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The operability of airports following a major earthquake is dependent upon minimal facility damage and functioning infrastructure systems. The immediate operation of airports provide valuable air functions during disaster response, and are a necessity for quick recovery of societal and economic functions. The San Francisco Bay Area is fortunate to have 24 public airports (Oakland International and North Field are considered separate), one federal airport, and one military airport which together provide a redundant network of runways across the nine county region. This network however, will be stressed by a major hazard event. This report maps airports, roadways, passenger rail, fuel, electric, and water systems, and highlights their interaction with seismic hazards. Publicly available information is used to describe each system to gain a high-level understanding of how the system operates, and the potential consequence should the system be damaged. The report does not state specific restoration timelines nor damage estimates, but does reference restoration timelines experienced in past comparable events. Instead, the report focuses on the seismic exposure of many systems and their significant consequence for airports and other stakeholders. The key findings warrant keen attention from regional and state actors.

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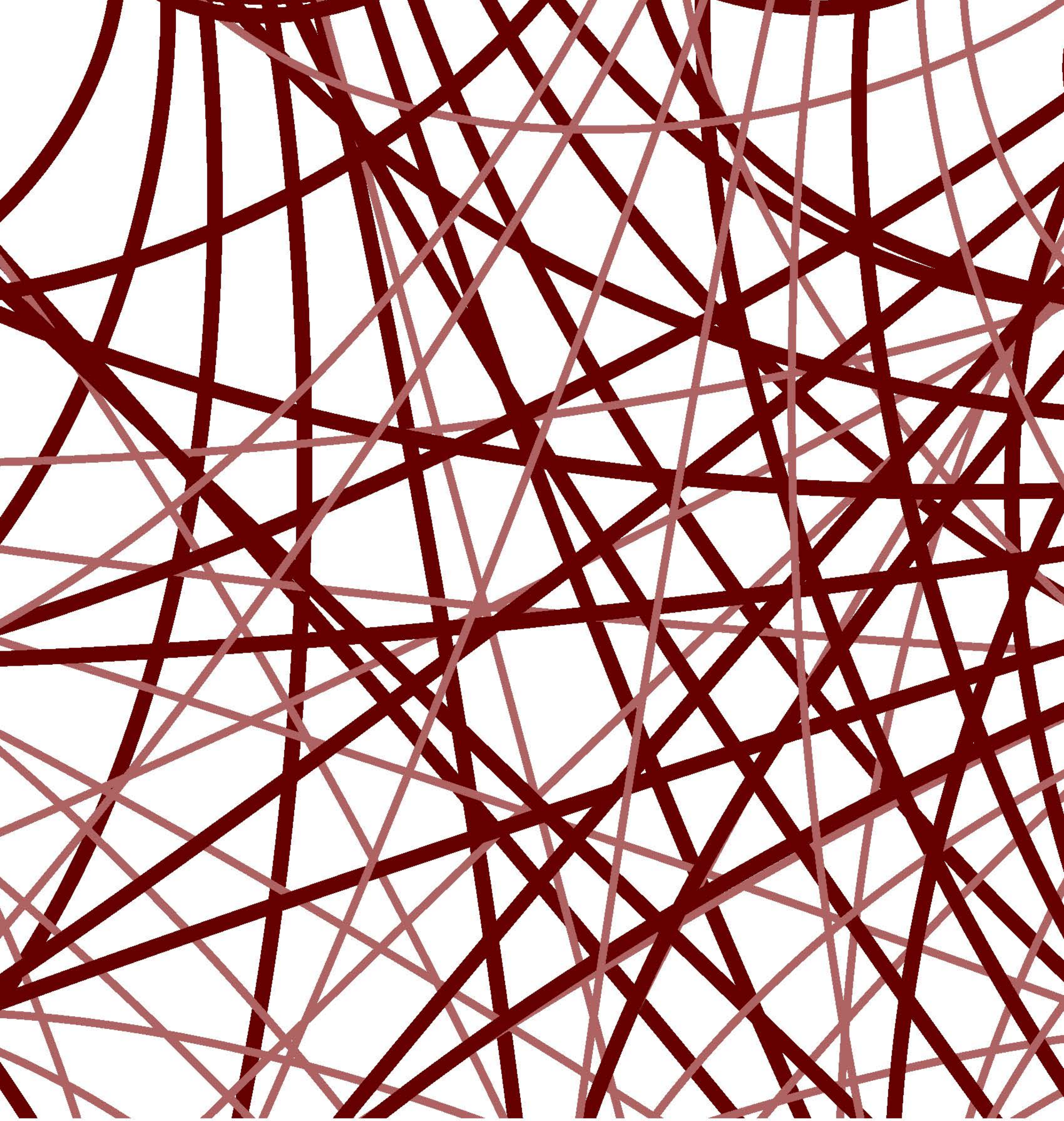

Cascading Failures: Earthquake Threats to Transportation and Utilities

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ASSOCIATION OF BAY AREA GOVERNMENTS

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EXECUTIVE SUMMARY

The operability of airports following a major earthquake is dependent upon minimal facility damage and functioning infrastructure systems. The immediate operation of airports provide valuable air functions during disaster response, and are a necessity for quick recovery of societal and economic functions. The San Francisco Bay Area is fortunate to have 24 public airports (Oakland International and North Field are considered separate), one federal airport, and one military airport which together provide a redundant network of runways across the nine county region. This network however, will be stressed by a major hazard event.

In the Bay Area a number of earthquake faults can produce strong shaking and significant damage in all nine counties. A single earthquake event is unlikely to cause damage at every Bay Area airport, but damage to key infrastructure systems could result in outages at many or all airports. A geographically dense fuel system and a single electric system service the whole Bay Area and neighboring counties outside the region. A complete outage of either would impact all airports. The water and transportation networks, while more redundant, could also experience large outages that impact many airports simultaneously. To properly mitigate seismic risk, airports and other stakeholders must improve infrastructure reliability alongside improvements to airport facilities.

This report maps airports, roadways, passenger rail, fuel, electric, and water systems, and highlights their interaction with seismic hazards. Publicly available information is used to describe each system to gain a high-level understanding of how the system operates, and the potential consequence should the system be damaged. The report does not state specific restoration timelines nor damage estimates, but does reference restoration timelines experienced in past comparable events. Instead, the report focuses on the seismic exposure of many systems and their significant consequence for airports and other stakeholders. The key findings warrant keen attention from regional and state actors.

Key Findings

Airports

- Airports are well distributed around the region.
- In San Andreas and Hayward scenario events the three international airports will simultaneously experience strong to violent shaking. 19 of 26 Bay Area airports are within five miles of an active Alquist-Priolo mapped fault, and 23 of 26 are within ten miles.
- Of the 24 airports that completed the Caltrans Division of Aeronautics Emergency Plan Survey, 21 have an Airport Emergency Plan, 16 of which have sections that cover earthquakes.

Ground Transportation

- San Francisco International Airport (SFO) and Oakland International Airport (OAK) are near parallel highway networks: I-280 & US 101 at SFO, and I-880 & I-580 at OAK. These parallel roadways will be subject to different hazards in San Andreas and Hayward events, with the inland routes (I-280 & I-580) experiencing violent and very strong ground motions, and the bay side routes (I-880 & US 101) experiencing liquefaction as well as very strong ground motions.
- Large-scale seismic retrofit programs have resulted in much more resilient rail and highway networks. Still, a single failure along non redundant corridors can severely disrupt travel.

Fuel

- Fuel refineries are likely to have correlated performance, if one is damaged it’s likely others are damaged too. A conservative restoration estimate of damaged refineries is months.
- Damage to the fuel transmission system would severely impact counties beyond Solano and Contra Costa where most refineries are located. Transporting the normal fuel demand by truck after a disaster simply is not feasible.
- Damage to pipes that cross the Bay, or an inability to pump fuel east would cause fuel supply interruptions across Northern California and Nevada.

Electric

- Damage to the region’s electric generation facilities along the Carquinez Strait, or interruption in the natural gas system could result in long power supply interruptions.
- In the immediate aftermath, most critical facilities (including airports) plan to use fuel-powered generators to restore electric services. The interruption of fuel could limit this backup capacity and delay immediate restoration of service.

Water

- Most of the 11 Bay Area water districts studied have multiple water sources or have invested in robust, redundant, and repairable systems that contribute to system resilience. When reservoirs and groundwater reserves are above half full there is significant regional water storage available if regional systems require repair. Distribution pipeline failures will govern service for many.
- Restoration of water distribution systems in areas of liquefaction can require weeks to months. The region’s three international airports, and a number of general aviation airports located on the bay margins, are in liquefaction susceptibility zones.
- Agencies dependent on Delta water would be significantly impacted if levees failed, causing flooding and salt water intrusion.

Functional infrastructure systems are necessary for achieving community resilience. The consequence of infrastructure damage cascades well beyond the costs to repair the immediate damage. The failure of one system limits the functionality of other key regional assets, like airports, and will cause interruption for both households and businesses. While it is unrealistic to expect systems to be earthquake proof, knowing what to expect provides the users of infrastructure systems the information they need to take measured preparedness actions. Currently, the vulnerability of many infrastructure systems is not well known or not well communicated to the public. With a lack of information, airports have no baseline for predicting the benefits of possible preparedness or mitigation strategies. Going forward, the region must understand and communicate the vulnerability of infrastructure systems to inform stakeholders on what to expect so that they can make informed decisions to limit their impacts should systems fail.

This study is a first step in understanding the risks to transportation, fuel, electric, and water systems. The report should be used to inform actions in the present, and also as a call for greater study of the region's infrastructure systems, and their impact on Bay Area stakeholders.

