- Mobile phones through WEA or the Android operating system. Users automatically receive these disseminated alerts without the need to specifically “enable” them. Additionally, users could download purpose-built applications such as MyShake.
- Digital message boards.
- Audible warning through an internal radio system or staff intercoms.
- Voice over Internet Protocol (VoIP) phones could broadcast an audible alert to all facility phones or target some extensions.

For a number of automated responses in Section 4.2, system operators could manually initiate the actions if the automated initiation fails. All airport staff should be well-trained in the types of alerts and automated actions implemented at the airport, what they can expect when alerts are triggered, and how they are expected to respond based on their respective jobs and environments. Instruction could be done through a combination of online and in-person training or through informative signage in different parts of the airport. The airport should also have routine earthquake drills to identify and work on any gaps in staff training.

Key Implementation Considerations

The key considerations when implementing EEW staff alerts include the following:

- The alert should be simple to interpret and customized for different staff and people in different airport locations.

- People with access or functional needs should be considered. If they are unable to self-protect, their protection should be planned for. For example, a flashing strobe light might be used to alert people.
- Appropriate communication channels should be used for staff stationed at different airport locations.

Limitations and Challenges

There are several limitations and challenges to effectively deliver earthquake warnings to staff, especially given the strong social implications of safety systems in diverse settings like airports (McBride et al., 2022). These include:

- Employee trust in EEW alerts could be affected by false or inaccurate warnings. False alarms could cause a "cry wolf" effect, reducing the likelihood of people responding to future alerts. In these situations, it should be emphasized to staff to follow established EEW protocols rather than their own judgment in the airport.
- Communication barriers, such as cultural and social factors and language differences, could influence and affect how individuals react to alerts. This is even more pronounced in airports due to the diversity of airport workforces. This challenge could be reduced by directly addressing these barriers during staff training.
- The response to EEW alerts is limited by human behavioral response times. Milling is a common response to warning messages and could be mitigated with clear messaging and staff training (Johnston et al., 2007).

Benefits and Costs

The main benefit of EEW staff warnings is that they protect people and infrastructure during earthquake events. These warnings also enhance the ability of the system to remain operational or quickly return to normal status after an earthquake.

The costs associated with EEW staff alerts include:

- **Communication Infrastructure Costs:** These may include costs to set up new telecommunication networks or integrate EEW alert systems with existing networks.
- **Staff Training:** Routine employee training and public awareness campaigns require recurring expenses to facilitate trainers and training materials.

- **Testing:** There are costs associated with testing, maintaining, and upgrading communication systems.

4.2 Automated Responses

EEW could be used to trigger a wide array of automated responses, such as slowing down trains and people movers, stopping elevators and escalators, and shutting off gas valves. This section discusses potential automated responses that EEW could activate in response to anticipated shaking at an airport. Section 6 includes a full breakdown of the benefits and costs associated with each option.

4.2.1 Elevators and Conveyances

Elevators and conveyances, such as moving walkways and escalators, are critical components of airports needed to efficiently move people between different locations. Their operation during earthquakes could significantly impact passenger safety. Elevators could lose power and trap occupants. In a large urban earthquake, it may take days for rescue staff to extricate all occupants trapped in stalled elevators (Porter, 2020). An EEW system with automated responses integrated with elevator and conveyance controls could prevent entrapment and injuries by stopping elevators at the nearest floor before strong shaking occurs.

Operational Best Practice

Effective EEW automated response integration with elevators and conveyances involves the following:

- **Immediate Response:** Upon receiving an earthquake warning, elevators should promptly stop at the nearest floor, open doors to allow occupants to exit safely, and issue alerts for personal protective measures (Allen et al., 2009; Gasparini et al., 2007). On the other hand, conveyances, such as moving walkways, should slow and stop in a controlled manner to prevent accidents and injuries.
- **Automatic Controls:** The automated response action should function without the need for human intervention to ensure timely action (Velazquez et al., 2020).
- **Regular Testing:** System checks help maintain the functionality of the EEW automated action.

- **Clear Communication and Training:** There should be clear communication of the required actions to elevator occupants and to the airport staff to prevent confusion during the elevator or conveyance EEW automated action. All staff should undergo EEW training and drills.
- **Stakeholder Involvement:** Collaboration among engineering, operations, safety, and emergency preparedness departments at the airport while planning for these EEW system automated responses is essential. Early involvement of all stakeholders ensures that technical and operational challenges are addressed.

Key Implementation Considerations

The key considerations when implementing EEW automated response systems for elevators and conveyances include the following:

- **Regulatory Compliance:** Adherence to building codes and safety regulations is essential when implementing these automated actions.
- **System Integration:** Elevators and conveyances must be equipped with controls that can receive and act on EEWS signals.
- **Building Infrastructure:** For airports with older infrastructure, upgrades may be required to support EEW automated response integration.
- **Occupant Communication:** Clear instructions and signage are necessary to guide elevator or conveyance system occupants during an EEW system-triggered stop.

Limitations and Challenges

Some of the limitations and challenges in implementing the EEW system automated response actions for elevators and conveyances include:

- **Costs:** Depending on the complexity of the elevator system, upgrades to existing elevator control systems could be expensive.
- **False Alarms:** False alarms present a significant challenge since each alarm triggers a protocol requiring time-intensive inspections and system resets. These unnecessary stops may keep elevators out of service for extended periods and reduce confidence in the system.

Benefits and Costs

Adoption of elevator and conveyance EEW automated response actions at an airport requires initial investments for upgrading elevator and conveyance control systems and staff training.

The main benefit of these automated actions is risk reduction. These actions decrease the likelihood of people being injured or trapped during an earthquake. Additionally, the response is encouraged because of its associated economic savings; it prevents the high costs associated with accident response, legal liabilities from injuries, and potential PTSD from being trapped.

4.2.2 Emergency Backup Generators

While there are fewer recorded examples of this application, using EEW to preemptively start backup generators is suggested as a front-running potential use of EEW systems in California (Johnson et al., 2016). Because backup generators can take tens of seconds to initiate after a power outage, the seconds of warning potentially granted by an EEW system could close the power gap and greatly reduce the impact of the earthquake at the airport, enabling staff to perform their jobs more effectively and focus resources on other aspects of emergency response.

However, a backup generator may be significantly more susceptible to damage if it is running during an earthquake. Because of this, appropriate actions could involve more complex logic based on the expected intensity of the shaking and are highly dependent on the facility’s infrastructure. For example, the generator could be installed on an isolation system, and a local accelerometer could shut it off if shaking reaches a level likely to cause severe damage.

Operational Best Practices

The operational best practice depends largely on the specific details of the infrastructure at the airport regarding the backup generators and critical machinery. These details and their consequences are as follows:

Speed of Generator Response: If generators do not turn on instantaneously, particularly if it takes long enough to cause machinery to shut down due to a lapse in power, it may be beneficial to turn on generators preemptively. In this case, if the earthquake causes a power outage, there will not be a lapse in power, avoiding costly delays. However, if the ground is still shaking when the generator turns on, or begins to shake afterwards, this could greatly increase the potential for the generator to become seriously damaged, which may cause much greater disruption than a lapse in power. To this end, understanding the fragility of the generator to ground shaking and setting an appropriate intensity threshold for an automated action is needed. Although fragility functions for static backup generators are well quantified as a function of shaking intensity, quantified fragility functions for running backup generators are lacking. Therefore, fragility functions of running backup generators and relevant thresholds can be developed from those of the static ones using expert opinion.

On the other hand, the generator may turn on automatically without a lapse if the power goes out. In this case, there is no need for an EEW automated action because there is already no gap in power. However, the potential for the generator to already be running while shaking is still occurring is much higher, and it may be appropriate to purposefully delay the generators as another type of EEW automated action to avoid damage from running during shaking. This will depend on the expected intensity of the shaking and the fragility of the generators to determine at what expected intensity this action should occur.

A decision-making matrix breaks down these scenarios in Table 4.1. In this table, the fragility of ground isolated generators is expected to be much lower than the fragility of non-isolated generators. Other considerations for this automated action are:

- **Number of Generators/Redundancy:** Where the airport facilities have redundancy in their generators, it may be desirable to operate different approaches for different generators. Some generators may be started preemptively and automatically to mitigate the risk of disruption from a lapse in power, while others may be kept off to decrease the risk of damage during shaking.
- **Restart Operation for Critical Airport Systems:** The final key consideration in determining an appropriate response is the scale and complexity of restarting critical airport infrastructure if they were to shut down from a lapse in power.

Table 4.1. Generator Types and Corresponding EEW Actions

	EEW Action	
Generator Type	**Low Levels of Shaking (Relative to Generator Fragility)**	**High Levels of Shaking (Relative to Generator Fragility)**
Instantaneous response	Allow generators to turn on automatically to avoid a lapse in power.	Prevent generators from starting up until after shaking subsides to avoid damaging them.

Delayed response	Preemptively begin generator start-up to avoid a lapse in power.	Prevent generators from starting up until after shaking subsides to avoid damaging them.

Key Implementation Considerations

The primary considerations for implementation are similar to those of many other discussed applications. This includes technical details, such as the complexity of connecting the EEW signal to the generators —whether they are already connected to the airport's information technology (IT) network or need to be manually started. These details heavily impact implementation costs.

Additionally, airports should be aware of the generator's current operational details in terms of how quickly it starts up, if it already starts up automatically, and in what conditions this occurs. Other important details include generator system redundancy and the impact of a lapse in power on the airport operations. Because of the capacity to improve the seismic resilience of the generators through structural upgrades, such as seismic isolation or added redundancy, and the impact this may have on changing behavior thresholds of the generator in response to EEW, airports may want to consider these infrastructure improvements in tandem with EEW implementation.

Limitations and Challenges

While EEW has significant usefulness in reducing airport disruptions due to power lapses or damage to the backup generators, it is especially beholden to the structural fragility of the infrastructure to which it is applied. For example, in the case of expected shaking that exceeds the structural capacity of the running generator for a unit that does not turn on instantaneously, EEW may be unable to prevent a lapse in power that could seriously impact the operations of the airport. As ever, early warning is only one aspect of earthquake safety and resilience, not a substitute for other aspects.

Additionally, because of the dire consequences of a damaged backup generator, airports may wish to be especially conservative when setting thresholds for preemptive startup protocols, further limiting the instances in which EEW may successfully prevent a lapse in power, though it could still be useful for avoiding a damaged generator in such cases.

Benefits and Costs

The potential benefits of EEW are substantial in terms of reducing operational disruptions at airports in the wake of an earthquake. Historical analysis of earthquakes at airports reveals the importance of backup power systems in mitigating operational disruptions in the wake of an earthquake (Hanaoka et al., 2013). Critical infrastructure such as IT systems, security devices, baggage handling systems, and conveyances may all be affected by a small lapse in power. These systems potentially require staff to be physically present to fully restart and reset each machine, so that even a few seconds of power outage could result in minutes to hours of disruption, as well as a substantial expenditure of labor. Because backup generators could take tens of seconds to initiate, the seconds of warning potentially granted by an EEW system could close these gaps in power and greatly reduce the impact of the earthquake at the airport, allowing staff to perform their jobs more effectively and focus resources on other aspects of emergency response.

Costs are highly dependent on the context of the airport. The number of generators, age, connectivity, and other functional details may add complexity and cost to the implementation process.

4.2.3 Fuel Systems

An airport fuel system is a complex network that consists of both on-airport and off-airport facilities and equipment, serving for fuel receiving, storage, transportation, and distribution (Airlines for America, 2018). Before being delivered to airports, jet fuel is stored at storage facilities. Tank farms are typical facilities used for offloading and storing jet fuel and can be located both on- and off-airport. If fuel needs to be transferred from off-airport storage to on-airport storage, local pipelines or trucks are used. Jet fuel is then distributed to airports through various methods from these storage tanks (Quilty, 2015). At larger airports, such as LAX, fuel is distributed to the airport apron through an underground hydrant system. At smaller airports like PSP, fuel distribution may rely on pump-equipped refueling trucks.

Airport fuel systems could experience significant damage and disruption from earthquakes (International Air Transport Association, IATA, 2018). The main risk that strong seismic activity poses to airport fuel systems is fuel spills, which can result in fuel fires and, in extreme cases, explosions. Earthquakes can damage major fuel facilities such as storage tanks, pumping stations, fuel loading and unloading devices, and pipelines. A tsunami-generating earthquake could create a secondary disaster, causing the fuel tank to float and fuel outflow. For instance, during the 2011 Great East Japan Earthquake, the Sendai Airport suffered massive damage, including the collapse of its fuel facilities.

The integration of EEW and automatic earthquake shutoff switches could be applied to reduce risks and damage to airport fuel systems during earthquakes. LAX is exploring a pilot project to automatically shut down the fuel hydrant system in response to EEW (Cal OES, 2023). The aim is to prevent jet fuel outflow, minimizing the risk of spills and fires and ensuring greater fuel availability (NIVA Inc., 2023).

Operational Best Practice

The application of shutoff valves in airport fuel systems initiated by EEW is feasible but remains largely hypothetical, with limited documented examples. However, similar applications have been used in the utility industry and manufacturing.

In Japan, EEW is used to trigger emergency shutoff valves in liquefied petroleum gas plants to stop the flow of gas and prevent leaks or explosions (Japan Meteorological Agency, 2023). By building an earthquake-actuated shutoff system, storage tanks for hazardous and toxic substances, high-pressure equipment, and bottom drain valves for heating equipment could be automatically shut off based on the estimated seismic intensity scales (Japan Meteorological Agency [JMA], 2024). Similarly, Istanbul Natural Gas Distribution Network integrates EEW to activate automatic shutoff valves at regulator stations when an EEW signal is received and seismic thresholds are exceeded (Alcik et al., 2009).

The integration of EEW into airport fuel systems could build on applying automatic shutoff valves. Potential aspects include:

- **Immediate Response:** Upon receiving an EEW signal, the system should automatically trigger shutoff valves to prevent the flow of jet fuel, reducing the risk of leaks, fires, and explosions.
- **Automatic Controls:** The shutoff mechanism should be designed to activate automatically without requiring manual intervention.
- **Pressure Management:** In addition to shutting off hydrants, the system should enable the depressurization of pipelines to prevent ruptures due to residual pressure.
- **Backup Mechanism:** If a central EEW signal is not received in time, the system could rely on local sensors to trigger shutoff valves based on set

seismic intensity thresholds. With proper thresholds, this backup mechanism may be as effective as shutting off valves upon the EEW signal if the valves could be shut off before the arrival of the damaging strong motion portion of the ground shaking.

- **Integration with Airport Operations:** The EEW-based automatic shutoff system should be integrated with other airport operations, such as communication systems and control centers.
- **Regular Testing and Training:** Since the failure of the automatic shutoff system could pose significant risks, regular testing and training are essential to ensure its reliability and effectiveness.

Key Implementation Considerations

The key considerations when implementing EEW automated response systems for fuel systems include the following:

- **PGV Threshold Values:** The threshold of response should be determined in terms of PGV, as the damaging effects of seismic waves to the pipelines in the soil (similar to the underground hydrant system used to distribute fuel to the airport apron in LAX) are proportional to PGV (Zuccolo et al., 2016). In their study, Zuccolo et al. (2016) used the gas pipeline fragility curves of Lanzano et al. (2015) to find thresholds for gas pipelines of the National Gas Company in Trinidad and Tobago.
- **Shutoff Switch Location:** While an EEW-based shutoff switch could discontinue the fuel flow at the ramp locations, activating multiple switches may leave fuel in the pipelines, which poses a risk if the pipelines rupture. To reduce this risk, it is safer to install shutoff mechanisms on the main fuel lines feeding the ramp from the storage. This would stop the fuel supply at the source (Zuccolo et al., 2016).
- **Timing and Coordination:** The automatic shutoff system should be triggered promptly after receiving an EEW signal. Delays or failures in activation have the potential to cause damage and lead to safety hazards. Coordination with other airport operations should also be considered to ensure safety and integration.

Limitations and Challenges

Some of the limitations and challenges in implementing the EEW system automated response actions for fuel systems include:

- **Limited Effectiveness:** If the damage thresholds are relatively high, the benefits of using EEW in airport fuel systems may be limited (Zuccolo et al., 2016). While shutting off valves in response to EEW could protect infrastructure and preserve fuel, it is generally seen as impractical due to the potential disruption caused if significant ground shaking does not occur (Hoshiba, 2014). Besides the risk of unnecessary disruption, another concern is the difficulty in restarting the system.
- **False Alarms and System Reliability:** The automatic shutoff system is sensitive to EEW signals. False alerts could trigger unnecessary shutoffs, disrupting airport fuel operations. The effectiveness of the EEW-based automatic shutoff system is dependent on the accuracy and reliability of the signals.
- **Delayed Response Time:** If the EEW signal is delayed or inaccurate, the system may not shut off the fuel hydrant in time, increasing the risk of fuel spills or fires.
- **Costs:** Integrating EEW with fuel systems may require significant investment to upgrade the current system and ensure ongoing maintenance.

Benefits and Costs

EEW automatic response systems help reduce earthquake-induced secondary effects by initiating timely protective actions (Strauss & Allen, 2016). The main benefit of implementing EEW-based shutoff valves is to prevent damage and fuel fires. Automatic shutoff valves, which operate within 30 seconds, could provide a significant advantage over manual valves, which may take up to 10 minutes to actuate (Fabbrocino et al., 2006).

While the benefits of EEW automatic controls are evident in maintaining long-term resiliency and safeguarding infrastructure, the integration comes with high costs. Significant investments are required to upgrade existing fuel systems and provide regular testing and maintenance. Additionally, if the EEW signal is delayed or inaccurate, the disruption caused by unnecessary shutoffs could incur further costs.

4.2.4 Baggage Handling Systems

Baggage handling systems consist of a complex series of conveyor belts and security machinery present at most commercial airports. The baggage and moving machinery represent an injury risk to those around them during an earthquake and may not be designed to withstand significant ground shaking.

Operational Best Practices

While no known instances of EEW-controlled baggage systems have been identified, emergency shutoff procedures are already in place across baggage systems. Manually and automatically activated procedures to shut off baggage conveyor belts are already in place to avoid injury and equipment damage. Baggage systems may automatically shut off in response to a fire alarm as well. An EEW-powered shutoff operation would function similarly to prevent injury to people near the machinery due to falling baggage or falling into moving parts of the systems.

Key Implementation Considerations

The technical design of most baggage systems should allow for a relatively simple implementation of an EEW-powered response. Automatic shutdown procedures are usually already in place, and system startup and shutdown are generally rapid and not costly. However, baggage handling system infrastructure is usually specific to each airport, and airports should be aware of the technical feasibility of connecting their specific system to an EEW signal. Staff training and setting system thresholds are also key considerations.

Limitations and Challenges

The biggest challenge airports might find in implementing an EEW baggage system response is the existence of multiple terminals. This adds both technical and institutional complexity due to the variety of baggage systems under different vendors, the varied management of terminal facilities, and the number of EEW systems to connect to the baggage systems.

Benefits and Costs

The estimated costs for more systems are low, and the installation times are short due to the presence of automatic shutdown procedures already implemented for other hazards. However, larger and more complex systems may incur additional costs. Benefits arise primarily from the reduced risk of injury to staff, and, in some cases, avoiding equipment damage, depending on the seismic resilience and exposure of the baggage handling system.

4.2.5 Fire Bay Doors

Fire following an earthquake is one of the greatest threats posed by a large-scale earthquake in California, with corresponding costs expected to be in the billions of dollars (Straus and Allen, 2016). Many airports, especially commercial airports, have dedicated on-site emergency response facilities. EEW has the potential to ensure that these services, which are invaluable in mitigating damages and providing continued service for medical emergencies, are able to operate at full capacity immediately following an earthquake by ensuring that emergency response personnel are prepared for the ground motion and vehicles do not become entrapped by jammed bay doors.

Operational Best Practices

Operational best practices are relatively straightforward for this application. Fire station bay doors should be automatically opened in response to the EEW signal based on a chosen threshold of expected shaking intensity. With the doors already open, there is much less risk of them impeding the egress of emergency services personnel and equipment from bay door jamming caused by ground shaking.

Limitations and Challenges

Several implementation challenges exist. One key organizational consideration is securing buy-in and cooperation from the fire department. The fire department may wish to establish EEW systems at facilities across their district, which could be a separate implementation process from airport EEW. Coordination across organizations is therefore critical to ensure compatible standard operating procedures (SOPs) and avoid confusion.

Another challenge that this practice poses is the access it gives to the fire station facilities. The EEW system may open the bay doors while the station is unattended, potentially posing a security risk. This becomes especially critical for stations that border an airport and have bay doors on both the landside and airside. This problem could be solved with remote security measures, such as security alarms and cameras that monitor the station and control the bay doors remotely.

While it seems intuitive that jammed fire station doors would inhibit firefighter response, this may not be the case. Fire personnel at one airport suggested that fire trucks, in an emergency, can simply break through jammed doors.

Benefits and Costs

Fires caused by ground shaking are among the biggest threats posed by earthquakes in California. Preemptively opening emergency bay doors adds significant resilience to emergency response systems and reduces the potential for significant delays in emergency response following an earthquake. By responding to fires and medical emergencies more quickly, there is the potential to save lives and protect critical infrastructure.

Because the logic of door opening is relatively simple, costs are not expected to be particularly high, although this depends mainly on the number of facilities. Additionally, if there is currently no infrastructure to accommodate automated openings (not necessarily triggered by an EEW signal), the unit cost would likely be significantly higher.

4.2.6 People Mover/Rail

Airports often have systems, such as automated people movers, in place to ease passenger movement between gates and terminals. Rail systems may also be used to transport travelers to and from the airport. Currently, only four California airports have people mover systems: LAX's Automated People Mover, SFO's AirTrain, SMF's Automated People Mover, and OAK's Airport Connector. LAX has already decided to move forward on an EEW system for its people mover, which is currently under construction.

Earthquakes pose significant risks to these systems, including potential derailments, passenger injuries, operational disruptions, and infrastructure damage. Automated EEW systems provide critical seconds of warning that could help minimize these risks. Advance notice could guide automatic responses, such as slowing or stopping rail systems in a controlled manner. For example, during the 2004 magnitude 6.6 Niigata earthquake in Japan, the EEW system issued a warning of 3.9 seconds after the earthquake began, cutting power to the system and applying brakes to the train. The S-wave hit 2.5 seconds later, but due to the automated response, it resulted in minimal damage, and all but one carriage remained on the tracks (Allen et al., 2009). Train systems are one of the earliest adopters of EEW automated responses. This is because of (a) the severity of potential effects of earthquakes on these systems; (b) the heavy investment by the rail industry, particularly in earthquake-prone countries, in EEW research and development aimed at safeguarding their operations; and (c) the automated nature of train control, which makes it easy to adopt automated responses.

Operational Best Practice

For automated people mover and rail systems, the EEW system automated responses are implemented through the computerized control mechanisms of the people mover or rail systems. Additionally, alarms are sent out to rail operators who then initiate safety protocols. Key practices involved in these automated responses include:

- **Threshold Setting:** Determining appropriate seismic intensity thresholds to trigger responses is crucial (Zhu et al., 2024). If thresholds are too low, false alarms may disrupt services unnecessarily. If they are too high, the system may fail to prevent accidents (Oliveira et al., 2015). Because people movers are generally traveling on aerial structures (railway bridges), the shaking they experience is amplified with respect to ground shaking, which should be considered in setting thresholds. According to statistical data on earthquake damage inflicted on the Japanese railway, when an earthquake's magnitude exceeds 5.5, it is likely to cause damage to trains during operational use. Thresholds are generally used to decide whether to send an alarm to train systems. Determination of these thresholds will depend on the earthquake hazard at the location, the level of structural vulnerability of the infrastructure, BCA, and other factors specific to a particular implementation, and therefore should be determined on a case-by-case basis.
- **Response:** Generally, the response of people mover and rail systems is to slow and stop the train at a safe spot. At this point, power supply to the trains is cut off to reduce the risk of fires, and the doors may be manually or automatically opened to aid evacuation. Operators then wait to ensure the hazard has passed before restarting.
- **Automatic Train Control Integration:** EEW system automated response should be seamlessly integrated with the train's control systems to enable automatic activation of emergency brakes without human intervention (Gasparini et al., 2007).
- **Human Communication:** In addition to automated responses, communications should be made to different staff who could take measures to further increase the safety of the people using the people mover/rail system.

Key Implementation Considerations

The key considerations when implementing EEW automated response systems for people movers or rail include the following:

- **Stakeholder Involvement:** Collaboration among engineering, operations, safety, and emergency preparedness departments is essential. Early involvement of all stakeholders ensures that technical and operational challenges are addressed.
- **Technology Integration:** The EEW automated response system must be compatible with existing train control systems. It requires robust

communication networks and reliable software to process data in real time.
- **Threshold Determination:** Engaging experts to conduct studies to continuously improve shaking thresholds that improve safety without significantly affecting operational efficiency is needed.
- **Maintenance and Monitoring:** Protocols should be established for regular system maintenance, updates, and monitoring to ensure continuous functionality of the automated response.
- **Clear Communication and Training:** There should be clear communication to prevent confusion during the people mover/rail EEW automated action. Staff should undergo EEW training and drills.

Limitations and Challenges

People movers are likely to be among the more technically complex EEW implementations at airports. Airport people movers involve unique infrastructure that prevents "drag and drop" implementations between airports for software that would automatically slow and stop trains and provide logic for when and how this should be done. Additionally, institutional complexity may be present in cases where the people mover is operated and/or funded by an organization other than the airport.

Benefits and Costs

Adoption of a people mover and rail EEW automated action requires initial investments for technology acquisition, system integration, and staff training. There are also recurring expenses for system updates and regular testing. On the other hand, the cost of slowing and stopping a train when the shaking is not that severe or due to a false alarm is low. This is because of the automated nature of train control systems that make it easy to quickly restart the system, minimizing the impact on passengers in case of a false alarm (Allen & Melgar, 2019).

One of the main benefits of rail EEW automated actions is risk reduction. These actions decrease the likelihood of train derailments and passenger injuries. Due to the high costs of rail and other people mover infrastructure, the response is also encouraged because of its associated economic savings. It prevents the high costs associated with rail accident response, infrastructure repair, legal liabilities, and possible infrastructure replacement (Zhu et al., 2024).

The automated responses also enhance operational continuity by enabling quick service resumption after an earthquake. These benefits enhance the public's trust in the safety and reliability of the airport people mover and rail systems.

4.2.7 Water and Gas Shut-off

In addition to fuel valves, EEW could automatically shut off airport water and gas systems. The basic functionality of these systems mirrors that of fuel systems, with EEW allowing for preemptive valve shutoff to reduce the risk of fire and flooding due to earthquake damage.

Operational Best Practice

Best practices and considerations are generally shared with fuel systems.

Gas shutoffs applied in the United States at Menlo Park Fire Protection District include valves for the ranges at the fire stations that automatically shut off, reducing the chance of gas leaks.

Water shutoff has been applied by the City of Grants Pass, Oregon, where valves for a 5-million gallon city water reservoir are automatically shut off to ensure adequate water supplies after an earthquake and reduce flood damage and injury risk. Plans are in place to further integrate EEW into upcoming water treatment plant facilities.

Benefits and Costs

While the costs of the water and gas system shut-offs are comparable (though dependent on the specific infrastructure of each airport), the benefits are generally higher for gas systems. This is primarily because the costs associated with fire damage are higher than those associated with flooding. However, this may vary depending on an airport's infrastructure and the disruption caused by flooding from water system damage.

4.2.8 Other

Beyond those listed, there is the potential for a large variety of other applications of EEW at airports, as any piece of infrastructure that could receive a digital signal and take automatic action may be connected to an EEW system. Due to the variety of physical infrastructure within and across airports, it is possible that a particular airport could have good uses of EEW that are unique. Airports should use this understanding of the flexibility of EEW to identify any other use cases that could reduce disruption and increase safety.

4.3 ATC Response

Air traffic controllers in the tower could use EEW to alert aircraft, on approach and on the airfield, of an impending earthquake. Based on this warning, aircraft on final approach could initiate a go-around, while arriving aircraft in the terminal area could go into holding patterns. Aircraft taxiing on the airfield or moving on the ramp could be advised to come to a stop, while those awaiting pushback could be held at the gate. The goal would be to cease aircraft movement on the airport surface. Once ground motion ceases, controllers could direct aircraft on the surface based on the condition of the runways and taxiways, which would be ascertained by SOP post-earthquake inspections.

Controllers would also advise Approach Control, which would in turn advise the Air Route Traffic Control Centers and the FAA Command Center so that aircraft en route could be diverted and those that have not departed could be held on the ground. The benefits of basing these advisories on the warning, as opposed to the earthquake itself, will be limited. For example, a 30-second advance warning is unlikely to prevent more than one, or at most two, aircraft from taking off for the earthquake-impacted airport. The main advantage is that the controllers, not yet experiencing the ground shaking, could communicate information about the impending earthquake without being affected by shaking.

The EEW would be communicated to the tower, probably to a computer used by the tower shift supervisor. Controllers are not permitted to use cell phones while on duty, so tower staff would be completely reliant on this computer connection to receive the warning. The FAA, out of concern for creating unnecessary distractions to tower controllers, restricts software applications that can be installed on the shift supervisor's computer, so installing the EEW application would require approval from FAA management. One potential obstacle to such approval is that the warning system is not an FAA product. According to one commentator, writing in 2011, ATC facilities are not allowed to receive tornado warnings for this reason.

Assuming approval can be obtained, the airport operator is likely to arrange the EEW tower installation as part of an airport-wide implementation. It is not uncommon for the airport operator to provide equipment to towers, or even finance the construction of the tower itself, so such an arrangement would not be expected to pose significant challenges.

As with other EEW use cases, realizing the value for this application depends on establishing well-designed SOPs. For example, how would the warning be communicated to aircraft on final approach or on the airfield? Aircraft on approach pose a particular challenge. There is a high probability that an aircraft could land during an earthquake without major difficulty. For example, there is a social media report that a United States military aircraft landed in Kathmandu, Nepal, at the beginning of a magnitude 8.5 earthquake that damaged the runway. The landing was bumpy, causing aircraft occupants, unaware of the earthquake, to tease the pilot about his technique, but they did not suffer serious damage or injuries. By proceeding with the landing despite the warning, a flight could avoid a lengthy hold for the post-earthquake airfield inspection, or, if fuel reserves are low, a costly diversion. These considerations pale against the possibility of an aircraft runway excursion or upset caused by ground shaking or liquefaction, but, as the Kathmandu example suggests, the risk of such outcomes is uncertain even for a very strong earthquake. Therefore, the most likely procedure would be for a local controller to relay the warning to aircraft on approach and advise a go-around. The precise phraseology for the warning would have to be established in the implementation process. A retired controller interviewed for this research suggested relaying the warning along with the advisory, "Land at your own risk." In contrast, when responding to earthquakes occurring without warning, controllers are more likely to simply instruct flights to go around.

It may be appropriate for a controller to expedite take-offs of aircraft in position to begin their take-off role so that wheels off occurs prior to any pavement failure. As with aircraft on approach, a risk analysis is required to balance the value of completing the departure prior to the onset of earthquake damage and the risk to accelerating aircraft of shaking, and possibly a damaged airport runway.

The EEW warning would also allow tower occupants to increase their personal safety during an earthquake. During the time between warning issuance and the beginning of shaking, controllers could remain at their positions and issue appropriate advisories to aircraft and then duck and cover once the shaking starts. This potentially prevents the dilemma posed when earthquakes occur without warning, and controllers may be forced to choose between personal protection and fulfilling their responsibility to advise pilots.

Towers have elevators, and it may be advisable to implement automated responses for these elevators, like those used for other airport elevators. Issues and considerations for this type of automated response are discussed in Section 4.2.1.

The specific procedures for controllers to follow after receiving an earthquake warning would ultimately need to be determined by Mission Support Services at FAA headquarters, in consultation with the FAA regional office in Seattle. Before establishing procedures nationwide, a pilot project in which EEW is implemented in a single tower or a few towers is recommended.

4.4 PSP Case Study

At PSP, the airport management and staff provided the research group with insights into the considerations and applicability of different EEW automated response applications. These were compiled, and staff used this information to apply priority levels for each application, which are explained here.

4.4.1 Notifications/Warnings

Public Alerts

PSP has a significant amount of glass in its terminals, and a public announcement could be helpful to guide people to safer locations nearby where they could perform the Drop, Cover, Hold On actions. The airport is planning to replace the PA system and install a new flight display system. The new system is expected to have more functionality, including visual alerts and pop-ups. These systems could be modified to support EEW public announcements.

From experiences with previous false fire alarms, it was found that, like staff, passengers in the airport usually react by milling, waiting to verify the risk before reacting.

From an organizational perspective, the airport could implement this system unilaterally, without requiring approval from airlines or vendors. However, these stakeholders should be notified about the new system. The message could be played for them in advance so they are familiar with it. Additionally, staff should receive internal notifications or training to ensure that they understand the message and can guide passengers to respond.

Priority/Applicability

Public alerts would be a high priority EEW response for PSP due to its low cost and simplicity of application.

Staff Alerts

Staff in operations roles currently check generators, the runway, and other critical areas if they believe an earthquake has occurred, but this process is not yet formalized, as there are no SOPs in place for EEW response.

PSP staff already rely on radios for communication, making it a viable option for EEW alerts, but radio alerts may not be quick enough for EEW. Applications like MyShake could be faster. These applications could easily be added to the suite of applications on employer-issued phones. However, only about one-third of staff have city-issued or airport-issued phones, and additional educational outreach would be needed to encourage employees to install the application.

Additionally, PSP is currently in the process of setting up a critical event management solution (i.e., Everbridge), which is expected to notify staff about different emergencies, including earthquakes. However, there is concern that these types of systems may not be the best approach, as they have significant time delays due to the human factor in inputting messages.

Priority/Applicability

Staff alerts would be a high priority EEW response for PSP due to its low cost and simplicity of application.

4.4.2 Automated Responses

Elevators and Conveyances:

PSP’s current elevators use old technology that cannot support an EEW automated response. However, PSP plans to replace the old elevators soon with new ones that will be equipped with a system that can support EEW automated responses.

In addition to ensuring elevator passenger safety during an earthquake, an EEW automated response could reduce the risk of elevator failure. If an elevator system malfunctions during an earthquake, the airport cannot restart it independently; they must call state-licensed staff to reset it.

PSP’s escalators are designed to roll to a stop and are already equipped with earthquake sensors that trigger automatic shutdown. However, an EEW response using a centralized ShakeAlert notification would be more reliable and would further enhance safety.

Priority/Applicability

Elevators and conveyances would be a high priority EEW implementation for PSP due to a relatively straightforward implementation process that can be aligned with the planned elevator upgrades.

Backup Generators

The airport relies on two power sources, with a cogeneration system that helps feed power to the airport. When a power issue is detected, switches assess power availability before activating the backup generators, which require 10–15 seconds for full transfer. During this time, emergency lighting remains on through battery backup, but other systems experience a brief power loss. Critical systems, such as the control center, security, and operations, could be supported by Uninterruptible Power Supply (UPS) backup for 20–30 minutes.

PSP has experienced minimal power issues in the past. Although IT systems are connected to backup power, there is no direct data feed to the generators. Plans are in place to install a live status system for real-time generator monitoring.

Priority/Applicability

Implementing an EEW-triggered backup generator response would be a high priority for PSP because the estimated cost of implementation is relatively low. Since PSP is already considering generator replacements, integrating this functionality could be feasible.

Fuel Systems

PSP has two fixed base operators that provide fueling services: Atlantic Aviation on the east side of the field and Signature Aviation on the west side of the field. The fuel used at the airport is supplied using trucks, which are filled from reservoir tanks in the fuel farm facility located close to the airport. All valves in the system are operated manually; therefore, without major upgrades to the system, automated EEW responses are not an option. There are no major risks to the current fuel systems in case of an earthquake.

The fuel reservoir tanks are double-walled, reducing the likelihood of significant structural damage. Additionally, all fuel piping is above ground and contained, limiting concerns about undetected underground leaks.

If a major earthquake occurred during fueling, the operator would likely release the dead-man handle, which would stop fuel flow.

Priority/Applicability

Fuel systems would be a low priority EEW implementation for PSP. The fuel systems are simple and well contained, reducing the potential benefits provided by EEW and the need for concern in case of an earthquake.

Baggage Handling Systems

PSP currently has a baggage system that can easily be shut off during an emergency and turned back on once it is safe to do so. The system is already equipped with a fire alarm response system. A similar system could be set up to respond to EEW.