CHAPTER 1

Introduction

Ground failures in the 1994 Northridge Earthquake.

A future large earthquake will impact the entire Bay Area region. Ground shaking near the fault and liquefaction of loose soils along the bay will cause severe damage to buildings and infrastructure systems in all nine counties that touch the Bay. Many homes and businesses will be severely damaged, displacing residents and businesses. Even in the largest scenarios individuals in seismically designed buildings or those not exposed to strong shaking will walk away with minimal damage to their home and workplace; however, they are likely to be severely impacted by infrastructure interruption. Damage to roads and water pipelines elsewhere will decrease the habitability of undamaged homes, close undamaged businesses, and test the operability of critical facilities like airports. A resilient region is reliant on functional infrastructure systems to keep key societal services operational to help damaged areas rebuild, to keep undamaged homes habitable, and businesses open during recovery. This report examines the interaction of Bay Area infrastructure systems with seismic hazards and the interdependence between mutually dependent systems.

This work builds off of past Bay Area and California infrastructure studies:

- *Earthquake Engineering Research Institute: Scenario for a Magnitude 7.0 Earthquake on the Hayward Fault (EERI, 2010)*
- *Urban Areas Security Initiative: Regional Catastrophic Earthquake Logistics Response Plan, Appendix G Critical Lifelines (UASI, 2014)*
- *City & County of San Francisco Lifelines Council: Lifelines Interdependencies Study I (2014)*
- *California State Hazard Mitigation Plan: Lifeline Annex (2013).*

It will also be joined by other similar work scheduled for release over the next 18 months:

- *FEMA Region 9: Bay Area Earthquake Plan*
- *USGS: Haywired*
- *City & County of San Francisco Lifelines Council: Regional Coordination of Lifelines Restoration Working Group*

- *City & County of San Francisco Lifelines Council: Post-Disaster Fuel Supplies Working Group*.

Infrastructure systems can be interrupted by any number of natural or manmade events. This study examines infrastructure systems through the lens of earthquakes. In past California earthquakes and recent global earthquakes infrastructure systems have been severely damaged, testing the resilience of regions. Earthquake hazards and three Bay Area earthquake scenarios are defined in:

- Chapter 2: Earthquake Hazards & Scenarios

While this assessment is focused on seismic events, the background research on each studied infrastructure system can be a resource to examine system performance in other hazard events.

The study draws from publically available data sets for each lifeline system, and when possible, provides a regionally complete perspective of the system. The information presented will be a useful tool for a number of Bay Area stakeholders, but Bay Area airports are the primary audience for this report. The 25 airports in the region are geographically distributed and are unlikely to all be damaged in a single event, but these regional air assets are all reliant on the same infrastructure systems which are vulnerable to interruption in a future earthquake. Airports and individuals are directly reliant on a number of publically and privately provided infrastructure services to maintain operability. The study focuses on:

- Chapter 3: Airports
- Chapter 4: Transportation - Roads & Passenger Rail
- Chapter 5: Fuel System
- Chapter 6: Electric System
- Chapter 7: Water System.

This list is not a comprehensive review of all infrastructure systems but recognizes the limitations of a single study. Other systems deserving of future study are freight rail, natural gas, waste water, communications, and bio-fuels. In Chapters 3 through 7 individual systems are overlaid regional earthquake scenarios identified in Chapter 2. A seismic vulnerability assessment of each system provides only an initial evaluation of system performance under earthquake loading.

Each system is dependent on other infrastructure systems which may have also been damaged. The interdependence between systems can result in cascading outages, an increased repair time, or can limit the utility of functional systems (i.e. functional roadways, but disrupted fuel system). Including study of the interdependence between lifeline systems reveals a more complete picture of system performance. These interactions are discussed in:

- Chapter 8: Interdependencies

Geographic Information System (GIS) mapping, case studies, technical reports, planning documents, and interviews were used to develop profiles of the Bay Area's infrastructure. GIS was used to map infrastructure systems and hazards, highlighting features of interaction. This analysis by itself provides an infrastructure exposure analysis. When fragility attributes about system components were known the analysis was expanded to consider these features. Case studies of past earthquakes and earthquake engineering research were used to highlight components of each system that were most likely to fail in various seismic hazard loadings, and to identify which system components were most likely to govern the restoration of each system. The likelihood of failure, time required to repair given failure, and consequence of failure were the attributes used to focus analysis on the most important system components. Lastly, interviews with experts who are familiar with the Bay Area's infrastructure and hazards provided additional knowledge into the past performance of infrastructure, their dependence on other systems, and expert guidance.

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A community without water and wastewater service following the 1994 Northridge earthquake relied on portable water and wastewater stations to service resident needs.

©BAREPP, 1994

CHAPTER 2
Earthquake Hazards & Scenarios

In California, earthquakes can result from a slip on any number of faults. This study focuses on earthquake faults within the Bay Area region. While earthquakes outside of the region can have a direct impact on the Bay Area, earthquakes epicentered within the region will cause both local damage and interrupt infrastructure systems. This study uses three scenarios to study earthquake impacts on regional infrastructure systems: M7.9 San Andreas fault scenario, M7.0 Hayward fault scenario, M6.8 Concord fault scenario. These scenarios were chosen because of their regionwide impact, and their considerable interaction with regional infrastructure systems.

Study of infrastructure system vulnerabilities requires an understanding of the earthquake hazards that exist, their likelihood, and how systems are uniquely vulnerable to each force. The many types of earthquake hazards are defined in this chapter and are mapped for common earthquake scenarios. The System Vulnerability portion of Chapters 3-7 detail how scenario earthquakes interact with infrastructure components, calling out the most vulnerable interaction between infrastructure component type and hazard type.

EFFECTS OF EARTHQUAKE HAZARDS

Earthquakes produce a variety of different effects: ground shaking, fault rupture, liquefaction, lateral spreading, landslide/rockfall, tsunami/seiche, and secondary hazards. Below, the main earthquake hazard effects are defined.

Ground shaking is the effect most associated with earthquakes. It is measured in units of acceleration, often as a percentage of gravity. Predicting the shaking intensity at geographic locations has some uncertainty due to local soil conditions, rupture directivity, and a variety of other unique characteristics which can each amplify or lessen ground accelerations. The United States Geological Survey (USGS) has created ground shaking scenario maps that take into account soil conditions but many other ground characteristics result in a range of likely shaking levels. The scenario maps in this study use the Modified Mercalli Intensity (MMI) scale (quake.abag.ca.gov/shaking/mmi/).

The Modified Mercalli Intensity (MMI) scaling is used to describe shaking intensity on a scale of 1-12. MMI values less than 5 don't typically cause significant damage. MMI greater than 10 has not been experienced.

- MMI 5 (Light) correlates to pictures on walls moving.
- MMI 6 (Moderate) is felt by everyone with objects falling off shelves and some windows and weak plaster walls cracking.
- MMI 7 (Strong Shaking) is difficult for people to stand or walk with damage to masonry structures.
- MMI 8 (Very Strong Shaking) wood frame homes can move on foundation if not bolted, overall moderate damage.
- MMI 9 (Violent Shaking) results in heavy damage to unbolted wood frame structures.
- MMI 10 (Very Violent Shaking) results in damage to even well-built structures.

Surface fault rupture occurs when movement on a fault breaks through to the surface. The fault location is often known, and maximum probable rupture displacements for faults are known with some confidence. Earthquakes can occur on unknown faults, which was the case in the 1994 Northridge earthquake. Most

SIDEBAR 1:
Surface Fault Rupture Over Time: Hayward Example

Post-seismic slip (slip that occurs after earthquake shaking) can be difficult to manage as infrastructure may need to be continually re-straightened, complicating restoration of systems that cross the fault.

The Hayward fault provides a number of lessons in fault rupture. The fault is part of the Hayward – Rodgers Creek fault system. Individual earthquakes can be isolated to just the Rodgers Creek fault, or northern and southern sections of the Hayward fault. It is also possible for both sections of the Hayward fault and the Rodgers Creek fault to slip in one large earthquake.

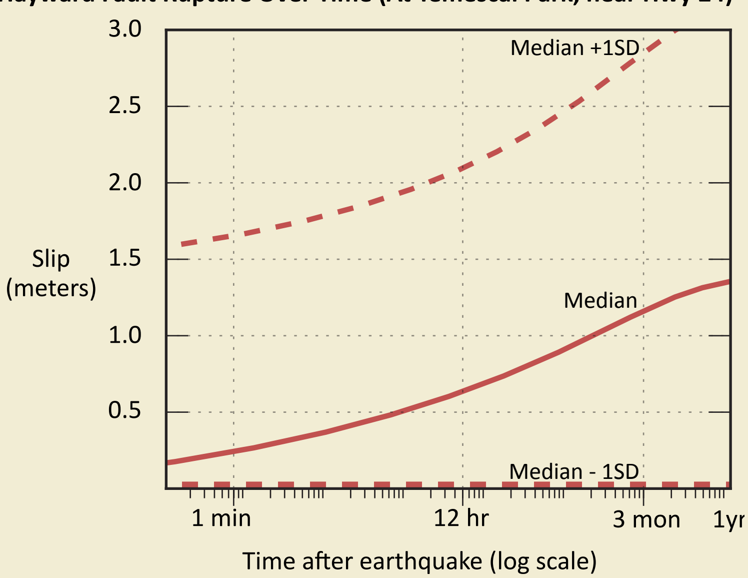
In this report we focus on a scenario where the north and south portions of the Hayward fault rupture resulting in a M7.0 event. As seen in Figure 3 on p12, the fault rupture displacement changes over different segments of the fault. In addition to differences in rupture across space, the rupture will occur over a one- to two-year period.