The baggage system is in the category of nonstructural components, is expected to have a robust seismic performance, and there is little concern about major damage to the system during an earthquake. The primary benefit of shutting off the system during an earthquake is to protect staff working near the system from injury.

Priority/Applicability

The ease of installation, low risk of false positives, and potential to reduce injury make this a high priority application for PSP.

Fire Bay Doors

The fire station bay doors at PSP have an EEW system that is currently non-operational due to past issues with false alarms and a lack of trust in the system. The old system frequently triggered the doors to open randomly, leading to its disconnection.

Priority/Applicability

Fire bay doors would be a low priority EEW implementation for PSP. Given that fire trucks can drive through the closed doors if necessary, the operational benefit of automated opening is low.

Water Shut-off

At PSP, water leaks following an earthquake would not have a significant effect on airport operations. Water leaks occur quite frequently due to different reasons, and the maintenance team is experienced in managing them when they arise.

Priority/Applicability

Water shutoff would be a low priority EEW implementation for PSP. The operational benefit of automated shutoff valves was considered low, and the cost is very high.

Gas Shutoff

During an earthquake, gas pipes may be damaged, increasing the risk of fires. Automatically shutting off gas following an EEW could significantly reduce this risk.

Priority/Applicability

Gas shutoff would be a high priority EEW implementation for PSP. The benefits of an automated gas shutoff are high with a relatively low cost. Given the potential to mitigate significant fire risks, the return on investment (ROI) for gas shutoff is high.

4.5 LAX Case Study

At LAX, the airport management and staff provided the research group with insights into the considerations and applicability of different EEW automated response applications. These were compiled, and the research team used this information to determine application priority levels, which are explained here.

4.5.1 Notifications/Warnings

Public Alerts

Public alerts at LAX are one of the more complex implementations. From a technical and institutional perspective, the large number of terminals and terminal operation models means that added expense and complexity are inherent in the implementation compared to smaller and more uniform airports. Additionally, the scale and public visibility of LAX as an institution means that false alarms could pose more of a risk in eroding public trust in EEW systems.

Several challenges with public announcements, which are shared at essentially all public airports, are exacerbated by the size and high level of international travel at LAX. These include diversity in primary languages spoken by travelers and a lack of familiarity with best practices in correct protective action to take in response to an earthquake.

Priority/Applicability

Public alerts could be added following the successful implementation of a first round of EEW systems. This would allow for ample time to build appropriate SOPs and refine threshold levels for alerts, reducing the risks of false positives and ensuring that staff are adequately prepared to help passengers respond to EEW appropriately.

Staff Alerts

Currently, LAX uses Everbridge as an airport-wide system for disseminating alerts to all staff members. However, the current system is not capable of issuing alerts quickly enough for staff to receive them prior to shaking. Because of this, EEW would require the use of another alert system, such as requiring staff to download an EEW application.

As with other airports, LAX has a wide range of staff from office positions to employees in baggage or on the airfield, which may impact noise levels and the awareness of staff to receive phone notifications. Radios, screens, or louder audio alerts over speakers may be more appropriate for immediate staff warnings in more industrial settings. However, airport staff operate over a vast physical area, and across a wide range of independent organizations operating on the airport site. Therefore, each additional vector for early warning alerts adds technical and institutional complexity to the implementation. This would increase costs and timelines associated with implementation.

Priority/Applicability

Despite the discussed logistical challenges, staff alerts remain one of the most applicable uses of EEW at LAX. Staff having situational awareness and having time to take personal protective action has a low risk of false positives in terms of operational disruption or erosion of public trust, which by itself makes it a leading candidate. Simply requiring a mobile application on employee phones would be in line with current LAX policies, while other implementations may depend more on specific vendor offerings, funding, and other logistics.

4.5.2 Automated Responses

Elevators and Conveyances

LAX has hundreds of elevators, escalators, and moving sidewalks across its facilities. Various vendors have installed these over the years. This makes the technical process of implementation difficult, but the high level of use of these systems also increases the potential benefits of EEW.

Analysis of the most beneficial or simplest implementations from a technical standpoint could be used to triage EEW implementation to minimize the costs of implementation or facilitate prioritization in a phased implementation approach. Based on discussions with airport staff, this is likely to be a preferable strategy for implementation, as the technical complexity of implementation across all conveyances at once is logistically prohibitive.

Priority/Applicability

The costs and complexity of a complete implementation across all conveyances are high enough that it is difficult to recommend for the initial phases. However, more selective implementation for high traffic elevators, moving sidewalks, or escalators could potentially reduce costs and complexity significantly while retaining much of the benefit.

Backup Generators

Except for one terminal, backup generators at LAX are mobile and need to be moved into place at a terminal prior to being turned on. This process would take tens of minutes to set up and initiate. Because of this, there is limited use of EEW to control backup power at LAX.

On the other hand, restarting processes for security equipment critical to airport operations can take tens of minutes. In an airport with hundreds of thousands of passengers per day, this level of delay would be extremely disruptive. While EEW-controlled backup generators for entire terminals may not be technically feasible, LAX may wish to explore smaller scale EEW-controlled backup power systems for critical infrastructure, such as machinery for the Transportation Security Administration (TSA) security.

Priority/Applicability

Because of the current use of mobile backup generators at LAX and plans to expand this moving forward, this is not currently an applicable use of EEW at

LAX. Other forms of backup power, such as batteries, specifically for security equipment, may be desirable and even a high priority because of the risk of operational disruption by even a small lapse in power.

Fuel Systems

Fuel at LAX is handled solely by LAXFUEL, which is owned by a consortium of airlines and operated by Aircraft Services International Group. This single facility supplies over 4,000,000 gallons of Jet-A to aircraft per day and is directly fed by pipelines from three different oil refineries. Like PSP, the airport does not own the fuel farm, so EEW responses for fuel systems would be the purview of the fuel farm owners and management company. This may happen in collaboration with the airport to some degree, but the details and level of collaboration would depend on the implementation, funding sources, and similar factors.

In contrast to PSP, the system’s scale and complexity add more points of seismic vulnerability but are necessary for the airport's operational scale. This makes implementation at LAX more complex and expensive. An engineering analysis is needed to determine where valve and pump shutoff would be most effective in preventing damage and spills.

Priority/Applicability

Fuel systems are one of the applications with the highest BCR at LAX. Although this makes it a potentially high priority application, the complexity of implementation introduces challenges. Therefore, this application could be considered following the successful implementation of a first round of EEW systems.

Baggage Handling Systems

LAX has a wide array of baggage handling systems across its 10 terminals, supplied and operated by different vendors. Baggage handling companies have staff on site to ensure the systems are well maintained and up to date. Because of this onsite service and the relative technical simplicity of adding a new input to automatically stop baggage handling systems, this is expected to be one of the more technically straightforward EEW implementations for LAX. However, the number of terminals with different management and different baggage handling system providers means that there may still be relatively high complexity from an institutional standpoint.

Priority/Applicability

Because of the more straightforward technical implementation, and particularly because of the low risks associated with a false positive, this is one of the more promising EEW-powered automated actions for LAX to implement initially. While a complete implementation across all terminals adds complexity, beginning with a limited number of terminals could be considered.

Fire Bay Doors

As with PSP, the decision of whether or not to implement this application would ultimately rest with the fire department rather than the airport. The extent to which systems or technologies are shared or kept separate between the fire department and the airport needs to be decided.

Priority/Applicability

EEW-controlled bay door operations for the airport fire station is another application with high quantified benefits and low risk of false positives, making it a good candidate as a high priority application. It also has the benefit of having preceding implementations in the United States, further streamlining implementation and helping with internal buy-in. Assuming institutional hurdles between the fire department and the airport could be overcome, this is one of the more straightforward applications at LAX.

Water Shutoff

Detailed engineering analysis would be required to fully understand the water system, the risk of flooding, and the potential benefits EEW could offer in reducing damage to airport infrastructure and disruption to operations.

Priority/Applicability

The Benefit Cost Ratio (BCR) estimate for this application at LAX is approximately 1.0 (refer to Chapter 6 for detailed calculations). A more detailed analysis using the structural characteristics of LAX terminal buildings may change this assessment, making it difficult to assign a priority without more information. However, compared to other applications on this list, the lack of a clear benefit places it at a lower priority.

Gas Shutoff

The risk of fire following an earthquake is significant at LAX. Further analysis would be required to determine the extent of the implementation that would be most appropriate for LAX to avoid unnecessary disruption while still minimizing the risk of fire due to a gas leak.

Priority/Applicability

Gas valve shut-off has one of the highest BCRs of the applications examined in this study and is a good candidate for prioritization. While a more detailed engineering analysis is required to fully assess the technical complexity of implementation, the benefits are high enough that it is unlikely that a BCR of less than one would occur.

5 Airport Acquisition and Implementation

As airports seek to enhance safety and resilience against seismic events, EEW acquisition and implementation have the potential to serve a role in mitigating risks and ensuring operational continuity. This section explores the key steps involved in integrating EEW technology into airport infrastructure, from system selection and procurement to deployment and coordination with emergency response protocols. It examines regulatory requirements, funding considerations, and best practices for optimizing EEW effectiveness in an airport setting. Additionally, the section highlights implementation challenges, including interoperability with existing safety systems, and strategies for minimizing disruptions during installation. The section concludes with a discussion of how EEW could be acquired and implemented at the PSP and LAX case study airports.

5.1 Institutional Goals and Considerations

Implementing EEW within an institution, such as an airport, requires careful planning and coordination. This research revealed several key institutional considerations, including:

- **Ensuring Regulatory Compliance:** Adhering to federal, state, and local regulations governing aviation safety, seismic safety, and emergency response is critical. As such, there is a need to ensure compliance with regulators and industry standards (e.g., FAA regulations for airports, Occupational Safety and Health Administration for workplace safety, etc.). Implementing EEW may require additional coordination with agencies such as the FAA, FEMA, California Governor's Office of Emergency Services (Cal OES), USGS, and local emergency management offices.
- **Integration with Existing Emergency Protocols and Processes:** There is a need to align EEW with established emergency response plans, including evacuation procedures after the earthquake, and continuity of operations. Training may be needed for staff to effectively respond to

alerts. As such, there could be a role for emergency drills and simulations to test system and staff responses to EEW alerts.

- **Technology and Infrastructure Readiness:** When employing EEW at an airport, there is a need to assess the compatibility of EEW with existing technologies and communication systems. There is also a need to ensure the redundancy and reliability of EEW alerts to prevent false alarms and/or missed warnings. Cyber and data security should be proactively addressed, particularly for any automated responses.
- **Institutional Coordination and Stakeholder Engagement:** There may be a need to establish clear roles and responsibilities among different departments, agencies, and private sector partners. Engaging stakeholders, including first responders, airport operators, airlines, and others, could aid in the development of internal and public communications strategies to educate employees and travelers about EEW.
- **Financial and Operational Feasibility:** There may be a need to identify funding sources, including federal grants, state funding, and public-private partnerships. Estimating costs for acquisition, installation, maintenance, and staff training is necessary for any EEW deployment in a specific airport. ROI in terms of risk reduction and operational resilience needs to be quantified using airport characteristics.
- **Legal and Risk Management Considerations:** There is a need to understand the liability implications if the system fails or provides insufficient warning. There is also a need to establish policies for system activation (i.e., response thresholds and response protocols). It may be necessary to ensure contractual and insurance coverage for potential damages related to EEW implementation.
- **Performance Monitoring and Continuous Improvement:** There is a need to develop and implement a framework for testing, evaluating, and enhancing EEW over time. Airports may consider establishing a feedback mechanism to collect input from key stakeholders to refine alerts and alert protocols over time. Finally, like other types of technologies, there will likely be a need to update EEW as technology advances in the future.

5.2 Alternative Pathways

There are multiple pathways available to airports to make use of the ShakeAlert signal. Determining which one is best suited to a specific airport is one of the first decisions in the EEW implementation process. Accessing the ShakeAlert signal requires a License to Operate (LTO), which is a legal and technical partnership with USGS. The goal of the LTO process is to ensure that ShakeAlert signal users are operating within specified technical specifications and that appropriate training and education are provided alongside the use of the warning system. Because of this, there are two primary options open to airports:

- **Technical Partnership:** Airports can choose to become a technical partner, obtaining their own LTO directly from USGS. This is known as being a ShakeAlert Technical Partner.
- **Vendor:** Airports can choose to hire an EEW vendor that has already obtained an LTO and is able to install an EEW system for the airport. MyShake is one such vendor, though it differs from the others in that it could provide its services to California institutions free of charge. This can be used for the purposes of staff alerts only, at the time of writing.

Each pathway has a different logistical and technical implementation process, and choosing the preferred option will largely depend on the context of each airport.

In both cases, the actual signal and information received by the airport about the earthquake are the same, but the institutional and legal relationships that define the implementation and ownership of the system are significantly different. This section details the steps involved in each pathway and gives insight into the factors to consider when determining which pathway to take.

5.2.1 Technical Partner Pathway

The process to become a Technical Partner with USGS is a legal process that takes roughly 2 years to complete. This process is broken into the following steps:

1. Identify key applications for EEW at the airport.
2. Complete and carry out the Pilot License Agreement (PLA).
3. Complete the performance review.
4. Convert the PLA to a complete LTO.
5. Provide ongoing communication, changes, and updates.

Each of these steps is described in detail below.

Step 1: Identify Key Applications for EEW at the Airport

Identifying how the ShakeAlert signal will be used—what automated warnings and actions will be utilized—is the first step in the Technical Partnership process.

This step also involves understanding the Technical Performance Guidelines and Education and Training Guidelines and ensuring that the airport understands the requirements and can reasonably expect to meet them.

Key staff to assist at this stage are Technical Engagement Regional Coordinators (TERCs). These staff members could engage with the airport to help navigate the process of becoming a Technical Partner. At the time of writing, there are two TERCs in California, one for the northern region and one for the southern region. These staff can help understand useful implementations, get answers to technical questions about the system's performance and operation, identify and address common questions and pitfalls during the process, and provide other assistance as necessary. Involving them early and often is a recommended best practice. They are generally able to provide expertise through the first two steps of this process, but become less involved after the PLA is finalized.

Step 2: PLA

The airport fills out the PLA using the USGS-provided template[30]. The PLA stipulates the use of the ShakeAlert signal by the airport as well as implementation plans, training, and messaging. The PLA should be a robust document providing adequate details and legal stipulations around EEW implementation, as well as flexibility to accommodate the airport's future goals for its EEW system. It will be transferred directly to an LTO following completion of a performance review and approval.

Most importantly, the PLA contains the statement of work (SOW), where the airport determines various details about its implementation to meet USGS requirements and get the PLA approved. These details are broken into the following sections in Table 5.1.

Table 5.1. ShakeAlert Technical Partner PLA Description

Section	Description
Goals/Aims	Specifies the deliverables for implementation.
Pilot scope	Explains the intended use, defines end users, and provides a general nontechnical overview of the system being developed.
Licensee's obligations	Includes subsections about the technical details (hardware, software) of the system, a development timeline, alerting specifications, product testing details, and marketing and education descriptions.

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[30] https://www.shakealert.org/technical-partner-resources/shakealert-licensing-center/#pilot-license

This process is accompanied by bilateral communication between USGS and the airport to ensure that both parties agree on the legal and technical details. The legal components of this process often drive the timeline and include ensuring that both parties are content with the stipulations around privacy and intellectual property.

To expedite the PLA creation process and maximize the chance of a successful LTO, several practices are recommended. First, the TERC should be heavily involved. Second, because the PLA serves as the basis for the LTO agreement, the airport should ensure that the document is flexible enough to accommodate future changes and adaptations to the implementation. Significant changes beyond the scope of the LTO agreement could require a new PLA process. Clarification of these details can be determined with the assistance of the TERC working with the airport.

PLA completion grants the airport access to the technical documentation required to access and utilize the ShakeAlert message, so the airport can begin creating its specific implementation of the EEW system.

Step 3: Performance Review

Once the PLA is in place, the system will go into effect and will be subject to a performance review to transition from a PLA to an LTO. A complete list of the guidelines can be found on the ShakeAlert website[31]. Some of the most important requirements are as follows:

- Within 5 seconds of receiving the signal, 95% of the system end users (specific staff, automated actions, or the public) should receive their alert.
- A specific plan is in place to include education and training for relevant staff members. If the message is planned to go to the public, messaging that explains the alerts and correct protective action should be included as well.
- The system needs to be able to determine if there is a live connection to ShakeAlert or a lost connection at any time.

Meeting these guidelines and other requirements laid out in the SOW allows the airport to continue to the next step, which is full conversion to an LTO agreement with USGS.

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[31] https://www.shakealert.org/

Step 4: PLA to LTO Conversion

After 1 year, the PLA term comes to completion, and within a period of 90 days from the end of the term, the airport is required to meet with USGS. This meeting determines which of four routes the airport will pursue:

1. Extend the period of the PLA.
2. Modify the PLA in some way.
3. Plan conversion of the PLA to an LTO.
4. Terminate the PLA.

Going from the PLA to the full LTO allows the airport to fully operate its system, including delivering and acting upon the ShakeAlert message.

Step 5: Ongoing Communication, Changes, and Updates

After the LTO conversion, the airport has minor ongoing obligations with the USGS. Primarily, it is required to provide a yearly report showing that its system is functioning within the parameters described by the SOW. Smaller changes in the LTO SOW may be made with USGS approval, while larger changes may require a new PLA before implementation.

Additionally, technical changes occur regularly as USGS continues to update and improve ShakeAlert, and airport systems change as the airport upgrades its own IT infrastructure, messaging services, and so forth. Changes on either side may require modifications to the EEW system software or hardware, and the airport should be prepared to accommodate those changes as needed, as well as the flexibility it offers while following an implementation process airports are already familiar with.

5.2.2 End-User/Vendor Pathway

In choosing the vendor LTO pathway, the airport opts to contract with a company that has obtained an LTO through USGS that allows them to install EEW systems at other institutions. In this case, the company holds the LTO rather than the airport, and there is no direct organizational connection between the airport and USGS. For most California airports, the vendor pathway is the more viable option due to the Technical Partner pathway’s technical and logistical requirements.

In this scenario, the airport would follow a similar protocol that it used for other contractors and vendors it hires. Generally, this involves the following:

1. Determine which applications are suitable for the airport.

2. Develop a request for proposals (RFP).
3. Select the preferred option among the available vendors.
4. Work with the vendor to establish an installation plan.

In this option, much of the process is determined by internal processes particular to the airport. Depending on the airport's organizational structure and processes, one to several years should be anticipated from project inception to installation. However, installation is often relatively rapid, with installations of physical hardware to connect to the ShakeAlert signal typically taking place in under a day.

Vendor costs can vary widely depending on implementation complexity and vendor selection. On the low end, airports can expect to pay low tens of thousands of dollars, up to mid-hundreds of thousands of dollars for installation. Similar variation can be found in the ongoing subscription fee, which can range from hundreds to thousands of dollars a month.

Different vendors may have an LTO with different automatic actions and warnings in their SOW. Table 5.2 gives a complete list of these vendors with business-to-business offerings at the time of publication.

Table 5.2. List of Current Vendor LTOs[32]

Licensed Operator	Can Automate Infrastructure Actions Allowed Under Agreement with USGS	Current Implementation Examples
Early warning labs	Yes	PA systems, speakers, VoIP, voice-activated fire alarm boxes, handheld two-way radios, gates, and fire station bay doors, stopping elevators at the nearest floor, throttle valves, train control systems, or shutting down or turning on industrial systems.
Global security	No	Audio and visual alerts delivered via FM radio to Alert FM voice, text, Bluetooth, desk, and wall receivers, including an ADA strobe light.

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[32] Adapted from Pacific Northwest Seismic Network, https://pnsn.org/pnsn-data-products/earthquake-early-warning/shakealert-LtOs

systems / AlertFM		
Kinemetrics	No	Deliver audio and visual alerts via the OasisPlus Earthquake Response Platform. Provide rapid safety assessments that enable informed decision-making, rapid emergency response, and enhanced building occupant safety.
RH2 engineering	Yes	Initiate alarms; throttle valves; turn off motorized equipment; de-energize electrical control panels; integration with staff alerting systems, including WIN911, SMS.
SkyAlert	Yes	Stop elevators at the nearest floor and prevent manual operation; open fire station bay doors; stop machinery; turn off gas valves. Alerting methods include strobe lights and audible alerts.
Valcom	No	Audio and visual alerts using intercom, VoIP, or PA speakers, including ADA message boards via Valcom intercom hardware.
Varius Inc.	Yes	Initiate alarms; throttle valves; turn off motorized equipment; de-energize electrical control panels; send alerts via PA systems, email, SMS; monitor pre- and post-earthquake building condition.

MyShake Option

Choosing MyShake as the vendor of choice includes a somewhat different process from the for-profit vendors. In this case, the use case is limited to alerts on staff devices, including mobile phones or personal computers. This option is suitable for airports with smaller budgets or that would like to pursue a more limited EEW implementation without automated actions, public announcements, or use of proprietary staff alerting or communication systems.

Initiating this can be done with the assistance of a TERC or by communicating directly with the MyShake team at the BSL[33]. The team will work with the airport to add MyShake functionality to devices at the institution and assist with training materials and other implementation logistics.

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[33] https://earthquakes.berkeley.edu/research/eew_basics.html

5.2.3 Pathway Comparison

IT capability and availability usually determine which pathway to pursue. Many airports simply may not have software development staff on hand, and those that do may not have the bandwidth to take on the creation, testing, and maintenance of an EEW system. For these airports, utilizing a vendor is the clear route forward. For airports that do have the time, capability, and interest, the decision may come down to other factors, including the timeline and process required for implementation, flexibility in applications, etc. Table 5.3 summarizes some of the key differences and similarities in the process for each pathway.

Table 5.3. EEW Implementation Pathway Comparison

Consideration	Technical Partnership	Vendor/End-User
Technical staffing capabilities and bandwidth	Software development could take two to three software developers 1 to 3 months to build, though this could be longer for more complex implementations. Small changes to the software may be required for technical changes in the ShakeAlert message and for changes in airport systems and practices. Performance metrics must be provided to USGS on a regular basis, and code must be updated with some regularity due to technical changes in the ShakeAlert signal.	IT staff support is required to coordinate with the vendor's hardware installation and software integration with airport systems.
Novelty of implementation	Allows for novel applications, as the airport will develop its own SOW to define which applications it will build into its EEW system.	Novel applications may be possible, depending on similarity to what the vendor is already licensed to perform. More unique implementations may require partnership and a new PLA

Consideration	Technical Partnership	Vendor/End-User
		for the vendor, which would need to be worked out on an individual basis with the vendor.
System control	As a Technical Partner, the airport has complete control of the hardware and software in their implementation, with the ability to make changes, control security, and adapt to its current systems and infrastructure.	The vendor designs and owns the system. Different vendors may offer different levels of partnership and flexibility, but ultimately, there is less absolute control of the system by the airport in this pathway.
Cost	Costs are largely dependent on the implementation details, particularly the complexity of the applications to which EEW is being applied. Legal costs associated with the initial implementation process should be expected to be higher in the technical partner process and discussions regarding details of the PLA and LTO could be time consuming.	Same as with Technical Partnership.
Timeline	The timeline is determined partially by internal processes at the airport but largely dictated by the USGS LTO process timeline, which airports could expect to take 18 to 24 months to complete fully.	The timeline is determined by internal processes at the airport, including decision-making and RFP procedures, institutional size and structure, as well as EEW implementation specifications. Case study airports expected multiple

Consideration	Technical Partnership	Vendor/End-User
		years for project completion in the vendor scenario.

5.3 Phasing

While this report details numerous applications of EEW systems for airports, airports will likely want or need to adopt them in stages. Prioritization of applications can vary significantly by airport, depending on institutional goals, budgets, the context of the airport's seismic risks, BCA, airport size, and institutional complexity or structure.

There are, however, some technical and institutional aspects of certain applications that are relatively consistent and which may be more favorable to airports in initial implementation. Applications with relatively low initial costs and complexity, and little risk of operational disruption in the case of false positives, represent relatively "low-hanging fruit" for airports. Because of the lack of widespread EEW use in North America, this may be helpful in instilling institutional and public confidence in EEW systems and creating appropriate staffing training and SOPs.

Staff warnings are perhaps the best example of a likely initial application. Staff warnings could have very low costs associated with them, such as simply requiring that staff download free EEW applications. Moreover, the risk of false positives is low, as training and staff members' situational awareness could prevent large operational disruptions from occurring.. Finally, the benefits from staff warnings could be significant as staff could take actions to protect themselves and equipment, avoiding injury and reducing the impacts of an earthquake on the airport.

Automatic action phasing will depend largely on the technical and logistical aspects of the airport's infrastructure. For example, elevators may be a very low-cost and straightforward application for airports with few elevators in nonessential areas. Costs and operational risks may be higher for airports where elevators are critical for public movement or the number of elevators is very large. The biggest factor in determining the cost of automatic actions is generally the extent to which a particular application is already connected to the airport's IT system. Items that are already connected may likely be of higher priority due to their lower costs and the logistical ease of implementation.

Institutional priorities will impact how EEW implementation priorities are made. For example, larger airports may be less budget constrained and more sensitive to disruption because of the scale and public visibility of their operations. Institutional goals should be established and understood early in the implementation process to guide initial prioritization and scope.

5.4 Thresholding

Thresholding is an important element of EEW systems. Most of the applications employ thresholds based on ground shaking intensity. Two prime examples are the mass transit systems in San Francisco (BART) and Los Angeles (Metrolink). After the arrival of the ShakeAlert notification that includes the magnitude and location of an earthquake, the servers of these mass transit systems run an algorithm that estimates the shaking intensity, expressed in terms of MMI, in their service regions. Trains are slowed down or stopped based on the results of these computations. It is noted that the MMI thresholds are not universal across mass transit systems, and each system has its own specific thresholds. For example, there are three different shaking level ranges employed by Metrolink for different actions: MMI<4.5 = no action; 4.5□MMI<5.5 = brake signal sent to train to initiate the slow down action to restricted speed; and 5.5□MMI = brake signal sent to train to initiate the train stop action. In contrast, BART uses a single threshold, and automatic brake signals are sent to trains when MMI exceeds 4.0 at any point in the BART service area.

The thresholds used for activating the airport EEW applications discussed in Section 4 are application specific and can be determined using the information of risk and consequences quantified as a function of shaking intensity and infrastructure fragility. Section 6 discusses the methodology used for characterizing the thresholds for each application, along with specific threshold values in each application, in detail.

5.5 Operational Readiness

Earlier sections of the report discussed the benefits, challenges, and issues surrounding different airport EEW use cases. While these discussions focus on EEW, airports implementing this technology may benefit from following a process developed over the past decade that enables airports to effectively manage any transition to a new technology, facility, or system. The acronym for this process is ORAT, in which the "OR" refers to Operational Readiness, while the "AT" has different interpretations, including Airport Transfer, Asset Transfer, or (as adopted here) And Transition. This range of interpretations reflects the scalability of the concept application, from replacing an entire airport with a new one, to adding a new terminal, to replacing a baggage handling system, to acquiring and implementing an EEW.

ORAT developed in response to a variety of experiences in which grand openings of airport assets devolved from celebrations to crises. For example, the Bradley West project at LAX, which opened in 2013, was beset by problems such as repeated false fire alarms, elevator malfunctions, water contamination, and inadequate visibility for air traffic controllers. Other cautionary tales include the Berlin Brandenburg Airport in Germany, whose 2013 opening schedule was delayed 9 years after inspections revealed some 120,000 defects, from malfunctioning automatic doors to faulty wiring, and the new Hong Kong International Airport, whose 1998 opening was beset by computer problems leading to flight delays and widespread baggage mishandling. While these are major projects, similar issues often arise in smaller capital projects.

Conceptually, the purpose of ORAT is to reduce the lifecycle cost of an asset, most of which is incurred during the operations and management stage, by devoting more resources to the planning and design stages when there is far more flexibility to make modifications. ORAT emphasizes rigorous planning, including stakeholder engagement, developing operational concepts, and detailing standard and contingency operating procedures. In addition, thorough training and testing are performed to ensure that staff know how to use the new system and that the system and its associated operating procedures work properly prior to full-scale deployment.

The growing adoption of ORAT processes in the airport community could facilitate the implementation of EEW. Some airports, such as LAX, have staff dedicated to carrying out the ORAT process. When such staff exist, they are the natural choice to spearhead EEW deployment. Airports lacking such staff could also benefit from viewing EEW implementation through an ORAT lens and use the EEW implementation experience as a vehicle to gain experience and skill with ORAT processes that could make their airport more technologically agile. ORAT information, training, and services are available from several organizations, including Airports Council International, International Civil Aviation Organization, and International Air Transport Association.

One issue with applying ORAT to EEW is that EEW is a warning system for rare events. While early stage ORAT processes are readily applicable for such a system, testing and training in realistic scenarios may be challenging. The Great ShakeOut Day may be an occasion for airports implementing EEW to perform large-scale testing involving airport passengers, while tabletop exercises or other silent drills involving airport staff should also be incorporated into the ORAT process.

5.6 Challenges

Some of the general challenges in implementing EEW at airports are:

- **Various Airport Entities:** There are various independent entities and stakeholders operating at airports, such as airlines, TSA, ATC, the fire department, ground handlers, and retail operators, all of whom must be involved in EEW response. These stakeholders often have competing expectations and interests regarding airport operations and investments, which could hinder the EEW implementation process. Additionally, EEW system implementation can be affected by jurisdiction overlaps and differences in their communication systems. ATC's reliance on radio channels versus retail operators’ use of digital platforms necessitates multiple avenues of communication. The response time of a group could be affected by the communication method they use.
- **False Alarms:** False alarms present a significant challenge since each alarm triggers a protocol requiring time-intensive inspections and system resets. These unnecessary interruptions could delay service in the airport for extended periods and reduce confidence in the system.
- **Security:** Airports have many restricted areas both for security and safety purposes. It is important to ensure the security of these areas while the public takes protective action during an earthquake warning.
- **Diverse Infrastructure:** Airports have a variety of physical features, such as broad panes of glass, hanging panels or art installations, conveyances,

people movers, and automated baggage systems. These features could lead to a diverse set of appropriate actions for individuals to best protect themselves, all of which may be difficult to incorporate into messaging.
- **Human Behavior:** The response to EEW alerts is limited by human behavioral response times. As previously discussed, milling is a common response to warning messages. This behavior could be reduced through clear messaging on response actions and staff training.
- **Regulatory and Policy Barriers:** EEW responses need to fit into existing regulations and policies that are effective at airports, including fire department regulations, city and municipal codes, FAA regulations, and TSA security requirements.

5.7 Timeline

Timelines for EEW implementation at airports should be expected to be on the order of years. While the physical product can be installed in as little as a few hours for a more straightforward application, internal decision-making, planning, and other institutional processes will drive the timeline universally in airports. Airports host many organizations, including the TSA, FAA, vendors, fuel suppliers, airlines, and more. These organizations have overlapping jurisdiction with regard to decision making and responsibility. Managing these varying perspectives, objectives, and institutional processes is a time-consuming process that will contribute to more complex implementations that involve a greater number of applications and organizations.

Exact timelines should not be expected to have much uniformity, as organizational structures and processes are highly unique across airports. This applies to management, ownership, and funding models. Broadly speaking, implementation can be expected to be somewhat shorter at smaller airports and longer at larger ones. This stems from the added institutional complexity of larger airports, which elongates internal processes. Additionally, more expensive implementations often involve a greater number of stakeholders as airlines and other entities may contribute financially to infrastructure improvements beyond certain cost thresholds, adding more perspectives and objectives to consider.

5.8 PSP Case Study – Acquisition and Implementation

5.8.1 Institutional Context

PSP is focused on improving safety and operational resilience while balancing financial constraints. The airport has expressed interest in implementing low cost and easy-to-integrate EEW applications, but budget limitations are a key factor in decision making. The airport operates as an enterprise fund; it does not rely on the city's general fund for financial support. It must cover its own costs, including payments to the fire department and other administrative charges. Any additional expenditure, including costs of setting up the EEW system, could increase airline rates, which may result in airlines reconsidering their presence at PSP. External funding sources, such as grants, would greatly promote the implementation of EEW applications.

5.8.2 LTO Pathway

PSP has limited IT resources available to develop and manage an in-house LTO system, making it unlikely to pursue direct LTO implementation for EEW. Instead, the airport would need to work with a vendor, ensuring that EEW responses are effectively integrated without overwhelming existing IT staff and infrastructure. Additionally, PSP is more familiar with the process of obtaining a vendor compared to establishing legal partnerships, which would be required to become an LTO partner with USGS. PSP's aging infrastructure means that future system upgrades could impact EEW implementation. Opting for a vendor-managed LTO pathway would allow PSP to scale EEW applications based on future needs and promote flexibility while minimizing complications caused by in-house software development.

5.8.3 Phasing/Prioritization

Given the current infrastructure and financial constraints, PSP's approach to EEW implementation will focus on prioritizing applications that are cost effective and easy to implement. Employee alerts, public announcements, elevators and escalators, and gas shutoff applications are considered high priority implementations because of either their high BCR or ease and convenience in technical implementation. Public announcements and elevator EEW implementations could be implemented following planned upgrades to those systems. Similarly, real-time monitoring for backup generators is in the planning stage and is expected to support EEW integration once installed. Given the airport's budget cycle and stakeholder considerations, phasing will align with infrastructure upgrades and available funding.

5.8.4 Timeline

Timelines for EEW implementation at PSP will largely depend on its budget cycles, stakeholder approvals, and infrastructure upgrades. The airport is currently planning its 2-year budget, meaning any EEW implementation considered for near term adoption must be included in this cycle. Further discussions with stakeholders (airlines, ATC, TSA) are required to determine feasibility and financial commitments. Additionally, EEW integration for the new terminal under construction has not yet been considered, but may be explored as a future possibility. Since the implementation process is influenced by financial constraints and stakeholder coordination, exact timelines may vary based on project approvals and funding availability.

5.8.5 Challenges

The implementation of EEW at PSP airport presents a number of challenges, including financial constraints, stakeholder coordination complexity, regulatory and policy barriers, and EEW measure integration with existing infrastructure.

PSP has multiple stakeholders with competing expectations and interests regarding airport operations and investments. These stakeholders include the city council, airlines, and PSP's airport commission. Communication barriers and differing priorities among stakeholders could hinder the EEW implementation process. EEW responses also need to fit into existing regulations and policies in effect at PSP airport, including fire department regulations, city and municipal codes, FAA regulations, and TSA security requirements, all of which further complicate the process of EEW implementation.

Finally, one of the main challenges in implementing EEW at PSP is the need to integrate new technologies with its existing infrastructure. The elevators, generators, and public alert systems at PSP currently use old technologies that cannot support EEW, making its integration difficult. For all three systems, there are plans to upgrade them, and the new systems are expected to be able to support EEW.

5.9 LAX Case Study – Acquisition and Implementation

5.9.1 Institutional Context

LAX is focused on maximizing safety and operational resilience through improved emergency response with EEW. While budgetary considerations are still relevant to LAX, it would have a strong impetus to find funding for applications that are projected to deliver proportional benefits. This benefit-cost focus drives much of the consideration in prioritizing and selecting EEW implementation options.

5.9.2 LTO Pathway

LAX is one of the few airports in California with enough IT resources to become a potential LTO partner rather than going through a vendor. For a variety of reasons, this path may still be undesirable, however. The institutional complexity impacting so many of the applications at LAX, as well as the rapidly changing infrastructure, means that there would be significant value in being able to add and/or remove applications ad hoc, and investing in in-house software development and support removes some flexibility in this regard. It would potentially add sunk costs that may be difficult to recover if the infrastructure changes. For these reasons, LAX would likely choose a vendor for LTO implementations as its preferred pathway moving forward.

5.9.3 Phasing/Prioritization

Phasing at LAX will follow institutional goals while minimizing risks. Highest benefit projects are likely to be prioritized, except in cases where risks of false positives are present in any significant way. As previously mentioned, risks of false or missed alerts are enormous at LAX because of the public visibility and tightly connected complex internal operations.

5.9.4 Timeline

The timeline for EEW implementation at LAX could be on the order of years. Procuring a vendor involves an RFP process of at least 9 months. After this, all timelines are largely driven by internal processes. Because of this, exactly what steps are involved and thus the specifics of timelines may vary significantly by application due to the institutional complexity as discussed in the LAX application sections of this report.

6 Benefits and Costs of Airport EEW

This section estimates the benefits and costs for different EEW applications at PSP and LAX. Subsections 6.1 and 6.2 discuss the methodology used for calculating the benefits and costs of different applications, along with the obtained results. Subsection 6.3 provides a summary. Subsection 6.4 introduces recommended activation thresholds based on the benefit calculation methodology. Subsection 6.5 examines the earthquake hazard and potential EEW warning times across all California airports.