Co-seismic slip is displacement that occurs during the event, and post-seismic slip is the displacement that occurs after the event. The graph below shows the fault slip over time. A median fault rupture over time might have the following characteristic:

> *"afterslip progressing at a rate of about 10% in the first minute, 25% in the first hour, 35% in the first 6 hours, 40% in the first 24 hours, 70% in the first 30 days, 85% in the first 6 months, and a little more than 90% in the first year." (Aagaard, 2012)*

There is uncertainty in the magnitude of surface fault rupture as well as its development over time. The dashed lines in the graph show the median plus and minus one standard deviation.

Hayward Fault Rupture Over Time (At Temescal Park, near Hwy 24)



Bay Area faults are strike slip faults which result in a horizontal shifting of the ground. Some faults, like the Mt. Diablo Fault, are thrust faults and have vertical displacements. Surface fault rupture on either fault type typically occurs in two phases: co-seismic slip, which occurs during the earthquake, and post-seismic slip which is slip that continues for upwards of a year after the earthquake. Sidebar 1 (on this page) details the probabilistic fault rupture of the Hayward Fault over time.

Structures and infrastructure components can be severely damaged by fault rupture. When considering infrastructure systems it is important to know:

(1) Fault rupture displacement. Will the displacement damage or destroy crossing infrastructure during co-seismic slip or post-seismic slip?

(2) Fault rupture length. Will fault rupture damage parallel infrastructure which cross the fault miles apart from one another? For parallel infrastructure systems, does rupture break both links?

In large San Andreas events the surface fault rupture displacement can be upwards of 25 feet. In smaller events on the San Andreas, or other Bay Area faults the displacement can still be as large as 5 to 10 feet (Aagarrd, 2012; Thatcher 1997).

Ground failure, liquefaction, lateral spreading, landslide, and rockfalls, have also been mapped with varying levels of uncertainty by the USGS. Liquefaction occurs at sites that have "loose" unconsolidated sand and silt soil saturated with water, which are common near existing or historic water features. For liquefaction to occur, the site must be shaken long and hard enough by the earthquake (ABAG, 2001). Liquefaction can result in uneven ground settlement and loss of soil strength which can cause building foundations to sink.

Lateral spreading occurs when a layer of gently sloping ground at the surface is carried down the slope on an underlying layer of liquefied material (ABAG, 2001). Similarly, earthquake-induced landslides and rockfalls occur when the stability of slopes are disturbed by ground shaking. Infrastructure that crosses ground failures both above and below ground can be broken by movements in the soil. Some below ground components (pipes, conduit boxes, tanks, etc.) may also float if the soil liquefies and they are less dense than the surrounding water-saturated soil.

Tsunamis and seiches are most likely to be caused by distant earthquakes, like the 2011 Tohoku, Japan earthquake or 1964 Alaska earthquake. They can also be caused by local earthquake faults that cause above- or under-water landslides that displace large amounts of water. Faults that pass underwater could also produce tsunamis if their rupture has a vertical component. Tsunamis are caused by the displacement of a large volume of water that then travels rapidly until it reaches a shoreline, often innundating the coastline. Seiches occur on lakes and rivers and cause water to oscillate which can result in innundation and waves.

The USGS studied the predicted impact of a M9.1 Alaska earthquake and its tsunami on California (USGS, 2013). The scenario results in damage to the Bay Area ocean coast and bay shores, but the bay shoreline is expected to have less damage than the ocean coasts of California. For this tsunami event the maximum tsunami height is 2.9 ± 0.9 ft occuring along San Francisco's bay shoreline and along the East Bay from Oakland to Richmond. Port and marina damage are expected, but not of a catastrophic scale. Lifelines along the Bay are likely to be impacted due to both flooding and strong water velocities in channels and ports (USGS, 2013). Small tsunamis can be caused within the bay by local fault rupture with vertical characteristics, and slides displacing water.

Secondary hazards are used to describe a long list of cascading earthquake hazards. The most damaging secondary hazard is fire following earthquake. Fires fueled by broken gas lines, exposed electrical wires, or overturned hazardous materials have been responsible for urban conflagrations that cause more damage than the earthquake itself.

"The two largest peace-time urban conflagrations in history have been fires following earthquakes – 1906 San Francisco and 1923 Tokyo, the latter event's fires causing the great majority of the 140,000 fatalities," (Scawthorn, 2011).

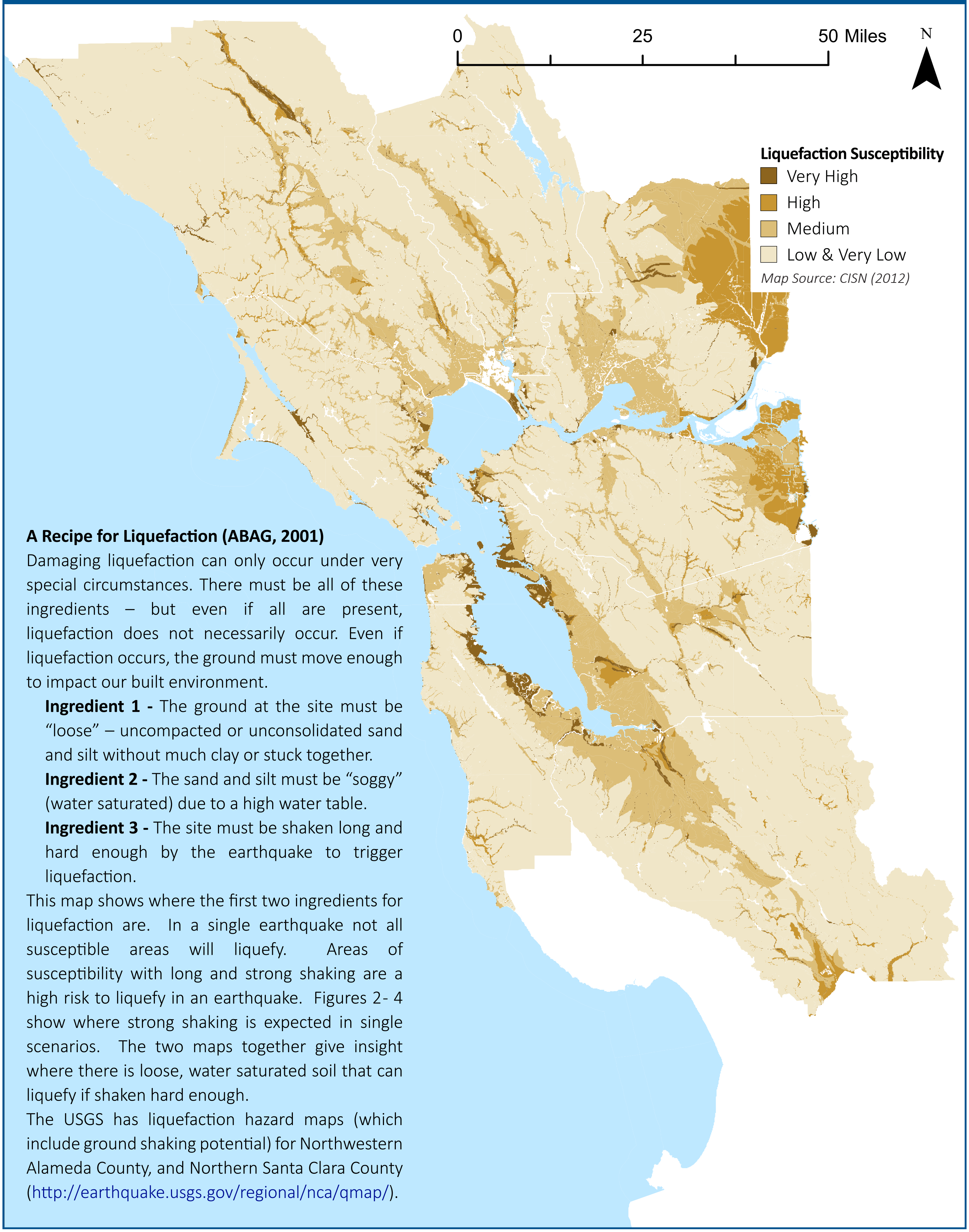
Flooding is the other common secondary hazard, and can be caused by damaged dams, levees, water tanks, or broken water mains.

Broken gas and water mains on Balboa Boulevard in Granada Hills created this scene of flood and fire in the 1994 Northridge Earthquake.

Study Scenarios

When studying infrastructure systems, scenario events are a helpful tool to understand the overall exposure of a system in a discrete event. Figures 2-4 (pages 11, 12, and 13) show and describe the ground shaking, and fault rupture expected in each scenario: M7.9 San Andreas, M7.0 Hayward, and M6.8 Concord. Figure 1 (page 10) shows liquefaction susceptibility which is not a scenario map, but provides insight into areas of the Bay Area that have high potential to liquefy under strong shaking. There are other faults that can cause devastating damage to buildings and infrastructure in the Bay Area. These three faults were chosen based on their interaction with key Bay Area infrastructure components, their higher likelihood of occurrence, and the level of existing information about these fault systems.