6.1 Benefits

The following subsections discuss the methodology used to calculate benefits, along with the computed benefit values at PSP and LAX for each considered application.

6.1.1 Warnings to the Public and Airport Staff

The benefit of EEW warnings to the public and airport staff is the reduction of injuries. To quantify this benefit in terms of monetary values, this analysis uses the falling of suspended ceiling tiles as a specific cause of injuries. As discussed in Section 2, this is a commonly observed damage type in airports in past international and local earthquakes and could result in injuries. To calculate the EEW benefits of reducing injury probability at an airport, four sets of information are needed:

1. The probability of suspended ceiling failure during earthquakes that could occur near the airport.
2. The rate of injuries given suspended ceiling damage.
3. The rate of reduction in injuries due to EEW, given suspended ceiling damage.
4. The cost of injuries.

Of these four items, the third and fourth use available information from literature, and the second uses an intuitive assessment. The first item depends on the probability of different shaking levels at the airport (PSP or LAX), the intensity of floor accelerations in airport buildings under these shaking levels, and the probability of suspended ceiling failure given these floor accelerations.

Considering these factors, Equation 6.1 calculates the probability of suspended ceiling damage during earthquakes that could occur near an airport.

$$P(SCD) = \sum_{PGA} P(SCD|PGA)P(PGA) \qquad (6.1)$$

$P(PGA)$ is the probability of different shaking levels that could occur at an airport over a period of 50 years, with the shaking characterized in terms of the PGA; $P(SCD|PGA)$ is the conditional probability of suspended ceiling damage given a specific value of PGA; and *P(SCD)* is the resulting probability of suspended ceiling damage in the terminal buildings of the airport.

The term *P(PGA)* is computed from Probabilistic Seismic Hazard Assessment using the information of existing seismic faults near the airport, the magnitude and frequency of earthquakes that these faults can produce, and the ground shaking that occurs at the airport in these earthquakes. The probability distribution of PGA, *P(PGA)*, at PSP and LAX, calculated using this information, is plotted in Figure 6.1. The calculation in Equation 6.1 uses *P(PGA)*, however, seismic hazard is typically expressed as the probability of exceeding a given PGA value (meaning the probability of PGA being equal to or greater than this specific value). This is a more commonly used representation and is known as the hazard curve. The hazard curve at PSP and LAX is plotted in Figure 6.2. It is noted that while Figure 6.1 and Figure 6.2 represent identical information, Figure 6.1 directly uses probability, whereas Figure 6.2 uses the probability of exceedance.

Figure 6.1. Probability of PGA (Expressed in Terms of Acceleration of Gravity) at PSP and LAX

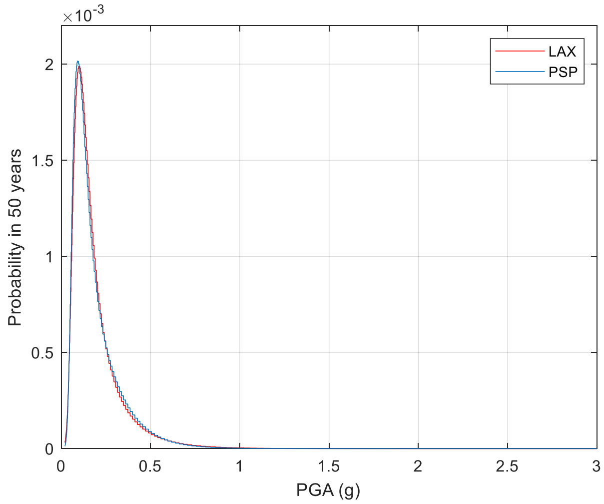
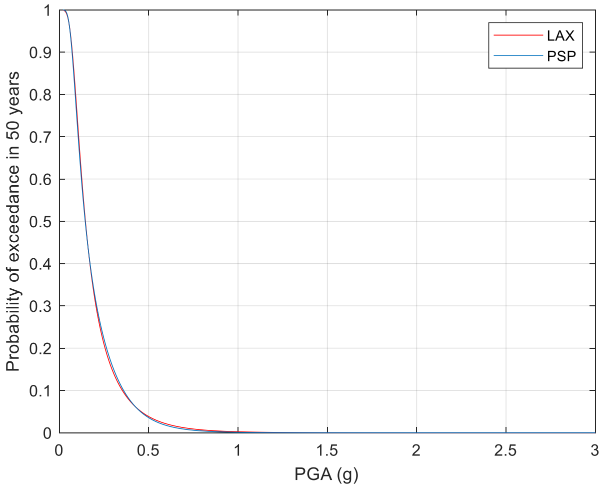


Figure 6.2. Hazard Curve (Expressed as the Probability of Exceedance of PGA over a 50-year Period) at PSP and LAX



The term *P(SCD│PGA)* represents the conditional probability of suspended ceiling damage given a specific value of PGA and is referred to as the fragility curve. Fragility curves are derived from experimental testing or detailed numerical simulations. The probability of damage to a suspended ceiling depends on the peak acceleration of the floor to which it is attached. In this analysis, the Peak Floor Acceleration (PFA) is derived from the ASCE-22 (2022) equation that provides the horizontal seismic design force, F_p, for nonstructural components (Equation 6.2).

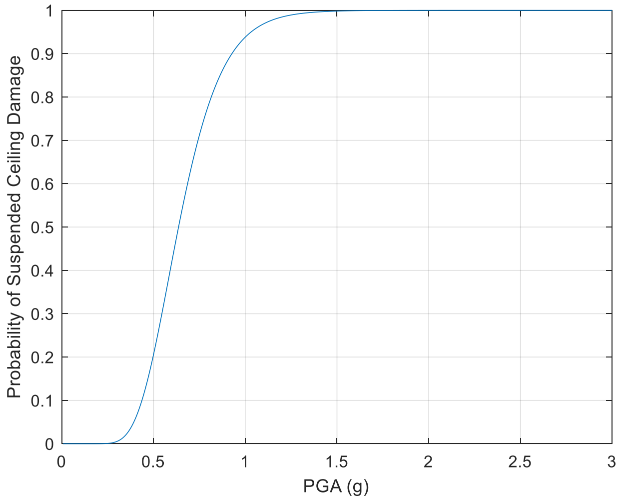
$$F_p = 0.4S_{DS}\left(1 + 2\frac{z}{h}\right)\frac{a_p}{(R_p/I_p)}W_p \tag{6.2}$$

F_p is the seismic design force, S_{DS} is the spectral acceleration at the short period (expressed in g), *z* is the height of the floor where the nonstructural component is attached, *h* is the height of the building, a_p is the component amplification factor, R_p is the component response modification factor, I_p is the component importance factor, and W_p is the weight of the nonstructural component. In this equation, $0.4S_{DS}$ corresponds to PGA, and (1+2z/h) represents the amplification factor for floor acceleration. The parameters a_p, R_p, and I_p express the relation between the floor acceleration and the acceleration of the nonstructural component. Using this information, PFA is expressed with Equation 6.3. From this equation, considering amplification at the top level of the PSP terminal buildings with a single story and the LAX terminal buildings with two stories, PFA is considered to be three times the PGA. It is noted that this estimate could be conservative because the inelastic response of the building itself generally limits the floor accelerations. However, given that this approach is typical for nonstructural component design in building codes, it is considered reasonable and acceptable.

$$PFA = PGA\left(1 + 2\frac{z}{h}\right) \tag{6.3}$$

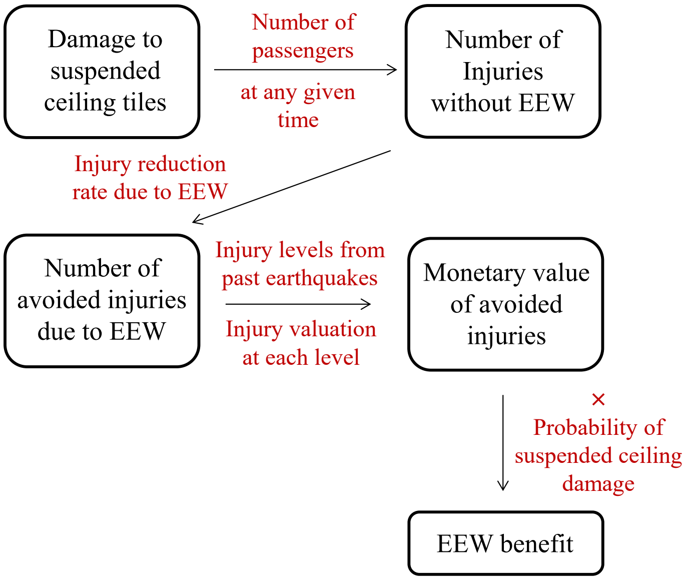
Using this linear scaling between PGA and PFA, the fragility curve for suspended ceiling damage is obtained for a damage state defined as 50% ceiling grid and tile damage. The fragility curve depends on the type of suspended ceiling. In the absence of specific information, the suspended ceilings at PSP and LAX are assumed to be a Suspended Lay-in Acoustic Tile Ceiling, with supports comprising vertical hanging wire, diagonal wires, and compression posts. The resulting fragility curve (cumulative lognormal with a median PFA of 1.91 g, corresponding median PGA of 1.91/3=0.64 g and Coefficient of Variation (COV) of 0.3 in FEMA-P58 (2018) is presented in Figure 6.3. Using the hazard and fragility curves in Figure 6.2 and Figure 6.3, along with Equation 6.1, the probabilities of suspended ceiling damage resulting from an earthquake at PSP and LAX over a 50-year period are calculated to be 2.3% and 2.5%, respectively.

Figure 6.3. Probability of Suspended Ceiling Damage (Defined as the Damage to 50% of the Tiles) as a Function of PGA



After computing the probability of suspended ceiling damage, the flowchart in Figure 6.4 is used to calculate the EEW benefit due to injury reduction.

Figure 6.4. Calculation of EEW Benefit Due to Injury Reduction



In the absence of an EEW system, it is assumed that damage to 50% of the suspended ceiling tiles, which is the damage state characterizing the fragility function in Figure 6.3, results in injuries to 25% of individuals in terminal areas. This assumption accounts for each dislodged tile's potential to cause harm and the likelihood that some people might evade falling debris.

PSP served more than 3.2 million passengers in 2023 (City of Palm Springs, 2024), corresponding to 365 passengers per hour. Given that passengers spend an average of 3 hours in the airport, the number of passengers at any given time is around 1,095. Consequently, damage to 50% of the suspended ceiling tiles could result in 1,095 × 25% = 274 injuries at PSP. The reduction in injuries due to EEW warnings and corresponding Drop, Cover, Hold-on actions is estimated to be 29% (Catalyst et al., 2020). Therefore, 79 injuries are avoided in PSP due to EEW.

To estimate a monetary value for this reduction, we must consider the severity of the injuries. A common approach is based on a classification known as the Abbreviated Injury Scale (AIS), in which injuries are classified into six categories. FEMA provides valuation for these categories (Table 6.1). Based on data from past earthquakes (e.g., 1994 Northridge earthquake, Porter et al., 2006), 76, 3, and 0 are in AIS categories 1-2, 3, and 4-5, respectively. Using the injury values in Table 6.1 and the 2.5% probability of suspended ceiling damage, **a total EEW benefit of $149,000 ($0.15 million) is computed at PSP for the application of Warnings to the Public and Airport Staff over a period of 50 years**.

With 182,000 passengers passing through LAX daily (Los Angeles World Airports [LAWA], 2024), there are approximately 7,600 passengers per hour. Given that passengers spend an average of 3 hours in the airport, the number of passengers at any given time is around 22,800. Consequently, damage to 50% of the suspended ceiling tiles could result in 22,800 × 25% = 5,700 injuries at LAX. The reduction in injuries due to EEW warnings and corresponding Drop, Cover, Hold-on actions is estimated to be 29% (Catalyst et al., 2020). Therefore, 1,653 injuries from suspended ceiling damage are avoided in LAX due to EEW.

Based on data from past earthquakes (e.g., 1994 Northridge earthquake, Porter et al., 2006), 1,597, 55, and 1 of these 1,653 injuries are in AIS categories 1-2, 3, and 4-5, respectively. Using the injury values in Table 6.1 and the 2.5% probability of suspended ceiling damage, **a total EEW benefit of $3.1 million is computed at LAX for the application of Warnings to the Public and Airport Staff over a period of 50 years.**

Table 6.1. Injury Values for AIS and FEMA Injury Severity Levels[34]

AIS	Injury Severity	Treatment	FEMA Injury Severity Levels	FEMA Injury Value
1	Minor	Self-treatment	Minor	$14,000
2	Moderate	Out-of-hospital treatment	Minor	$14,000
3	Serious	Emergency room	Major	$1,800,000
4	Severe	Hospitalized	Major	$1,800,000
5	Critical	Hospitalized	Major	$1,800,000

6.1.2 Elevator Stop at Nearest Floor

During an earthquake, elevators may experience mechanical damage or may stop operating because of power outages. As observed in past earthquakes, backup generators in airports generally function properly; therefore, the negative consequences are mostly due to mechanical damage to elevators. Automated elevator stop at the nearest floor upon EEW notifications has three benefits: (a) avoiding mechanical damage to elevators and the corresponding repair costs, (b) reducing the number of people getting trapped in an elevator and the corresponding costs of detailed medical exams, and (c) saving first responders' time, as well as the time of people trapped in elevators.

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[34] Catalyst et al., 2020.

According to this background, four sets of information are needed to calculate the EEW benefits due to the elevator stopping at the nearest floor at an airport:

1. The probability of mechanical damage to the elevators at the airport.
2. The cost of repairs needed to fix elevators with mechanical damage.
3. The number of people who may get trapped in the airport elevators due to elevator malfunctioning and need a detailed medical exam, and the cost of these medical exams.
4. The number of emergency staff needed to rescue people from each elevator, the number of hours they need for rescue, and their compensation. In terms of the time of rescued people, the same number of hours and compensation are used.

Equation 6.4 calculates the probability of mechanical damage to the elevators at an airport.

$$P(ELD) = \sum_{PGA} P(ELD|PGA)P(PGA) \tag{6.4}$$

$P(PGA)$ is the probability of different shaking levels that could occur at the airport over a period of 50 years, with the shaking characterized in terms of the PGA; $P(ELD|PGA)$ is the conditional probability of mechanical damage to elevators given a specific value of PGA; and *P(ELD)* is the resulting probability of elevator damage in the terminal buildings of the airport.

The term *P(PGA)* is the same across all applications at an airport and is expressed in Figure 6.1 for PSP and LAX. The term $P(ELD|PGA)$ represents the fragility function of elevator damage expressed in terms of PGA. Like the suspended ceilings, the probability of elevator damage predominantly depends on PFA. The elevator damage fragility curves in FEMA P-58 (2018) are based on the first floor PFA in a building. Considering that the PSP terminals serve two floors and the LAX terminal buildings include two levels, first floor PFA is two times the PGA from Equation 6.3. The elevator damage fragility curve is characterized for the most severe damage state of a hydraulic elevator. This damaged state is defined as a combination of damaged entrance and car door, flooring damage, oil leak in the hydraulic line, and hydraulic tank failure. The resulting fragility curve, cumulative lognormal with a median first floor PFA of 0.5 g, corresponding PGA of 0.25 g, and COV of 0.3, is presented in Figure 6.5. Using the hazard and fragility curves in Figure 6.2 and Figure 6.5, along with Equation 6.4, the probability of elevator damage at PSP and LAX over a 50-year period is calculated as 24.0% and 23.0% respectively.

With the probability of mechanical damage to elevators computed, the flowchart in Figure 6.6 is used to calculate the EEW benefit due to the elevator stopping at the nearest floor.

Figure 6.5. Probability of Elevator Damage (Defined as a Combination of Damaged Entrance and Car Door, Flooring Damage, Oil Leak in Hydraulic Line, Hydraulic Tank Failure)

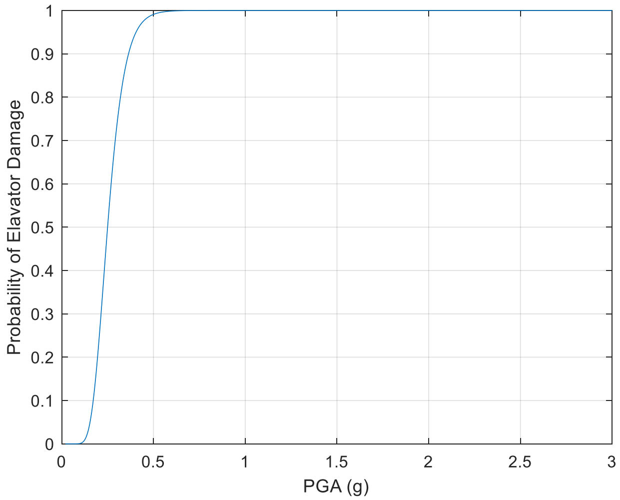
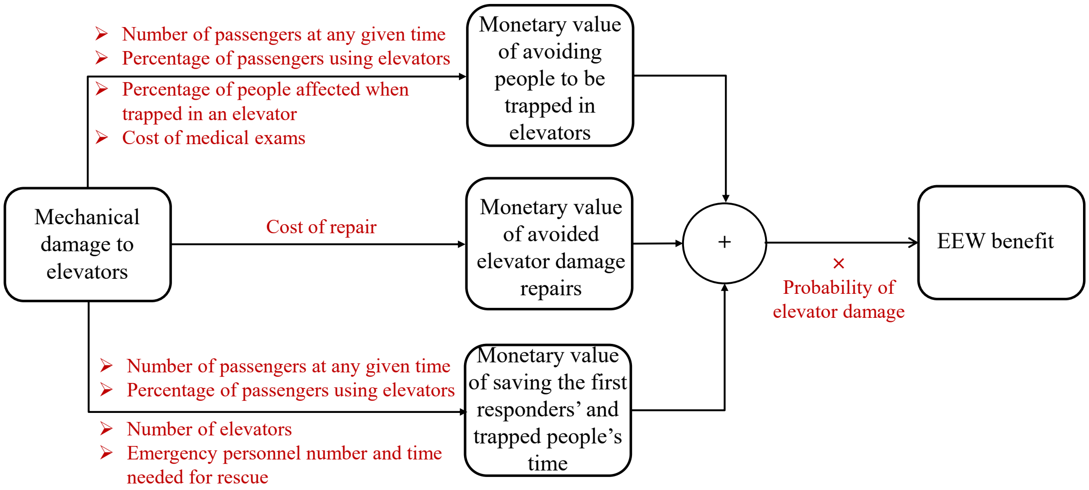


Figure 6.6. Calculation of EEW Benefit Due to Elevator Stop at Nearest Floor



The monetary values for the three benefit categories discussed earlier are calculated for PSP as follows:

1. The median repair cost of a hydraulic elevator with the damage state is $2,300 (FEMA P-58, 2018). Considering three elevators in PSP, the benefit in this category is $2,300 × 3 = $6,900.

2. In large airports, 3% of the passengers use elevators, while a majority prefer to use escalators (TransSolutions et al., 2012). Assuming that this is also applicable to PSP, and that the number of passengers in PSP terminals at any given time is around 1,095, this results in 33 people getting trapped in elevators if elevator damage occurs. It is assumed that 10% of people trapped in elevators go through a detailed medical exam, resulting in 3.3 people. Considering that the cost of such exams is approximately $2,000, the resulting benefit is $2,000 × 3.3 = $6,600.
3. On average, it takes three emergency personnel to rescue people from elevators, with an average rescue time of 3 hours. Assuming that there are three elevators in PSP terminals, this corresponds to 3 × 3 × 3 = 27 hours of emergency personnel. With a compensation rate of $50 per hour, the cost savings for emergency personnel are $1,350. Considering the same compensation rate, the savings for people trapped inside elevators are 33 × 3 × 50 = $4,950. Therefore, the total benefit in this category is $1,350 + $4,950 = $6,300.

The combined benefit of these three items is $19,800. This value multiplied by the 24% probability of elevator damage results in **a total EEW benefit of $4,750 at PSP for the application of Elevator Stop at Nearest Floor over a period of 50 years.**

The monetary values for the three benefit categories discussed earlier are calculated for LAX as follows:

1. The median repair cost of a hydraulic elevator with the damage state discussed earlier is $2,300 (FEMA P-58, 2018). Considering 100 elevators at LAX, the benefit in this category is $2,300 × 100 = $ 230,000.
2. In large airports, 3% of the passengers use elevators, while a majority prefer to use escalators (TransSolutions et al., 2012). Considering that the number of passengers in LAX terminals at any given time is around 22,800, this results in 684 people getting trapped in elevators if elevator damage occurs. It is assumed that 10% of people trapped in elevators go through a detailed medical exam, resulting in 69 people. Considering that the cost of such exams is approximately $2,000, the resulting benefit is $2,000 × 69 = $138,000.
3. On average, it takes three emergency personnel to rescue people from elevators, with an average rescue time of 3 hours. Assuming there are 100 elevators at LAX, this corresponds to 100 × 3 × 3 = 900 hours of emergency personnel. With a compensation rate of $50 per hour, the cost savings for

emergency personnel are \$45,000. Considering the same compensation rate, the savings for people trapped inside elevators are 684 × 3 × 50 = \$102,600. Therefore, the total benefit in this category is \$102,600 + \$45,000 = \$147,600.

The added benefit of these three items is \$515,600. This value multiplied by the 24% probability of elevator damage in 50 years results in a total EEW benefit of \$123,744 at LAX for the application of Elevator Stop at Nearest Floor.

It is noted that this analysis considers direct costs and does not consider the indirect costs resulting from disruptions to airport operations due to non-operational elevators. Given the low percentage of passengers using elevators in airports, these indirect consequences are not expected to be significant.

6.1.3 Water Shut-off

During an earthquake, damage to fire sprinklers and water pipes could cause flooding. For example, the CCP in Concepción, the second largest airport in Chile, suffered major water damage in the 2010 Chile earthquake, with 5 inches of water accumulated throughout the main terminal building, caused by damage to fire sprinkler heads. Water damage could be prevented by automatically shutting off water upon EEW notifications. To calculate the EEW benefits due to the elimination of water damage at an airport, two sets of information are needed:

1. The probability of fire sprinkler and water piping damage at the airport.
2. The cost of water damage.

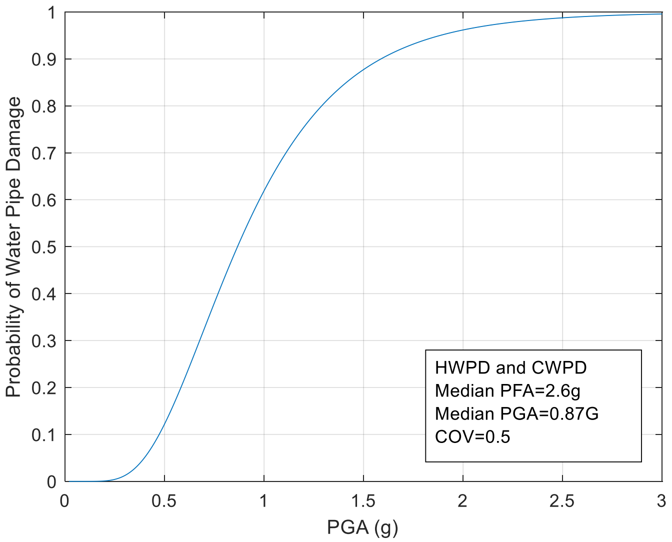
Flooding could occur because of damage to various water pipes. Considering these different pipes, Equation 6.5 calculates the probability of water damage at an airport.

$$P(WD) = \sum_{PGA} P(HWPD|PGA)P(PGA) + P(CWPD|PGA)P(PGA) \qquad (6.5)$$

P(PGA) is the probability of different shaking levels that could occur at the airport over a period of 50 years, with the shaking characterized in terms of PGA; *P(HWPD│PGA)* and *P(CWPD│PGA)* are the conditional probability of damage to hot water piping and cold water piping, respectively, given a specific value of PGA; and *P(WD)* is the resulting probability of water damage in the terminal buildings of the airport.

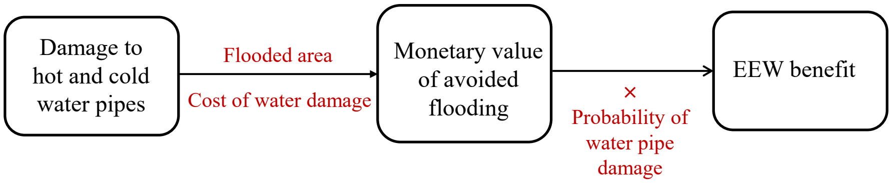
The term *P(PGA)* is the same across all airport applications and is shown in Figure 6.1 for PSP and LAX. The terms *P(HWPD|PGA)* and *P(CWPD|PGA)* represent the fragility curves of hot and cold water piping, respectively. Like the other cases, these fragility curves are based on PFA (FEMA P-58, 2022). Considering PFA is three times the PGA, the resulting fragility curve, which is the same for hot and cold water piping, is shown in Figure 6.7. Damaged fire sprinkler pipes could also cause flooding; however, it is not possible to shut off water in these pipes, considering the possibility of fire following an earthquake. Therefore, fire sprinkler water piping is not considered in this formulation.

Figure 6.7. Probability of Water Pipe Damage as a Function of PGA



Using the hazard and fragility curves in Figure 6 and Figure 6.7 along with Equation 6.5, the probabilities of water damage at PSP and LAX over a 50-year period are computed as 3.1% and 3.3% respectively. After computing the probability of damage to hot and cold water pipes, the flowchart in Figure 6.8 is used to calculate the EEW benefit due to injury reduction.

Figure 6.8. Calculation of EEW Benefit Due to Water Shutoff



The average cost of Class 1 clean water damage is \$5/ft^2 (Water Damage Advisor, 2024). The total area of the main terminal building, the Bono Concourse, and the Regional Concourse at PSP is approximately 60,000 ft^2. Therefore, the cost of water damage at PSP is 60,000 × 5 = \$300,000. Multiplying this value by the 3.1% probability of water damage due to earthquakes results in **a total EEW benefit of approximately \$9,300 (\$0.009 million) at PSP for the application of Water Shutoff over a period of 50 years.**

Assuming an average floor area of 40,000 ft^2 in the LAX terminal buildings, the cost of water damage in a terminal building with two levels is 40,000 × 2 × 5 = \$400,000. Considering that there are nine terminal buildings, the cost of water damage at LAX is \$3.6 million. Multiplying this value by the 3.3% probability of water damage due to earthquakes results in **a total EEW benefit of approximately \$0.12 million at LAX for the application of Water Shutoff over a period of 50 years.**

It is noted that this analysis considers direct costs and does not consider the indirect costs resulting from disruptions to airport operations due to water flooding, which could be significant. To calculate these indirect costs, the average time for water damage restoration and the cost of disruption to operations during this time are needed.

6.1.4 Fuel Shutoff

Ground shaking could cause damage to fuel pipelines. EEW cannot prevent such damage; however, automated fuel shutoff upon EEW notifications could reduce the consequences of damage to fuel pipelines, such as preventing fuel leakage and eliminating potential fires.

Smaller commercial airports, such as PSP, and general aviation airports receive fuel delivered by trucks; therefore, the fuel shutoff is not relevant to PSP, and the **total EEW benefit at PSP due to the application of Fuel Shutoff is \$0.** It is noted that a clear EEW action related to fuel systems was not identified during the discussions in the online and in-person meetings with PSP staff.

To calculate the EEW benefits of eliminating fuel pipeline damage at an airport (like LAX), two sets of information are needed:

1. The probability of damage to fuel pipelines.
2. The cost of fuel leakage and the corresponding fires.

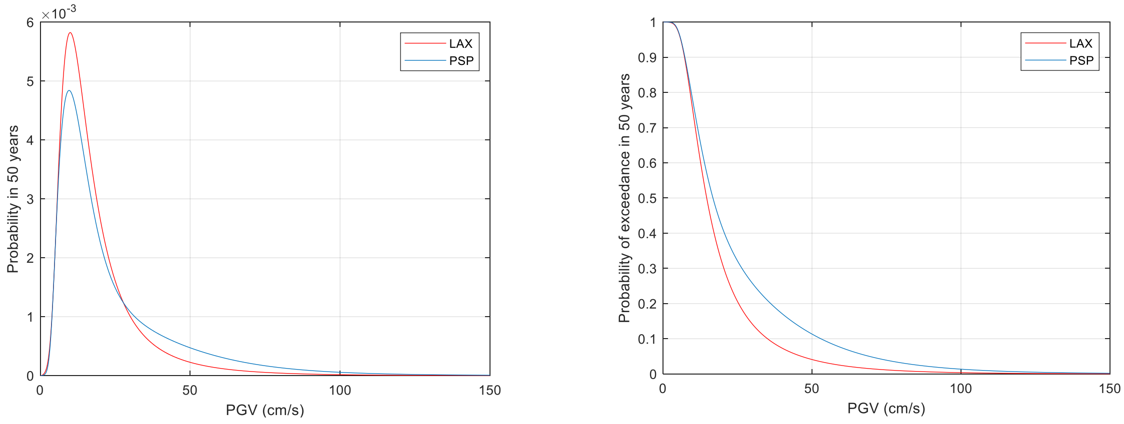
The probability of fuel pipeline damage is calculated with Equation 6.6.

$$P(FPD) = \sum_{PGA} P(FPD|PGV)P(PGV) \tag{6.6}$$

P(*PGV*) is the probability of different shaking levels that could occur at an airport over a period of 50 years, with the shaking characterized in terms of the PGV. $P(FPD|PGV)$ is the conditional probability of fuel pipeline damage given a specific value of PGV, and *P(FPD)* is the resulting probability of fuel pipeline damage near the airport.

It is noted that PGV is more closely related to fuel pipeline damage compared to PGA. This is attributed to the direct relation of PGV with longitudinal ground strain, which is a major factor that causes damage to buried pipelines during ground shaking (Tsinidis et al., 2019). Figure 6.9 plots the probability and probability of exceedance of PGV at PSP and LAX.

Figure 6.9. (a) Probability, (b) Probability of Exceedance (Hazard Curve), of PGV at PSP and LAX



(a) (b)

Buried pipeline fragility depends on several factors, including pipe dimensions, steel grade, soil properties, and the depth of the pipes below ground (Jahangiri & Shakib, 2018). Given the lack of specific information, the buried pipeline fragility from Lanzano et al. (2013), developed using damaged pipeline data from 29 earthquakes, is employed. This fragility curve (Figure 6.10) is developed for a damage state defined as a fracture in the pipe body or joint pull-out and represents a lognormal distribution with a PGV of 72 cm/s and a COV of 0.2. Using the hazard and fragility curves in Figure 6.9 and Figure 6.10, along with Equation 6.6, the probability of fuel pipeline damage at LAX over a 50-year period is computed as 1.5%. With the probability of fuel pipeline damage quantified, the flowchart in Figure 6.11 is used to calculate the EEW benefit due to fuel shutoff.

Figure 6.10. Probability of Fuel Pipeline Damage as a Function of PGV

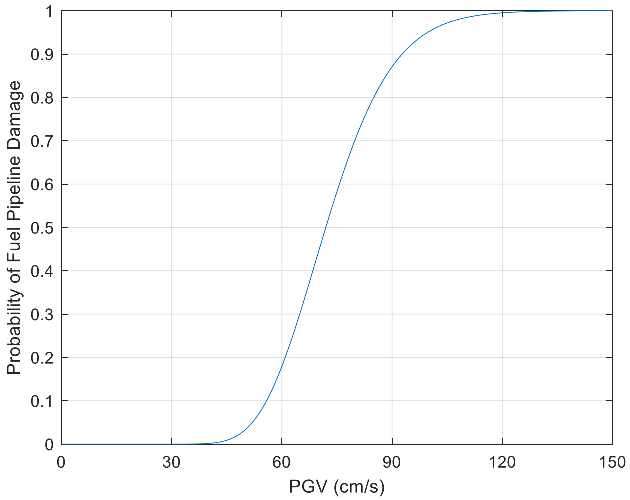
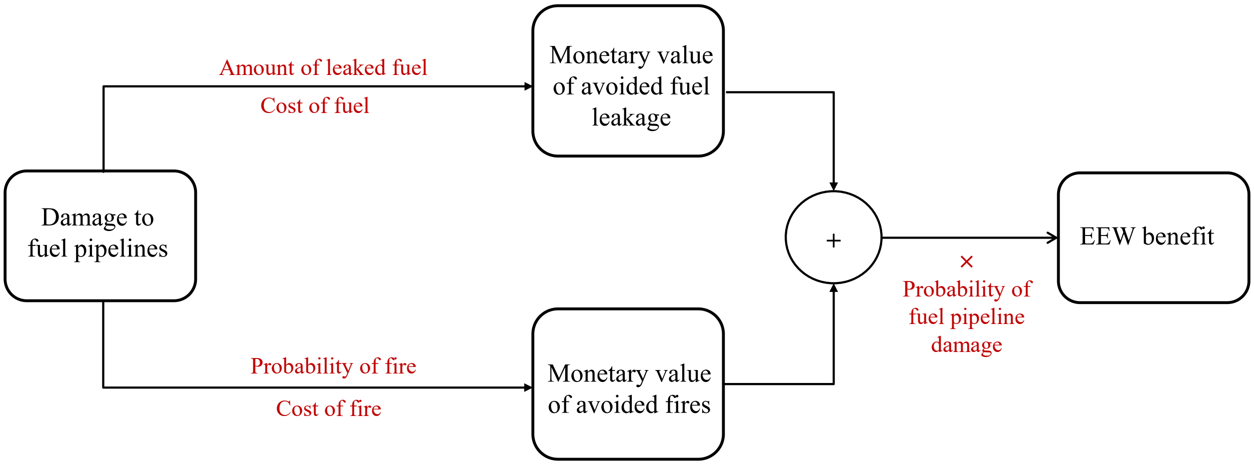


Figure 6.11. Calculation of EEW Benefit Due to Fuel Shutoff



Without the presence of EEW, airports have emergency protocols that address fuel leakage from the pipes. For example, in Narita International Airport in Japan, fuel operations are stopped if PGA exceeds 0.04 g. In this case, the EEW benefit is the cost of fuel lost due to leakage during the time it takes the operation to stop. To calculate the fuel loss due to leakage, the required parameters are the average flow rate in a fuel pipeline and the time it takes to stop the system in regular operation without EEW. Considering a 14-inch diameter pipe, a corresponding flow rate of 6,000 GPM, and 2 minutes duration, the lost oil is 12,000 gallons. A jet fuel price of $240/gallon results in $2.88 million lost. Multiplying this value by the 1.5% probability of fuel pipeline damage in 50 years results in an EEW benefit of approximately $43,200.

The other significant consequence of damage to fuel pipelines is the risk of fire. Using an event tree for pipeline failure, Dziubiński et al. (2006) calculated the probability of a fire caused by pipeline failure as 5%. Scawthorn (2010) estimates the losses due to a magnitude 7.2 earthquake on the San Andreas fault in the range of $2.8 to $6.8 billion. Multiplying the average value in this range, $4.8 billion, by the 1.5% probability of fuel pipeline damage, and 5% probability of a fire given fuel pipeline damage, results in an EEW benefit of approximately $3.6 million.

Adding these two benefits, avoiding fuel losses and preventing fires, leads to **a total EEW benefit of approximately $3.64 million at LAX for the application of Fuel Shutoff over a period of 50 years**.

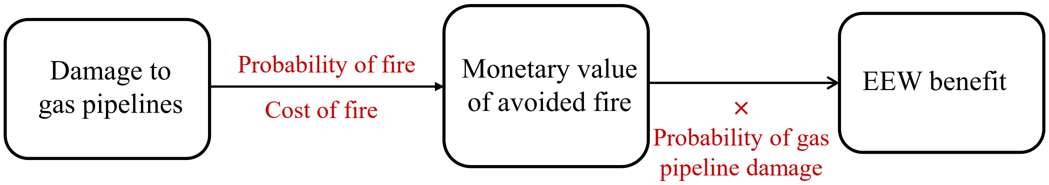
6.1.5 Gas Shutoff

The major consequence of damage to gas pipelines is the risk of fire. Using the hazard and fragility curves in Figure 6.9 and Figure 6.10, along with Equation 6.6, the probability of gas pipeline damage at PSP over a 50-year period is computed as 4.8%. Multiplying the average cost of a fire mentioned earlier, $4.8 billion, by the 4.8% probability of gas pipeline damage, and 5% probability of a fire given gas pipeline damage, results in **a total EEW benefit of approximately $11.5 million at PSP due to the application of Gas Shutoff over a period of 50 years**.