FIGURE 1:
Liquefaction Susceptibility



A Recipe for Liquefaction (ABAG, 2001)

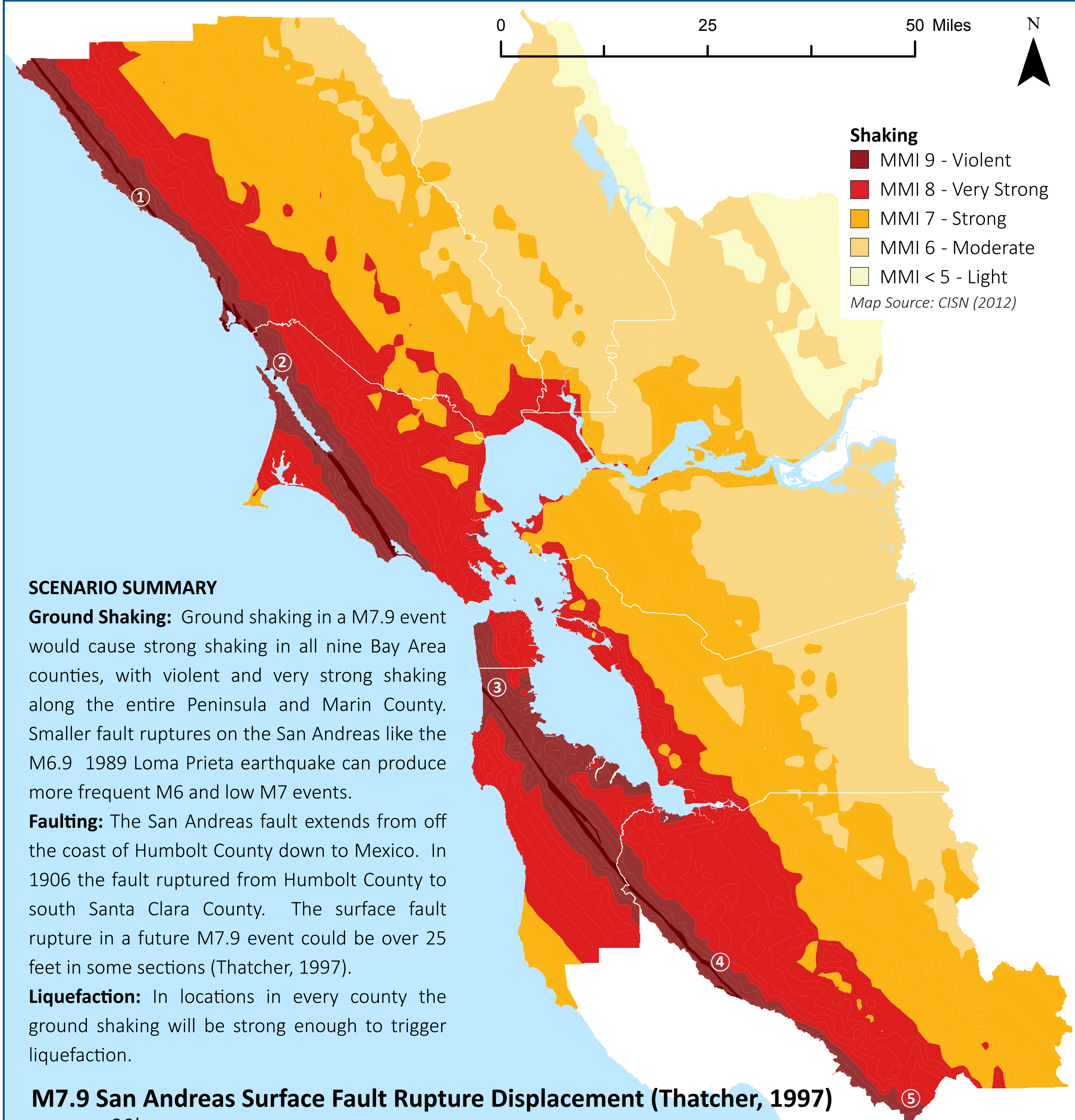
Damaging liquefaction can only occur under very special circumstances. There must be all of these ingredients – but even if all are present, liquefaction does not necessarily occur. Even if liquefaction occurs, the ground must move enough to impact our built environment.

- **Ingredient 1 -** The ground at the site must be "loose" – uncompacted or unconsolidated sand and silt without much clay or stuck together.
- **Ingredient 2 -** The sand and silt must be "soggy" (water saturated) due to a high water table.
- **Ingredient 3 -** The site must be shaken long and hard enough by the earthquake to trigger liquefaction.

This map shows where the first two ingredients for liquefaction are. In a single earthquake not all susceptible areas will liquefy. Areas of susceptibility with long and strong shaking are a high risk to liquefy in an earthquake. Figures 2- 4 show where strong shaking is expected in single scenarios. The two maps together give insight where there is loose, water saturated soil that can liquefy if shaken hard enough.

The USGS has liquefaction hazard maps (which include ground shaking potential) for Northwestern Alameda County, and Northern Santa Clara County (http://earthquake.usgs.gov/regional/nca/qmap/).

FIGURE 2:
San Andreas M7.9 Scenario



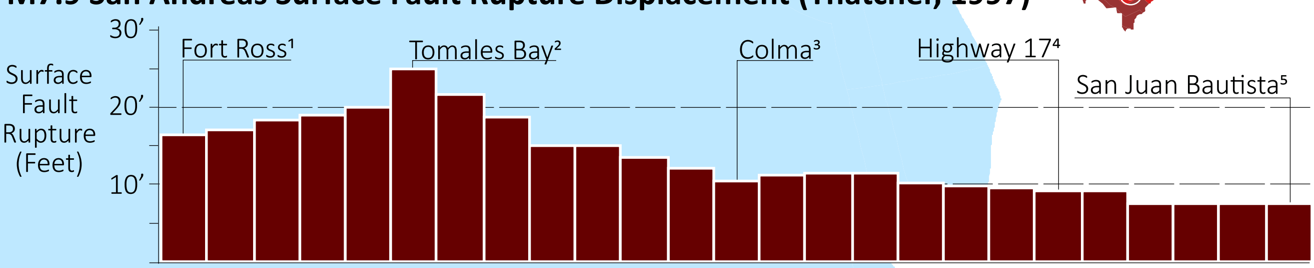
SCENARIO SUMMARY

Ground Shaking: Ground shaking in a M7.9 event would cause strong shaking in all nine Bay Area counties, with violent and very strong shaking along the entire Peninsula and Marin County. Smaller fault ruptures on the San Andreas like the M6.9 1989 Loma Prieta earthquake can produce more frequent M6 and low M7 events.

Faulting: The San Andreas fault extends from off the coast of Humbolt County down to Mexico. In 1906 the fault ruptured from Humbolt County to south Santa Clara County. The surface fault rupture in a future M7.9 event could be over 25 feet in some sections (Thatcher, 1997).

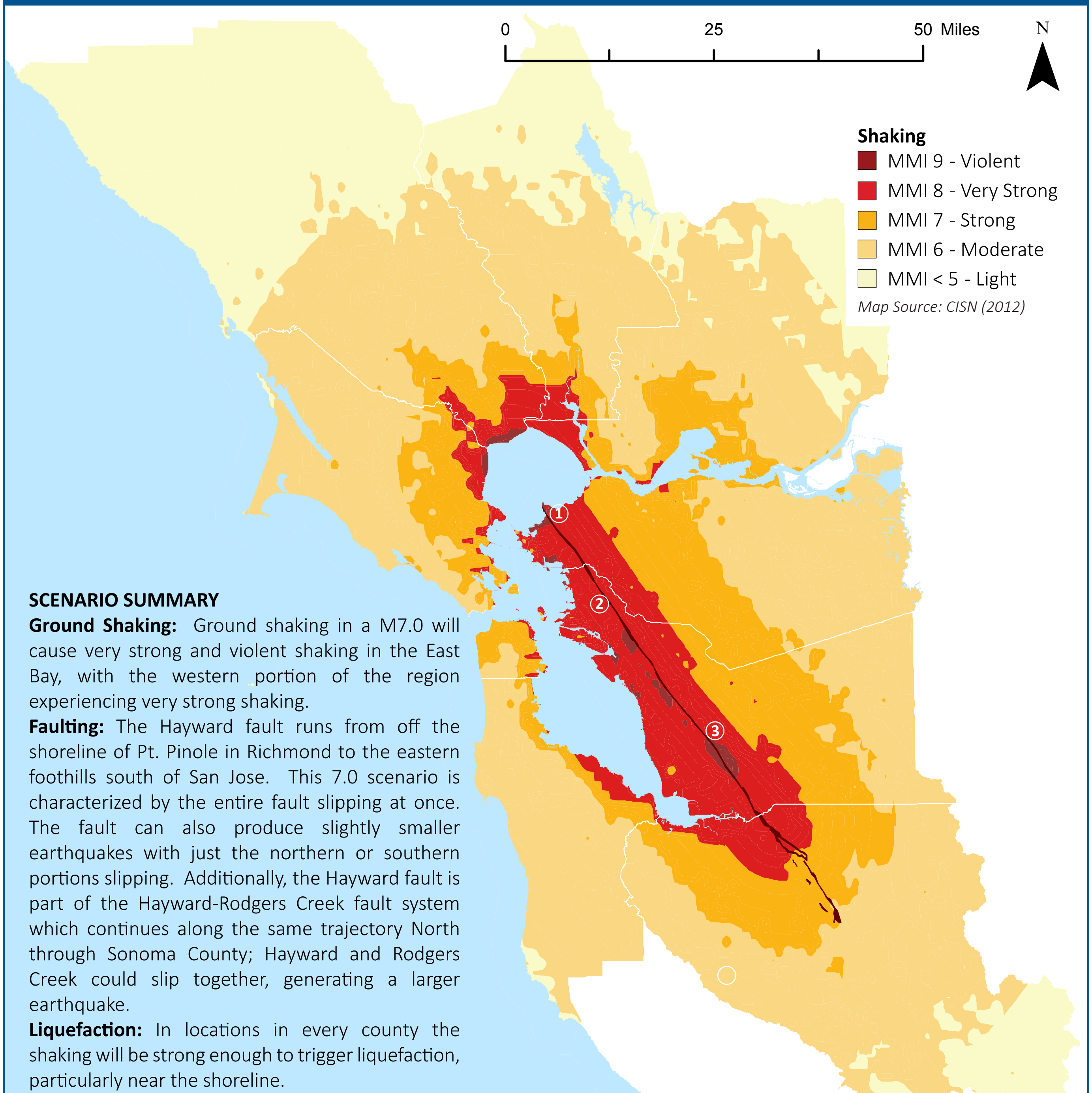
Liquefaction: In locations in every county the ground shaking will be strong enough to trigger liquefaction.

M7.9 San Andreas Surface Fault Rupture Displacement (Thatcher, 1997)



Location on Fault North to South (10km segments) *Rupture offshore Humbolt and Mendocino Counties not shown

FIGURE 3:
Hayward M7.0 Scenario



SCENARIO SUMMARY

Ground Shaking: Ground shaking in a M7.0 will cause very strong and violent shaking in the East Bay, with the western portion of the region experiencing very strong shaking.

Faulting: The Hayward fault runs from off the shoreline of Pt. Pinole in Richmond to the eastern foothills south of San Jose. This 7.0 scenario is characterized by the entire fault slipping at once. The fault can also produce slightly smaller earthquakes with just the northern or southern portions slipping. Additionally, the Hayward fault is part of the Hayward-Rodgers Creek fault system which continues along the same trajectory North through Sonoma County; Hayward and Rodgers Creek could slip together, generating a larger earthquake.

Liquefaction: In locations in every county the shaking will be strong enough to trigger liquefaction, particularly near the shoreline.

M7.0 Hayward Surface Fault Rupture Displacement (Aagaard, 2012)

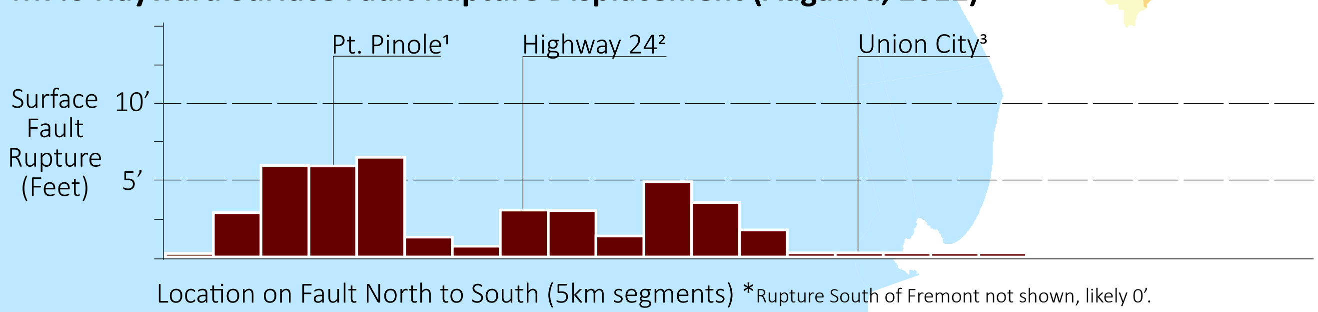
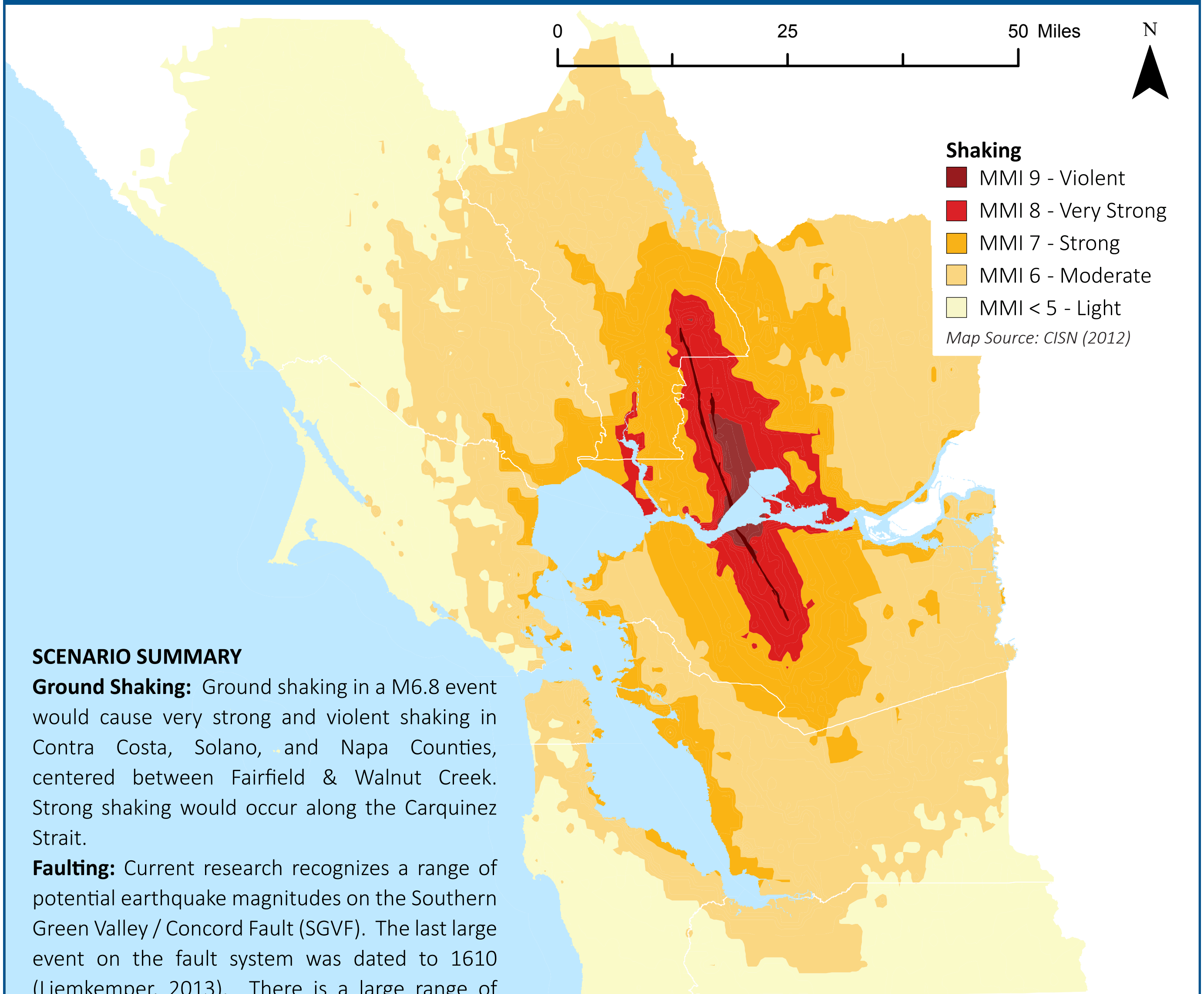


FIGURE 4:
Concord M6.8 Scenario



SCENARIO SUMMARY

Ground Shaking: Ground shaking in a M6.8 event would cause very strong and violent shaking in Contra Costa, Solano, and Napa Counties, centered between Fairfield & Walnut Creek. Strong shaking would occur along the Carquinez Strait.

Faulting: Current research recognizes a range of potential earthquake magnitudes on the Southern Green Valley / Concord Fault (SGVF). The last large event on the fault system was dated to 1610 (Liemkemper, 2013). There is a large range of earthquake return periods with smaller events occuring closer together. About a third of events on the SGVF develop over a longer time and involve longer ruptures along the Berryessa and Hunting Creek sections (north of the mapped fault). These events would reach higher magnitudes (Liemkemper, 2013).

Liquefaction: The scenario earthquake produces strong enough ground shaking to trigger liquefaction in all Bay Area counties. The violent shaking in the San Francisco Bay and Carquinez Strait can also result in dredged water channels edges sluffing (falling) into channels.

Surface fault rupture displacements have not been developed for this scenario.

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Lateral spreading at the Coronel Port container yard following the M8.8 2010 Maule, Chile earthquake.

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CHAPTER 3
Airports

KEY FINDINGS

- Airports are well distributed around the region.
- In San Andreas and Hayward scenario events the three international airports will simultaneously experience strong to violent shaking. 19 of 26 Bay Area airports are within five miles of an active Alquist-Priolo mapped fault, and 23 of 26 are within ten miles.
- Of the 24 airports that completed the Caltrans Division of Aeronautics Emergency Plan Survey, 21 have an Airport Emergency Plan, 16 of which have sections that cover earthquakes.

Bay Area airports provide residents and businesses the ability to travel and conduct business across the globe. The airports support the regional economy by providing airport sector jobs, economic access to domestic and global markets, air cargo services, and tourism access. Among the many important every day benefits of Bay Area airports, after a major earthquake they become key nodes to support both the response and recovery of the region. The accompanying report, *Roles of Airports in Regional Disasters* (2013) highlights the important resource airports provide in both short-term disaster recovery and long-term economic recovery of the Bay Area region.

In the Bay Area there are 24 public use airports, one federal airport, and one military airport. Three of the public use airports have international service. The airports are well distributed throughout the region, with airports in all counties except San Francisco. Twelve of the airports are within 1.5 miles of Highway 101 along the 175 miles between Cloverdale and San Juan Baustista. The majority of the airports in the region are classified by the FAA as supporting only medium to small aircraft (FAA, 2013). There are a number of factors that influence necessary runway lengths: wheel type, weight, site elevation, temperature, and others, but the FAA categorizes Bay Area airports as shown in Figure 5 (on page 16).