Using the same hazard and fragility curves, the probability of fire due to a gas pipeline failure (5%), and the estimated losses from a fire following an earthquake, the **total EEW benefit for the application of Gas Shutoff at LAX is $3.6 million over a period of 50 years**.

Figure 6.12 provides the flowchart for calculating the EEW benefit due to gas shutoff.

Figure 6.12. Calculation of EEW Benefit Due to Gas Shutoff



6.1.6 Backup Power

When a power outage occurs, it typically takes tens of seconds for backup power to activate. This short gap could cause workstations and servers to shut down, leading to operational disruptions. Immediate activation of backup power upon receiving an EEW notification could potentially prevent these issues. Observations from major historical earthquakes show that airports almost always experience a power outage during earthquakes but manage to continue operations effectively with backup power, even without EEW. Details of airport operations during past earthquakes, focusing on the period between power outage and backup power activation, are needed to quantify the monetary benefits for this application.

6.1.7 Fire Station Bay Doors

If the fire station building experiences significant lateral movement during an earthquake, and if the bay doors are closed, the doors may jam, preventing fire trucks from leaving the station. During the 2022 magnitude 6.4 Ferndale earthquake, the bay doors at the Rio Dell fire station jammed, trapping the fire engines inside. It took 15 minutes to pry these doors open, and firefighters could not respond to calls for help during this time (Johnson et al., 2022). Although some claim that, in an earthquake scenario, fire trucks could simply smash through jammed doors, the Rio Dell experience suggests that door jams can significantly delay emergency response.

An EEW alert could allow these doors to be opened automatically before strong shaking starts. To calculate the EEW benefits due to avoiding fire station bay doors from getting jammed, three sets of information are needed:

1. The probability of a fire station bay door jamming during earthquakes near the airport.
2. The probability of a reduction in fatalities and severe injuries due to timely medical emergency response.
3. The corresponding costs.

Equation 6.7 calculates the probability of a fire station bay door jamming during earthquakes near an airport.

$$P(FRDJ) = \sum_{PGA} P(FRDJ|PGA)P(PGA) \tag{6.7}$$

P(*PGA*) is the probability of different shaking levels that could occur at an airport over a period of 50 years, with the shaking characterized in terms of PGA. $P(FRDJ|PGA)$ is the conditional probability of the fire station bay door jamming given a specific value of PGA; and *P(FRDJ)* is the resulting probability of the door jamming of the fire station near the airport.

The term *P(PGA)* is the same across all applications at an airport and is expressed in Figure 6.1 for PSP and LAX. The term P(*FRDJ*│*PGA*) represents the fragility function of fire door jamming expressed in terms of PGA. Fire door jamming is related to the drift ratio (DR = horizontal displacement divided by story height) of the fire station building. Therefore, the DR of the fire station building due to ground shaking needs to be quantified. In this analysis, to express the DR in terms of PGA, the DR is obtained using Equation 6.8, following the methodology of Akkar et al. (2005) and Ay and Akkar (2008) for buildings with moment-resisting frames.

$$DR = \gamma_1\gamma_2(1.27)\sin\left(\frac{\pi h}{2H}\right)\left(\frac{S_d}{h}\right) \tag{6.8}$$

h is the story height, *H* is the total building height, S_d is the spectral displacement at the natural period of the building, and $\square_1$ and $\square_2$ are the correction factors as a function of the estimated sum of beam to column stiffness.

Fire station buildings are generally single-story buildings; therefore, *h=H* and sin(□*h/2H*) is equal to 1. For the calculation of other parameters, the natural period of the fire station building (T_n) is required. Considering a typical height of 15 ft and using the ASCE 7-22 equation for building period ($T_n = C_t(h_n)^x$, where C_t=0.016 and x=0.9 for a concrete moment resisting frame, and h_n = 15 ft), T_n is computed as 0.18s. At this period, $S_d = 2.5\ PGA\ /\ (2\square/T_n)^2$. For a beam to column stiffness of 1, $\square_1 = 0.91$ and $\square_2 = 1$. Using these values, DR is expressed in terms of PGA with Equation 6.9.

$$DR = 0.005PGA \tag{6.9}$$

The approach in Akkar et al. (2005) is developed for moment resisting frames, which are mostly flexible, and uses a period range of 0.2 seconds to 2 seconds. The natural period of the fire station is 0.18 seconds, and it is outside the short period extreme of this range. Therefore, Equation 6.9 is corrected by using the relationship between the strength factor (R), ductility (□), and period (T) at the short period [R=(2□-1)$^{0.5}$], with an R value of 4. With this correction, Equation 6.10 expresses the resulting relationship.

$$DR = 0.0094PGA \tag{6.10}$$

Forcael et al. (2014) reported that a residential door can get obstructed at a drift ratio of 0.6% due to excessive in-plane spacing, out-of-plane deformations, distortions at the door lock level, and flattening of the door frame. Chang et al. (2004) observed that exit doors operate smoothly if the drift ratio is less than the critical value of 0.5%. As the interstory drift ratio (IDR) reaches 0.7%, the door lock can get stuck. When IDR is greater than 1.1%, even the door frame can be severely distorted. Using the information from these studies, the door jamming fragility curve is defined as a cumulative lognormal function with a median drift of 0.6% (corresponding median PGA of 0.64 g) and COV of 0.3. Figure 6.13 plots the resulting fragility curve. Using the hazard and fragility curves in Figure 6.2 and Figure 6.13, along with Equation 6.10, the probability of door jamming at the fire station near PSP and LAX over a 50-year period is computed as 2.4% and 2.6% respectively. After computing the probability of fire station bay door jamming, the flowchart in Figure 6.14 is used to calculate the EEW benefit due to injury reduction.

Figure 6.13. Probability of Fire Station Door Jamming as a Function of PGA

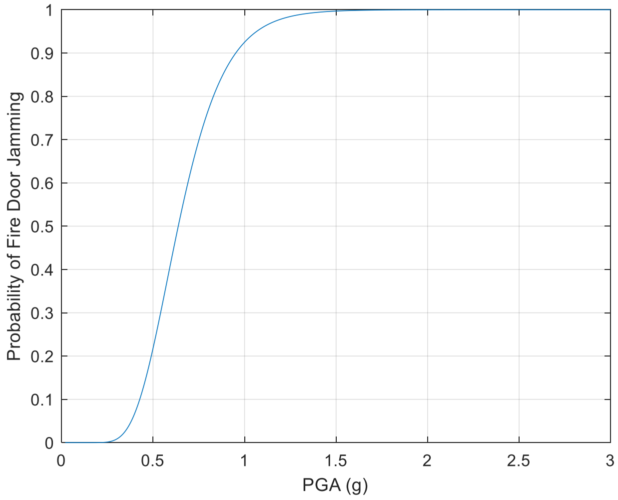
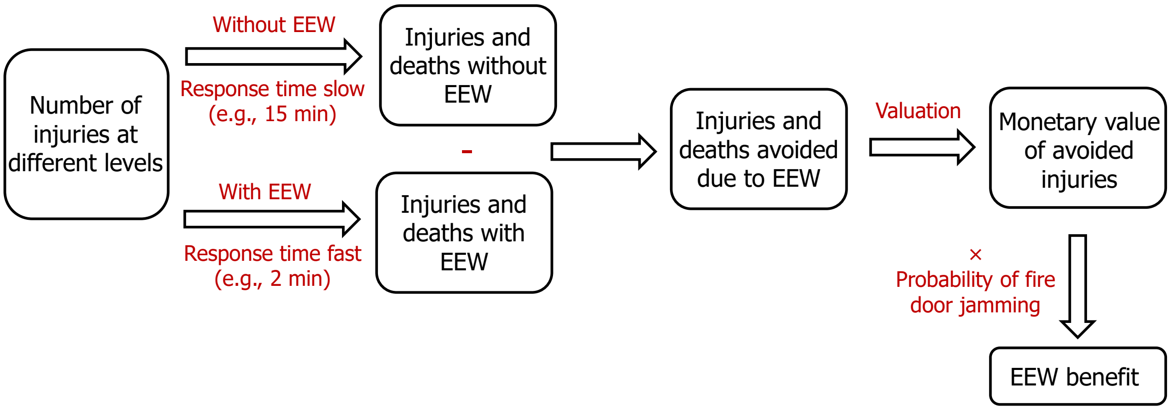


Figure 6.14. Calculation of EEW Benefit Due to Avoiding Fire Station Bay Door Jamming



The consequences of fire station door jamming are potential delays in containing fires and increased response time to injuries in the airport. The literature survey on past earthquakes demonstrated that fire following earthquakes is very rare in airports; therefore, the benefit calculation is conducted by considering response time to injuries.

From a survey of 5,424 emergency calls and corresponding data analysis, Blackwell and Kaufman (2002) reported that the mortality probability increases approximately six times from 0.003 to 0.018 when the response time increases from 2 minutes to more than 15 minutes, which is the time it took to pry the fire station doors open in the Ferndale earthquake.

In Section 6.1.1, the possible number of injuries at PSP was calculated as 195 and 274 in the case of suspended ceiling damage with and without EEW, respectively. Assuming that the Warnings to Public and Staff application is implemented and using data from past earthquakes (e.g., 1994 Northridge earthquake, Porter et al., 2006), 188, 7, and 0 of these 195 injuries with EEW are in AIS categories 1-2, 3, and 4-5, respectively; and 265, 9, and 0 of these 274 injuries without EEW are in AIS categories 1-2, 3, and 4-5, respectively. The injuries in AIS categories 3-5 can result in mortalities. The number of mortalities with EEW is obtained for a response time of 2 minutes, as the fire station is close to the airport. The number of mortalities without EEW is obtained for a response time of more than 15 minutes using the Ferndale earthquake example. The resulting number of mortalities is 7 × 0.003 = 0.02 and 9 × 0.018 = 0.16 for the cases with and without EEW, respectively. The Value of a Statistical Life (VSL) is used in BCA to estimate the benefits of a mortality risk. FEMA provides a VSL of $13 million. Therefore, the corresponding benefit is $13 million × (0.16 - 0.02) = $1.82 million.

Multiplying this value by the 2.4% probability of fire station door jamming due to earthquakes results in **a total EEW benefit of approximately $44,000 ($0.044 million) for the application of Fire Station Bay Doors over a period of 50 years.**

In the injuries section (Section 6.1.1), the possible number of injuries at LAX was calculated as 4,047 and 5,700 in the case of suspended ceiling damage with and without EEW, respectively. Assuming that the *Warnings to Public and Staff* application is implemented and using data from past earthquakes, 3910, 135, and 2 of these 4,047 injuries with EEW are in AIS categories 1-2, 3, and 4-5, respectively; 5507, 190, and 3 of these 5,700 injuries without EEW are in AIS categories 1-2, 3, and 4-5, respectively. The injuries in AIS categories 3-5 can result in mortalities. The number of mortalities with EEW is obtained for a response time of 2 minutes, as the fire station is close to the airport. The number of mortalities without EEW is obtained for a response time of more than 15 minutes using the Ferndale earthquake example. The resulting number of mortalities is 137 × 0.003 = 0.41 and 193 × 0.018 = 3.5 for the cases with and without EEW, respectively. Using the same value for VSL discussed above, the corresponding benefit is $13 million × (3.5 - 0.41) = $40.2 million. Multiplying this value by the 2.6% probability of fire station door jamming due to earthquakes results in **a total EEW benefit of approximately $1.05 million at LAX for the application of Fire Station Bay Doors over a period of 50 years**.

6.2 Costs

The costs of a potential EEW system at an airport can be broken down into two categories: (a) the cost of delivering the EEW notification to the airport and (b) the costs of implementing different applications. The following subsections discuss the costs in these two categories:

6.2.1 Delivering EEW Notifications to Airports

It is noted that the cost information in this section is obtained in communication with the ShakeAlert Technical Users Working Group at UC Berkeley.

A technology system used to receive ShakeAlert EEW notifications should be able to listen for ShakeAlert and process the ShakeAlert message to determine a response. Basic technology requirements used to provide this functionality include the following:

- Server/computer to provide the computing power that drives the system. Examples include enterprise-level servers, desktop computers, and embedded systems.
- Software and scripts to allow the system to connect to ActiveMQ Broker, an open-source Java-based message broker, and process the message data. Scripts would need to parse the XML content of the ShakeAlert Message to determine which, if any, actions to take, based on whether the location of the airport falls within the alerting region, whether predicted intensity levels warrant action, and any relevant application-specific system status (e.g., valves open, machinery running). Example software includes cURL, Python Stomp, Go, Java, Rust, and C/C++.
- Internet that has reliable access with near-100% uptime. Examples include fiber optic with dedicated IP, cable modem, and WiFi to the public system.
- Power with battery backup. Examples include UPS and lithium batteries. Battery backup is especially important during earthquake sequences to ensure receiving EEW notifications during strong aftershocks.

Most organizations already have a server or central computer that can run the software needed, as well as network access and battery backup. However, setting up a dedicated independent server can be preferable. Table 6.2 provides costs for three systems with varying levels of cost.

6.2.2 Applications

Cost estimates for different EEW applications were obtained from Dan Ervin of Varius Inc. (Dan Ervin, written communication) and are presented in Table 6.3. These estimates include hardware components. The inclusion of software costs depends on the application; if the end-point action in the application (for example, closing a valve or opening bay doors) is software based (for example, controlled by a Building Management System), software is needed to code that function and initiate the end-point action. If, however, the end-point action is mechanically actuated (for example, the garage doors are simply opened and closed by a door switch), then software and associated costs are not needed. The presence of a software-based system (e.g., a Building Management System) is airport specific; however, it is assumed that the end-point actions of considered applications are mechanically actuated, and software costs are not included.

Table 6.2. Airport ShakeAlert Notification System Costs

Item	**System 1: High Cost**	**System 2: Medium Cost**	**System 3: Low Cost**
Hardware	Enterprise grade server: $5,000	Desktop computer: $500	Arduino with WiFi: $30
Internet	Dual telemetry: $300/month × 12 months/year × 50 years = $180,000	Fiber-optic: $50/month × 12 months/year × 50 years = $30,000	Cable modem: $25/month × 12 months/year × 50 years = $15,000
Battery backup	High-capacity UPS: $2,000	UPS: $150	9-volt battery: $2
Engineering: set up	$10,000	$300	$300
Engineering: maintenance	$200/month × 12 months/year × 50 years = $120,000	$50/month × 12 months/year × 50 years = $30,000	$30/month × 12 months/year × 50 years = $18,000
Total	**$317,000**	**$60,950**	**$33,332**

Table 6.3. Airport EEW Application Cost Estimates

Potential Automatic Response	Lowest Potential Cost Scenario	Likely Potential Cost Scenario
PA Announcements/General Public Alert	• PA system already has broadcast notification capability. • Cost includes porting the analog or digital audio output from the central unit (i.e., the server, see costs above) to the PA system input. • **Cost: $1,500**	• The PA system does not have analog audio input capability or available Input/Output (I/O) for digital input. • Audio input board required, or additional I/O required. • Cost includes input board or additional I/O, configuration of that device, and connection to the server. • **Cost: $8,000**
Alerts Sent to Staff	• Alert is delivered via email and SMS text messages to staff. • Costs include compiling alert email addresses and phone numbers. • **Cost: $200**	• Same as the lowest cost scenario. • **Cost: $200**
Automatic Elevator Response	• Elevators include an external override, and the central unit (server) can be located within the same room as the elevator override connection. • Cost includes interconnect wiring from the elevator control panel to the server and override programming. • **Cost: $2,500**	• Elevators do not have override capability; the server is not co-located in the same room as the elevator controls, and the local fire authority must issue an override permit. • Cost includes the addition of an external override controller, wireless receivers to transmit the alarm signal to the elevator controller, and permits. • **Cost: $25,000**
Fuel Shutoff	• Fuel system includes a solenoid for remote shutoff. The central unit (server) is located within 100 ft of the solenoid valve.	• Fuel system does not have remote shutoff capability nor does it have a master shutoff solenoid actuated valve. • Cost includes wireless receivers to transmit the

Potential Automatic Response	**Lowest Potential Cost Scenario**	**Likely Potential Cost Scenario**
	• Cost includes wiring from the server to the shutoff solenoid. (Note: the server also has the capability to directly operate a 12 vdc or 120 vac solenoid). • **Cost: $1,500**	alarm signal, the addition of a solenoid actuated valve on the fuel piping, and the connection from the wireless receiver to the solenoid. • **Cost: $35,000 (per fuel line)**
Backup Generator Automatic Disable (prevents running until after shaking has subsided)	• Emergency generator (EG) has a remote start/stop contactor in the control panel. The central unit (server) is located within 100 ft of the EG set. • Cost includes wiring from the remote start/stop contactor to the server. • **Cost: $3,500**	• The EG set does not have a remote start/stop contactor, and the server is not co-located with the EG control panel. • Cost includes wireless receivers to transmit the alarm signal to the EG controller, and the addition of an interpose relay to interrupt the stop/start signal to the EG starter. • **Cost: $25,000**
Gas Shutoff	• The gas system includes a solenoid for remote shutoff. The central unit (server) is located within 100 ft of the solenoid valve. • Cost includes wiring from the server to the shutoff solenoid. (Note: the server also has the capability to directly operate a 12 vdc or 120 vac solenoid). • **Cost: $1,500**	• The gas system does not have remote shutoff capability or a master shutoff solenoid actuated valve. • Cost includes wireless receivers to transmit the alarm signal, the addition of a solenoid actuated valve on the fuel piping, and connection from the wireless receiver to the solenoid. • **Cost: $35,000 (per gas line)**
Fire Station Bay Doors	• Bay doors include an automatic operator with a remote open/close switch. The central unit (server) is co-located or within 100 ft of the	• Bay doors do not have an accessible remote open/close switch. The server is not co-located in the same room as the door opener switch.