HISTORIC SYSTEM PERFORMANCE

Airport facilities are susceptible to fault rupture, liquefaction, and ground shaking. Fault rupture and liquefaction can cause damage to runways requiring the re-grading and asphalting of the runway. The above ground components of airports (terminals, hangers, air traffic control towers, etc.) are vulnerable to all three hazards. Damage to facilities can be both structural or non-structural. In many earthquakes structural damage can be minimal, but poorly anchored heating and cooling equipment, architectural elements, and mechanical systems can result in closure. The accompanying report *Roles of Airports in Regional Disasters* has nine case studies of recent domestic disasters, and international earthquakes and their impacts to airports. It also highlights the services these facilities can provide in both response and recovery for their regions.

BAY AREA VULNERABILITY ASSESSMENT

In the Bay Area there are two airports that have a known risk of fault rupture, Napa County Airport, and Buchanan Field in Contra Costa County. In the region there are 15 airports with portions of their facility in high or very high liquefaction susceptibility zones. The airports near the bay are especially susceptible, but many have taken some level of mitigative action to address the liquefaction potential. An accompanying study to this report

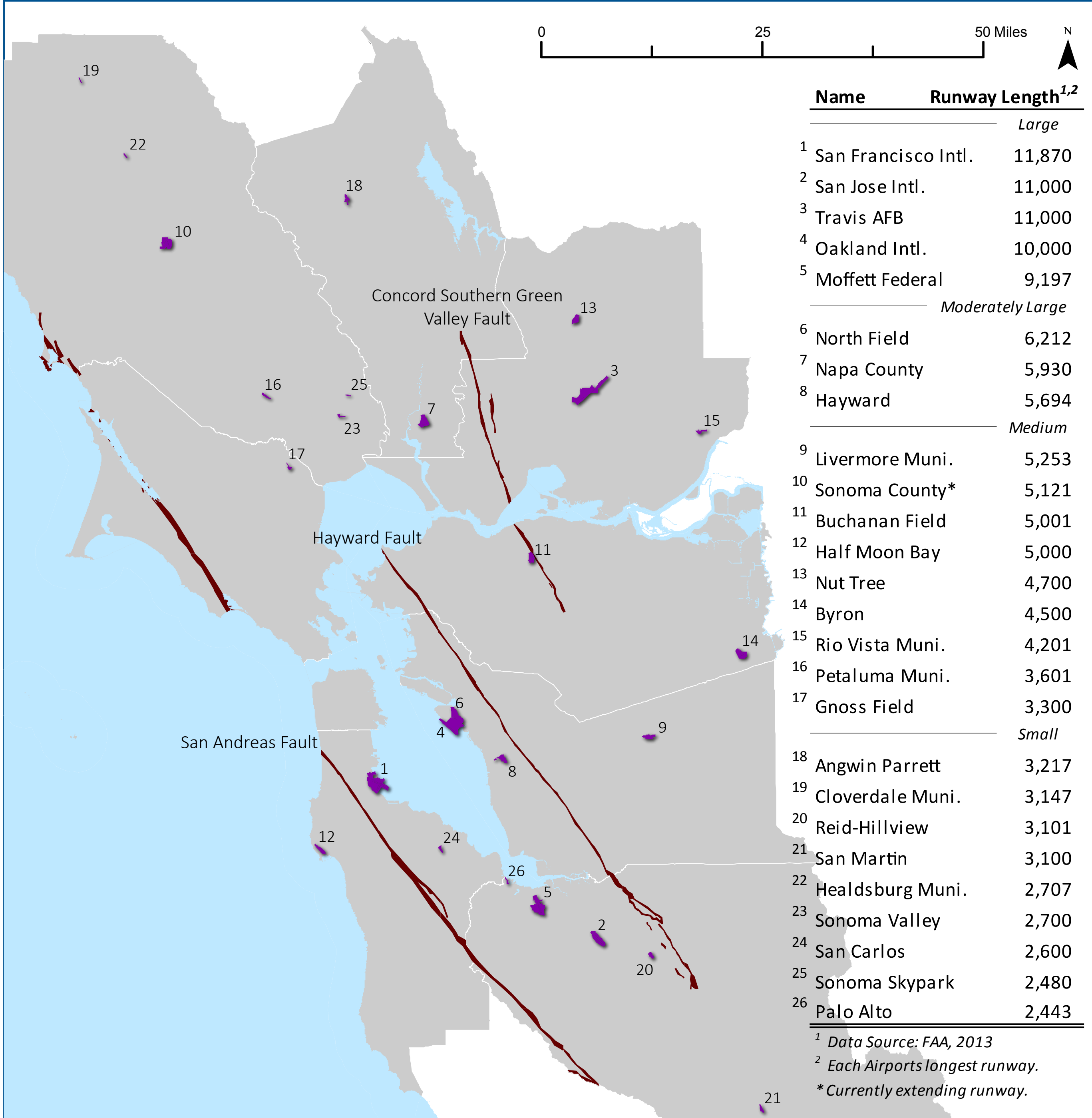
Accompanying Reports Specific to Airports

Roles of Airports in Regional Disasters

Preliminary Assessment of Earthquake-Induced Liquefaction Susceptibility at Five San Francisco Bay Area Airports

reports are available at resilience.abag.ca.gov

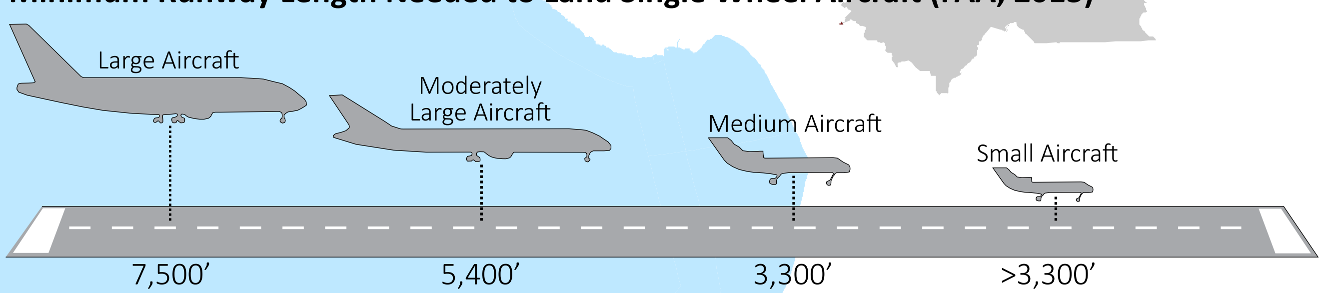
FIGURE 5:
Location of Bay Area Airports in Relation to the Three Major Faults



	Name	Runway Length[1,2]
		Large
1	San Francisco Intl.	11,870
2	San Jose Intl.	11,000
3	Travis AFB	11,000
4	Oakland Intl.	10,000
5	Moffett Federal	9,197
		Moderately Large
6	North Field	6,212
7	Napa County	5,930
8	Hayward	5,694
		Medium
9	Livermore Muni.	5,253
10	Sonoma County*	5,121
11	Buchanan Field	5,001
12	Half Moon Bay	5,000
13	Nut Tree	4,700
14	Byron	4,500
15	Rio Vista Muni.	4,201
16	Petaluma Muni.	3,601
17	Gnoss Field	3,300
		Small
18	Angwin Parrett	3,217
19	Cloverdale Muni.	3,147
20	Reid-Hillview	3,101
21	San Martin	3,100
22	Healdsburg Muni.	2,707
23	Sonoma Valley	2,700
24	San Carlos	2,600
25	Sonoma Skypark	2,480
26	Palo Alto	2,443

[1] Data Source: FAA, 2013
[2] Each Airports longest runway.
** Currently extending runway.*

Minimum Runway Length Needed to Land Single Wheel Aircraft (FAA, 2013)



Preliminary Assessment of Earthquake-Induced Liquefaction Susceptibility at Five San Francisco Bay Area Airports (2013) used available bore hole data to quantify the potential and degree of liquefaction to five Bay Area runways.

As the region experienced recently in the 2014 South Napa Earthquake, smaller faults in the region have the potential to cause damage to individual or a small subset of regional airports. Sidebar 2 highlights the fortunately minimal damage at the Napa County Airport in the South Napa Earthquake.

Because the airports in the region are well distributed throughout the region, there is an ability for air traffic to be rerouted in events. San Andreas and Hayward earthquake events will test the commercial travel in the region as the three international airports are between the two faults, along with Moffett Federal. Four of the region's five airports that can handle large aircraft will experience strong to violent shaking in both the San Andreas and Hayward Scenario. In the event of disruption to these four airports ,Travis Air Force Base in Solano County would be the only airport in the region with a long enough runway for large aircraft.

SIDEBAR 2:
M6.0 South Napa Earthquake

On August 24th, 2014 an earthquake occurred on a portion of the West Napa Fault that had previously not been mapped as an active fault zone (USGS, 2014). The known section of the West Napa Fault a few miles south of the earthquake epicenter runs directly through the Napa County Airport. This section of fault did not have significant fault rupture, but rupture displacements north of the airport were greater than 1 foot (GEER, 2014).

The Napa County Airport did sustain non-structural damage to the air traffic control tower, and to shelving units elsewhere in the terminal. The airport operated without an air traffic control communications for four days until a temporary air traffic control could be set up. The tower remained unoccupied for over a month while new windows and other non-structural damage was repaired (Stockdale, 2014).

Other than a 30 minute airport closure for inspection, the airport maintained operation. The facility was without power for 12 hours and ran on backup generators during this time. PG&E used a portion of the airport parking lot as their mobile command center, and provided additional generators to help power fixed based operator services during the short outage. Overall, the earthquake was a near miss for Napa County Airport and is a reminder of the region's high earthquake risk.