Potential Automatic Response	Lowest Potential Cost Scenario	Likely Potential Cost Scenario
	remote open/close switch. - Cost includes wiring from the server to the remote open/close door switch. - **Cost: $1,500**	- Costs include the addition of a contactor on the automatic opener to engage the door drive and a wireless receiver to transmit the alarm to the opener. - **Cost: $15,000**
Baggage System Shutoff	- Baggage conveyors are centrally controlled with a central remote shutoff switch. Central unit (server) is co-located or within 100 ft of the remote on/off switch. - Cost includes wiring from the server to the remote conveyor switch. - **Cost: $3,500**	- Baggage conveyors do not have an accessible remote on/off switch. The server is not co-located in the same room as the conveyor controllers. - Costs include the addition of a contactor on the baggage control system to disable the conveyor drives and a wireless receiver to transmit the alarm to the opener. - **Cost: $25,000**
Water Shutoff	- Supply line already has an automatic valve with solenoid controls. - Cost includes wiring from the server to the shutoff solenoid. - **Cost: $10,000 (per water line)**	- Water system does not have remote shutoff capability or a master shutoff solenoid actuated valve. - Cost includes wireless receivers to transmit the alarm signal, addition of a solenoid actuated valve on the water piping, and connection from the wireless receiver to the solenoid. - **Cost: $65,000 (per water line)**

Using the costs in Table 6.3, the following subsections compute and discuss the cost of each application at PSP and LAX. Because the technology is so new and utilization is so limited, it is assumed that the “Likely Potential Cost Scenario” applies to both airports. For the same reasons, the cost of receiving ShakeAlert EEW notifications is assumed to be the “High Cost” option in Table 6.2.

Warnings to the Public and Airport Staff

It is considered that the costs of "PA Announcements" and "Alerts Sent to Staff" listed in Table 6.3 apply to each terminal. Therefore, considering that there are three terminal buildings in PSP and 10 in LAX, **the corresponding costs are $24,600 and $82,000,** respectively.

Elevator Stop at Nearest Floor

As specified in Table 6.3, the cost of automatic elevator response is $25,000. This cost includes the addition of an external override controller and wireless receivers to transmit the alarm signal to the elevator controller. Considering each terminal building needs its own external override controller, it is assumed that $25,000 is the cost for automatic elevator response per terminal building. Considering three terminal buildings in **PSP**, **the cost in this category is $25,000 × 3 = $75,000**. Considering 10 terminal buildings in **LAX**, **the cost in this category is $25,000 × 10 = $250,000**.

Water Shutoff

The cost of an automatic water shutoff is $65,000 per water line (Table 6.3). Considering that there are seven water supply lines in PSP and 10 in LAX, the cost for the **water shut-off application in PSP and LAX is $455,000 and $650,000,** respectively.

Fuel Shutoff

The cost of automatic fuel shutoff is $35,000 per fuel line (Table 6.3). Smaller commercial airports, such as PSP, and general aviation airports receive fuel delivered by trucks; therefore, the fuel shutoff is not relevant to PSP, and the **total EEW cost at PSP due to the application of Fuel Shutoff is $0**. Four fuel lines serve **LAX, resulting in a cost of $140,000**.

Gas Shutoff

The cost of an automatic gas shutoff is $35,000 per gas line (Table 6.3). Considering that there are two lines providing gas to PSP and six to LAX, the cost for the **gas shut-off application in PSP and LAX is $70,000 and $210,000,** respectively.

Backup Power

The cost of the backup generator automatic disable is $25,000 in both PSP and LAX because there is only one generator in PSP, and only one of the terminals relies on backup power in LAX.

Fire Station Bay Doors

The cost of automatically opening fire station bay doors is $15,000 (Table 6.3). Considering that there is one fire station serving PSP and two serving LAX, the cost in this category is **$15,000 and $30,000,** respectively.

6.3 Summary of Benefits and Costs

Table 6.4 summarizes the benefits and costs of the discussed EEW applications. It is noted that the cost of delivering the EEW notification to the airport is distributed evenly among the applications.

Table 6.4. Benefit and Cost Summary of EEW Applications at PSP and LAX

Application	**PSP**			**LAX**		
	Benefit ($M)	**Cost ($M)**	**BCR**	**Benefit ($M)**	**Cost ($M)**	**BCR**
Smartphone Alert	0.150	0.070	2.1	3.100	0.122	25.84
Gas Shutoff	11.500	0.115	100.0	3.600	0.250	14.4
Fire Station Bay Doors	0.044	0.060	0.7	1.050	0.070	15.0
Elevator Stop	0.0048	0.120	0.04	0.124	0.29	0.43
Fuel Shutoff	0	0	NA	3.640	0.180	20.2
Water Shutoff	0.009	0.500	0.02	0.120	0.690	0.2
Baggage System Shutoff	NA	0.070	NA	NA	0.27	NA
Backup Power	NA	0.070	NA	NA	0.065	NA

Several observations about the values in this table are as follows:

1. The benefits of various applications, including Smartphone Alert, Elevator Stop, and Fire Station Bay Doors, are significantly higher at LAX compared to PSP, primarily due to the passenger volume. The effectiveness of these applications is directly proportional to the number of passengers; therefore, with LAX's substantially larger passenger count, the corresponding benefits are also considerably greater.

2. The only exception to the above observation is the Gas Shutoff application, where the benefit at PSP is triple that of LAX. The benefit in this application is not proportional to the number of passengers and is governed by the earthquake hazard intensity. As shown in the PGV hazard curve in Figure 6.9, there is a higher probability of exceeding almost all shaking intensity levels at PSP compared to LAX. Coupled with identical gas pipe fragility at both airports, this leads to a greater probability of gas pipeline damage at PSP, which is directly reflected in the increased EEW benefits.
3. In contrast to the benefits, the costs of EEW applications at PSP and LAX are comparable, leading to significantly higher BCRs at LAX. This observation suggests that EEW implementation offers greater value at larger airports than at smaller ones, provided the seismic hazard levels are similar.
4. One of the applications with a lower BCR value at both airports is Water Shutoff. This outcome is partially due to the omission of the indirect consequences of flooding on airport operations in the calculations. Another reason for the low BCR value is the high cost of this application.

6.4 Application Thresholds

As discussed in Section 5, thresholds used to activate different EEW applications are based on ground shaking intensity. This subsection explains the methodology used to determine these shaking intensity-based thresholds and provides values for each application.

6.4.1 Methodology

The thresholds for activating an EEW application can affect its effectiveness. Ideally, the lowest possible threshold ensures activation of an EEW action almost all the time when an earthquake occurs and is therefore a safe approach. However, lower levels of ground shaking do not cause harm. Therefore, activating an EEW application is unnecessary and could disrupt regular operations. For example, stopping an elevator at the nearest floor or shutting off gas valves not only affects the relevant services and utilities but also requires additional staff time and effort to restart these systems. The selected thresholds for different applications need to ensure safety while preventing unnecessary disruptions to operations.

To facilitate the proper selection of thresholds toward these intended objectives, information on the harm (e.g., damage to relevant infrastructure that could result in injuries) caused by different ground shaking intensities is needed. This information is available in the fragility curves presented throughout the section. For example, Figure 6.13 provides the probability of fire station door jamming as a function of shaking intensity, expressed in terms of PGA. From this figure, it is observed that the probability of fire door jamming is almost zero during shaking with PGA less than approximately 0.2 g. Using this information, 0.2 g can be used as a PGA threshold to automatically open the fire station bay doors before strong shaking begins. The PGA of 0.2 g (corresponding MMI of 6.9 computed using the relationship between MMI and PGA&PGV, Worden et al., 2012) is significant shaking. There is approximately a 32% chance that the ground shaking intensity at the sites of PSP and LAX is greater than 0.2 g over a 50-year period (refer to Figure 6.2). Therefore, this is a reasonable threshold and is not likely to result in unnecessary opening of the bay doors. However, if further analysis, guidance, or expert opinion shows that a low but nonzero risk of bay door jamming is acceptable, it may be justifiable to adopt even higher thresholds. The thresholds that correspond to 1%, 2%, and 5% probability of fire station bay door jamming are 0.31 g, 0.33 g, and 0.38 g (MMI of 7.6, 7.7, and 7.9), respectively.

6.4.2 Thresholds for Different Applications

Using the methodology discussed above and the fragility curves discussed in various subsections, shaking intensity thresholds corresponding to various risk levels are computed and tabulated in Table 6.5. It is observed that the minimum threshold in all applications, except Elevator Stop, corresponding to no likelihood of harm, is MMI 6.9. For a probability of harm up to 5%, the threshold can be as high as MMI 8.3. Therefore, the threshold varies between MMI 6.9 and 8.3, depending on the risk level. For the Elevator Stop application, the range is between MMI 5.8 and 6.4. Comparing these thresholds with the thresholds that are currently in use by other EEW systems, mass transit, for example, it is observed that all these thresholds are greater than the MMI 4.0 and 5.5 used by BART and Metrolink. It is noted that the thresholds used by these mass transit systems were obtained without any analytical or experimental simulations or relevant fragility curves; therefore, they are chosen low to be on the safe side.

The methodology presented here provides the means for informed and improved threshold values that ensure both safety and minimal disruption to operations. The provided threshold values are the best estimates, but they should not be taken for granted because of the potential variability due to the assumptions made in the development of the fragilities (for example, the type of suspended ceiling and elevator considered).

Table 6.5. EEW Application Thresholds Corresponding to Different Risk Levels

Application	Cause of Harm	Probability of Harm	Intensity Measure	Threshold	Threshold (MMI)
Warnings to the Public and Airport Staff	Suspended Ceiling Damage	0	PGA (g)	0.20	6.9
		1%		0.32	7.6
		2%		0.35	7.8
		5%		0.39	8.0
Elevator Stop at Nearest Floor	Mechanical Damage to Elevators	0	PGA (g)	0.10	5.8
		1%		0.13	6.2
		2%		0.14	6.3
		5%		0.15	6.4
Water Shutoff	Damage to Hot and Cold Water Pipes	0	PGA (g)	0.15	6.4
		1%		0.29	7.5
		2%		0.33	7.7
		5%		0.40	8.0
Fuel Shutoff	Fuel Pipeline Damage	0	PGV (cm/sec)	30.0	7.6
		1%		45.4	8.1
		2%		47.9	8.2
		5%		51.9	8.3
Gas Shutoff	Gas Pipeline Damage	0	PGV (cm/sec)	30.0	7.6
		1%		45.4	8.1
		2%		47.9	8.2
		5%		51.9	8.3
Fire Station Bay Doors	Bay Door Jamming	0	PGA (g)	0.20	6.9
		1%		0.31	7.6
		2%		0.33	7.7

		5%		0.38	7.9

6.5 Locational Considerations

As demonstrated in Section 6, benefits increase as ground shaking increases. On the other hand, airports located near seismic faults may not receive significant benefits in some earthquakes, as the time between detection and the arrival of S-waves can be minimal.

To characterize and explore these effects, shaking intensities and the S-wave arrival times at various California airports can be quantified using all possible fault ruptures in the Third Uniform California Earthquake Rupture Forecast (UCERF3). The (UCERF3) model (Field et al., 2014) defines the long-term rate of all possible earthquake ruptures in California above a minimum magnitude of 5.0. UCERF3 source models have approximately 250,000 unique scenario earthquakes (fault ruptures), where each scenario earthquake is defined by the rupture geometry, earthquake magnitude, and the probability of the earthquake.

The shaking intensity can be calculated by using state-of-the-art Ground Motion Models (GMMs), which provide equations for mean estimated shaking as a function of the earthquake magnitude, distance between the fault rupture and the location, and other earthquake source characteristics. The other needed quantity - S-wave arrival time - can be obtained by dividing the hypocentral distance, the distance between the hypocenter of the earthquake and the point of interest, by the S-wave speed.

7 Conclusion and Recommendations

Airports play a critical role in disaster response and recovery, yet they remain vulnerable to seismic events that can disrupt operations, compromise infrastructure, and pose safety risks to passengers and staff. This report explored the potential of EEW systems to mitigate these risks by providing advance notice of impending shaking, allowing airports to implement protective actions that enhance resilience and reduce operational disruptions.

The analysis of historical earthquake impacts on airports underscores the necessity of proactive seismic preparedness. Case studies from both international and California-based earthquakes reveal that structural and nonstructural damage, power outages, and communication failures have frequently disrupted airport operations. EEW offers a means of addressing these vulnerabilities by enabling automated responses such as stopping elevators, shutting off fuel lines, and triggering emergency protocols for ATC and ground operations.

A review of EEW technology, particularly the ShakeAlert system, highlights its growing capabilities and applications across various sectors. While EEW has been demonstrated in transit systems, emergency services, and utilities, its integration into airports is still in its early stages. The case studies of PSP and LAX provide insights into the feasibility of EEW deployment, demonstrating how tailored implementations have the potential to enhance safety and minimize disruptions.

The BCA in this report indicates that while initial investments in EEW infrastructure, training, and maintenance may be considerable, the long-term benefits—including reduced injuries, lower repair costs, and faster recovery times—could outweigh these expenditures. By implementing EEW, airports could improve their emergency preparedness while ensuring continuity of operations during and after seismic events.

Moving forward, airports should consider developing clear implementation roadmaps for EEW integration, including stakeholder collaboration. Additional research and demonstrations could help identify emerging and recommended practices, address potential technical challenges, and optimize EEW for airports.

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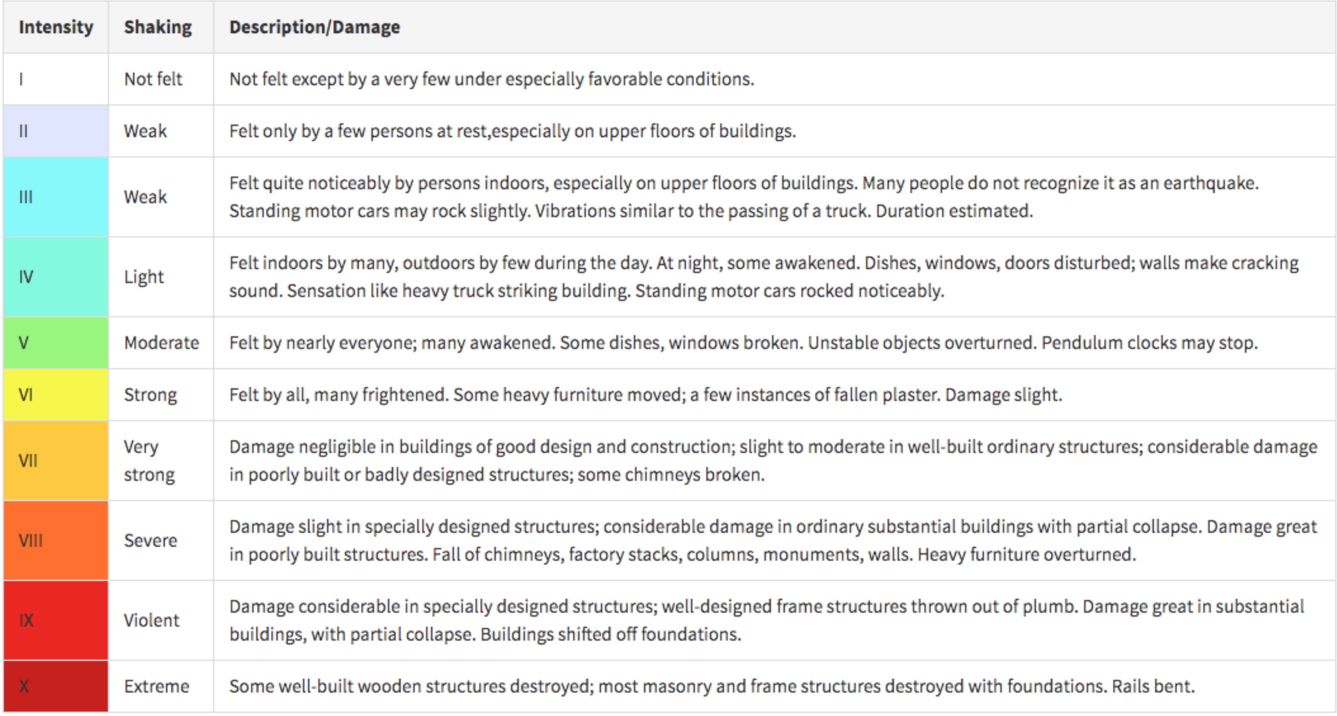
9 Appendix

9.1 MMI Scale



Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest,especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

9.2 Acronym Glossary

ABAG – Association of Bay Area Governments

ADA – American with Disabilities Act

AIS – Abbreviated Injury Scale

ARFF – Aircraft Rescue and Fire Fighting

ASCE – American Society of Civil Engineers

ATC – air traffic control

BART – Bay Area Rapid Transit

BCA – benefit-cost analysis

BCR – benefit-cost ratio

BSL – UC Berkeley Seismology Lab

Cal OES – California Governor's Office of Emergency Services

CCP – Carriel Sur International Airport

CEEWS – California Early Earthquake Warning System

CESMD – Center for Engineering Strong Motion Data

CGS – California Geological Survey

CISN – California Integrated Seismic Network

COV – Coefficient of Variation

CRS – Congressional Research Service

DR – drift ratio

EERI – Earthquake Engineering Research Institute

EEW – Early Earthquake Warning

EG – emergency generator

EPIC – Earthquake Point-source Integrated Code

FAA – Federal Aviation Administration

FEMA – Federal Emergency Management Agency

FinDer – Finite Fault Rupture Detector

FIS – flight information service

GFAST-PGD – Geodetic First Approximation of Size and Timing

GMD – ground motion database

I/O – Input/Output

IATA – International Air Transport Association

IDR – interstory drift ratio

IP – Internet Protocol

IT – information technology

LAWA – Los Angeles World Airports

LAX – Los Angeles International Airport

LAXFUEL – Los Angeles International Airport fuel farm

LTO – License to Operate

MMI – Modified Mercalli Intensity (MMI)

Mw – moment magnitude

NTT – Nippon Telegraph and Telephone

OAK – Oakland International Airport

ORAT – Operational Readiness And Transition

PA – public address

PEER – Pacific Earthquake Engineering Research Center

PFA – Peak Floor Acceleration

PGA – Peak Ground Acceleration

PGV – Peak Ground Velocity

PLA – Pilot License Agreement

PSMS – Post ShakeAlert Message Summaries

PSP – Palm Springs International Airport

PTSD – post-traumatic stress disorder

RFP – request for proposal

RIMI – Resilient and Innovative Mobility Initiative

ROI – return on investment

SFO – San Francisco International Airport

SJC – San José Mineta International Airport

SMF – Sacramento International Airport

SMS – Short Message Service

SOP – standard operating procedure

SOW – statement of work

TERC – Technical Engagement Regional Coordinator

TSA – Transportation Security Administration

UC ITS – University of California Institute of Transportation Studies

UPS – Uninterruptible Power Supply

UrEDAS – Urgent Earthquake Detection and Alarm System

USGS – United States Geological Survey

VoIP – Voice over Internet Protocol

VSL – value of statistical life

WEA – wireless emergency alerts

XML – Extensible Markup Language