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CHAPTER 4

Transportation - Roads and Passenger Rail

KEY FINDINGS

- SFO and OAK airports are near parallel highway networks: I-280 & US 101 at SFO, and I-880 & I-580 at OAK. These parallel roadways will be subject to different hazards in San Andreas and Hayward events, with the inland routes (I-280 & I-580) experiencing violent and very strong shaking, and the bay side routes (I-880 & US 101) experiencing liquefaction as well as very strong shaking.
- Large-scale seismic retrofit programs have resulted in a much more resilient transportation network. Still a single failure along non redundant corridors can severely disrupt travel.

An extensive network of both road and rail infrastructure provide the Bay Area region with multiple modes of travel across most of the region. Two main rail lines operate intra-regionally, Bay Area Rapid Transit (BART) and Caltrain. The Altamont Corridor Express (ACE) and the Capitol Corridor (managed by Capitol Corridor Join Powers Authority) trains provide service from Santa Clara County east and north out of the region. Figure 6 shows the map of these systems and their respective ridership levels along each section of track.

In the nine county Bay Area region there are over 1,400 miles of state highways, and another 20,000 miles of local roadways (Caltrans, 2011). Twenty-four of the 26 Bay Area airports are within 1.5 miles of a state highway; Angwin-Parrett (in Napa County) and Byron (in Contra Costa) airports are further from highways. California road networks have had catastrophic failures in both the 1989 Loma Prieta and 1994 Northridge earthquakes. Since 1989, Caltrans has spent over $12 billion to seismically retrofit over 2,200 bridges.

AIRPORT RELIANCE & CAPACITY

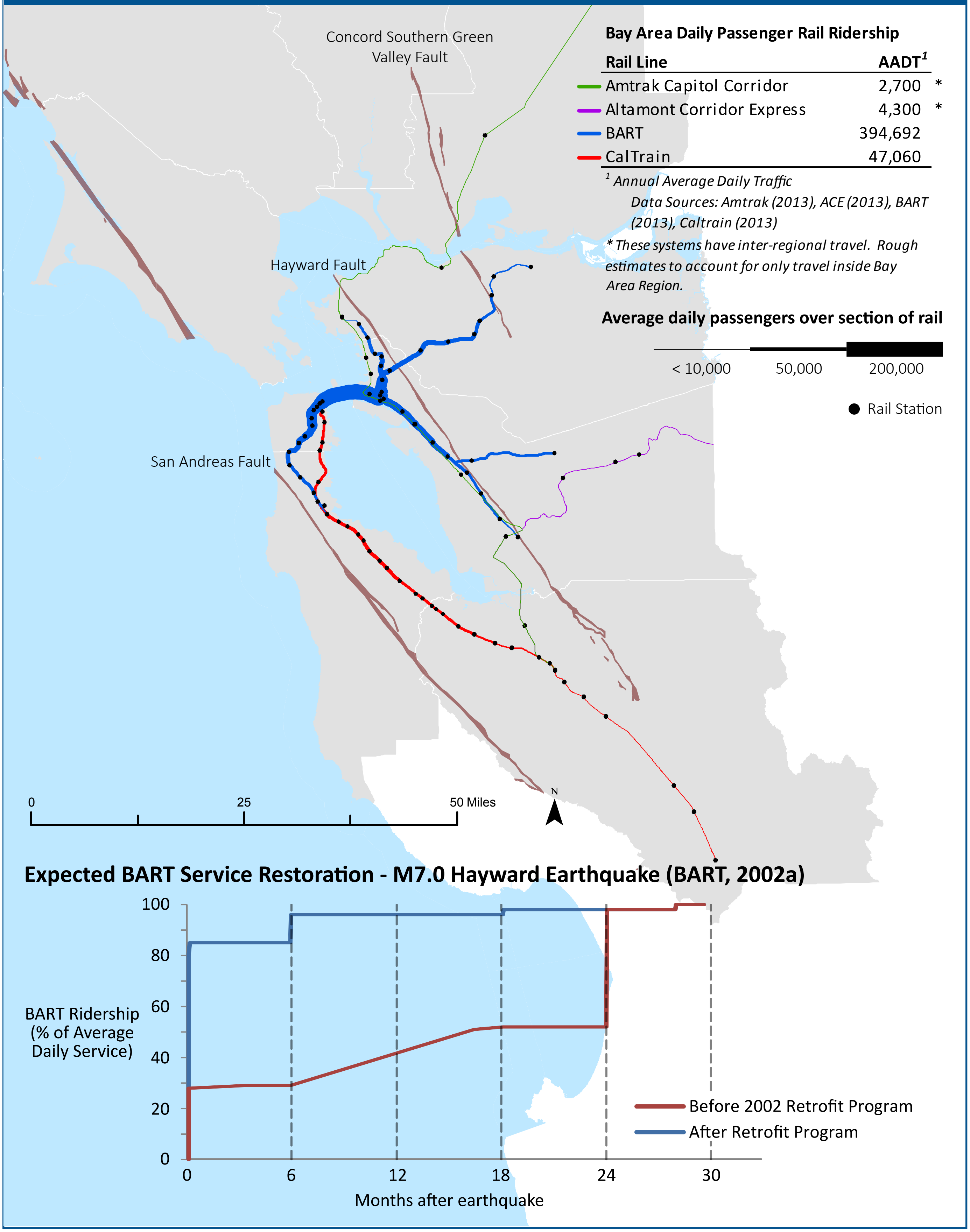
For airports to be useful regional transportation nodes they must be connected by roads and rail lines to the populations they serve. Transportation links are necessary to get airport staff, passengers, and cargo to and from the airport. San Francisco International Airport (SFO) and Oakland International Airport (OAK) both have BART stations at their facilities while all other airports rely on roads for bus and personal vehicle service. Even at SFO and OAK, BART trips are a fraction of overall trips, and do not provide any cargo movement. All ground vehicles require passable roadway systems and fuel for vehicles (either reformulated gasoline, diesel, electricity, or bio) to get to and from the airport.

Passenger travel is very reliant on road networks outward from airports. The average distance traveled for SFO, OAK, and SJC passengers is 25 miles. At Sonoma County Airport, Concord Buchanan Field, and Travis Air Force Base the average passenger travels 19 miles to the airport (RAPC, 2011). Under normal conditions, without accounting for any rerouting, a long section of the road network must be open for people to access the airport and they must have the fuel necessary to get to and from the airport.

SYSTEM VULNERABILITY

Roadways are typically divided into two components: roads and bridges. In past earthquakes both have experienced catastrophic failures. The most evocative failures of the Loma Prieta Earthquake were the collapse of the Cyprus Street

FIGURE 6:
Passenger Rail Layout & Expected BART Service Restoration following M7.0 Hayward Event



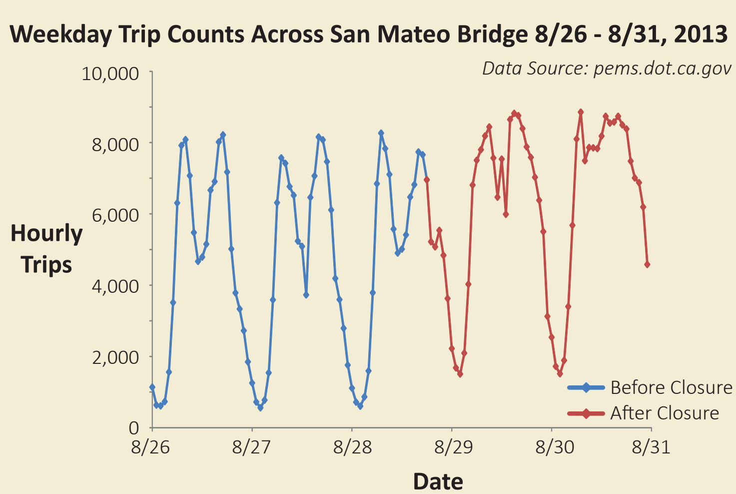
SIDEBAR 3:
Bay Bridge Closure Impacts on Parallel Corridors

When a single component within the transportation system is stressed, the parallel links within the greater system take on greater loads. The San Francisco - Oakland Bay Bridge offers three recent examples of network impacts to single failures.

In 2007, a gasoline tanker truck crashed causing a fire that collapsed a section of the I-80E to I-580E connector onto the I-80W to I-880S interchange. There was no damage to the Bay Bridge, but the crash and fire closed interchanges to the bridge, which typically carry 80,000 vehicles daily (Hoge, 2007). In the first day after the interchange closure Bay Bridge traffic was down 18%. The other modes across the bay saw a surge in the number of trips. On the first day, the Golden Gate Bridge had 7% more trips (4,180 additional vehicles), San Mateo had an increase of 8.6%, and BART increased its ridership by 7.1% (34,200 additional passengers) (Caltrans, 2007). The redundancy across the road networks and BART resulted in minimal traffic impacts across the bay during the 26 day repair.

In 2009, the system was strained again when a steel crossbeam and two steel tie rods fell onto the upper deck of the Bay Bridge. In the following days, BART continually set and reset historic ridership records with a 24% overall increase in ridership, and a 57% increase in the transbay portion of the system (BART, 2009). The San Mateo - Hayward bridge increased from a monthly average of 100,000 trips to above 140,000, and the Richmond Bridge increased from 65,000 to 83,000 trips.

The most recent Bay Bridge closure was the planned closure in 2013 to connect the new eastern span. The figure below shows hourly trip counts for the San Mateo Bridge. The peak has a slight uptick after the bridge closure, but the more important trend is the longer period of the day the bridge is at capacity. On Friday 8/31, the midday lull does not exist and peak traffic exists from 6am to 7pm.



Viaduct in Oakland and the Bay Bridge deck. Bridges can be damaged by fault rupture, liquefaction, or ground shaking. Also after the earthquake, Highway 17, the only multi-lane highway between Santa Cruz and Santa Clara counties, was out of service for a month while landslide damage was repaired. Historically speaking, bridge failures govern the restoration of the system because of the time it takes to design and construct a bridge above some other feature (river, active roadway, etc.) In the case of Highway 17, the roadways above unstable sloped ground also required significant time to reopen. Roadways are most susceptible to ground failures: fault rupture, liquefaction, and lateral spreading. Depending on the extent and location of ground failure, the roadway can be repaired quickly over flat areas. However, if ground failures require extensive re-grading, retaining wall work, or slope stability, the consequences and restoration timeline may be more similar to a bridge failure.

Rail lines are similar in their vulnerability. Rail bridges, or sections of rail interrupted by slope stability are often the governing failures. In addition to the network of rail, both the stations and operations center of the rail networks are critical nodes that may not be physically connected to the system, but could govern the system restoration if it is damaged. Transit stations, depending on their design, may be at grade structures with minimal vulnerability to shaking, or may also be above ground structures that may experience damage. Lastly, rail requires employees to operate the system, which following the Loma Prieta Earthquake was a challenge for the Caltrain system. Many Caltrain employees lived in Santa Cruz County and were unable to get to work because of the Highway 17 failure (Schiff, 1990).

The surface transportation system, both rail and roads, work together to provide regional travel. In 1989, the Bay Bridge carried 254,400 vehicles daily (Yashinsky, 1998) and was closed for a full month to repair the bridge deck damage.

"To meet increased transportation demands during this period, BART initiated 24-hour daily service. BART's daily ridership soon increased from a pre-earthquake level of 218,000 passengers to a post-earthquake peak of 357,000 passengers—a 64% increase," (Schiff, 1990).

Sidebar 3 (page 20) explores more recent failures and the redundancy achieved by parallel bridges and BART.

VULNERABILITY ASSESSMENT

Bay area roads can be severely damaged by all three studied scenarios. San Andreas and Hayward events are likely to cause the greatest damage because the faults parallel high volume freeways with entire corridors experiencing very strong and severe shaking. In both the scenarios the highways along the bay shore will likely be exposed to liquefaction. Figure 7 (page 22) highlights parallel corridors that will be tested by an earthquake on the San Andreas or Hayward fault. Despite their parallel system structure, the hazards are such that both highways could be severely interrupted by shaking damage to bridges on the inland corridor, or liquefaction damage to highways along the bay. A Hayward earthquake has the added hazard of fault rupture which can also be seen in Figure 7. Highways 80, 580, 24, 13, and 238 all cross the Hayward fault where rupture is expected in an earthquake. The fault also crosses I-680 but further south where fault rupture is less likely to be expressed at the ground surface.

In San Andreas and Hayward events the road damage will not be limited to the Peninsula or East Bay shoreline. Shaking in Santa Clara County will be strong enough to cause damage to the highway networks in the area. The San Andreas

TABLE 1: Completed Retrofits for All Bay Crossings

All bridges are designed to a level that, at a minimum, will ensure that the bridge will remain standing in an earthquake.

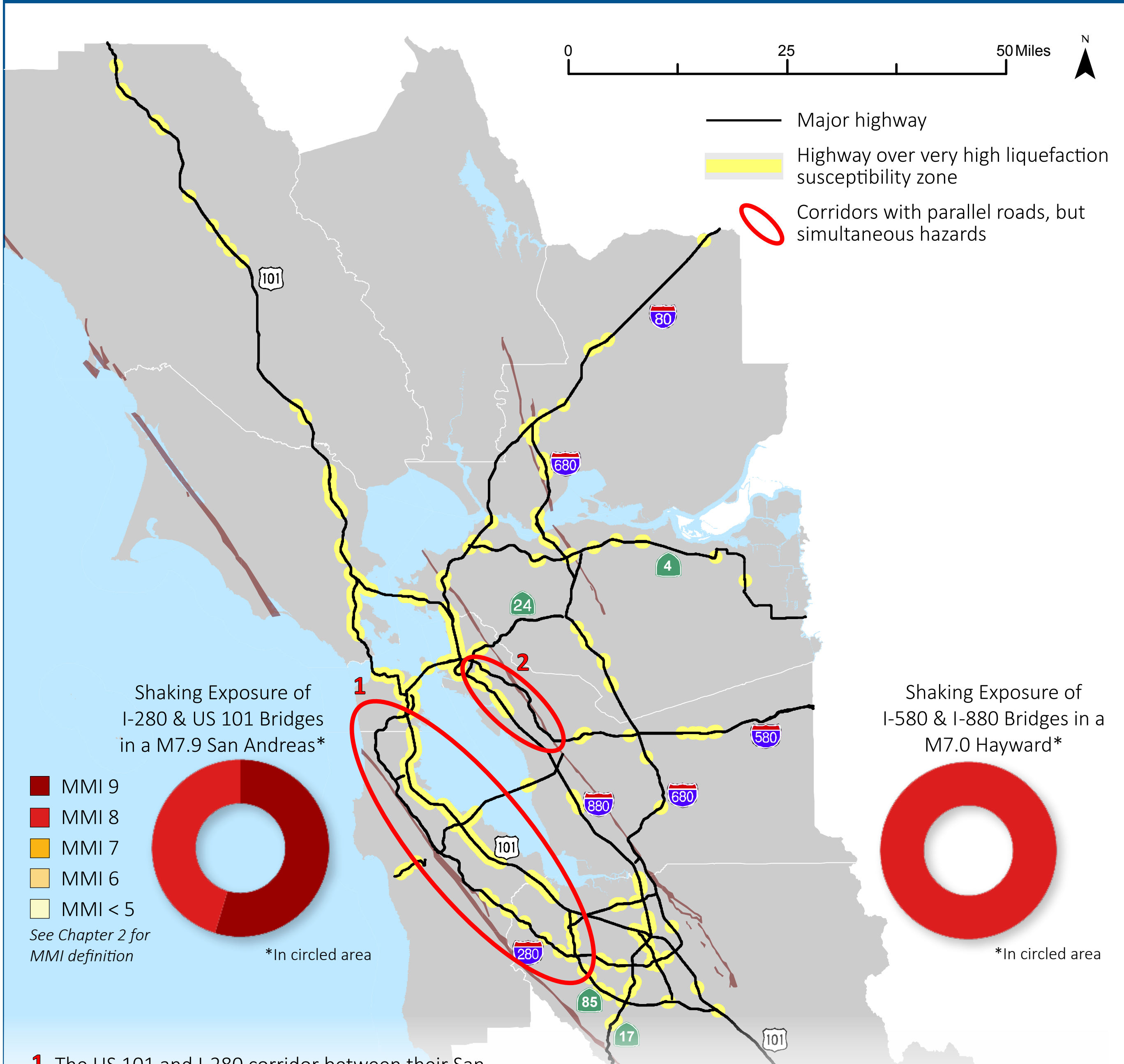
Bridge	Design Criteria[1, 2, 3]	Retrofit Strategy[1, 2, 3]
Antioch	Meet current seismic safety design standards	Strengthened/replaced structural elements, improved isolation features
Benicia - Martinez	Lifeline structure, minor to moderate damage expected	Strengthened/replaced structural elements, added isolation or dampening features
Carquinez (Eastbound)	Moderate to major damage	Strengthened/replaced structural elements, added isolation or dampening features
Dumbarton	Strengthened to withstand a Maximum Credible Earthquake	Strengthened/replaced structural elements, improved isolation features
Golden Gate	Strengthened to withstand a Maximum Credible Earthquake	Strengthened/replaced structural elements, added isolation features
Richmond - San Rafael	Avoid catastrophic failure	Strengthened/replaced structural elements, added isolation or dampening features
Bay Bridge (west span)	Lifeline structure, minor to moderate damage expected	Strengthened/replaced structural elements, added isolation or dampening features
Bay Bridge (east span)	Lifeline structure, minor to moderate damage expected	Constructed new bridge
San Mateo-Hayward	Moderate to major damage expected	Strengthened/replaced structural elements, added isolation or dampening features

[1] *Bay Area Toll Authority (2013)*

[2] *California Department of Transportation (2014)*

[3] *Golden Gate Bridge Highway & Transportation District (2013)*

FIGURE 7:
Liquefaction Susceptibility Along Major Bay Area Highways and Two Corridor Studies



1. The US 101 and I-280 corridor between their San Francisco interchange and the Hwy 85 interchange is exposed to multiple hazards in a M7.9 San Andreas scenario. Over this stretch of I-280 there are 86 bridges, over half of which experience MMI 9 severe shaking. Along this same stretch, over half of the length of US 101 is in a very high liquefaction zone. All bridges along this portion of US 101 experience MMI 8 or 9 as well. Each of these highways have portions that carry over 250,000 daily passengers, with most of US 101 carrying 200,000 daily passengers, and I-280 carrying between 100,000 and 150,000 passengers over this section. In a future San Andreas earthquake, this parallel section of roadway will experience multiple hazards across parallel links.

2. The I-880 and I-580 corridor between the 980 and 238 interchange is exposed to multiple hazards in a M7.0 Hayward scenario. Over this stretch of I-580 there are 44 bridges, all of which will experience MMI 8, very strong shaking. In addition to strong ground shaking, along this stretch of I-580, the road crosses the Hayward fault three times. Along this same stretch, I-880 crosses over many sections of very high liquefaction susceptibility, with all bridges along this portion of the freeway also experiencing MMI 8, very strong shaking. Each of these highways average between 175,000 and 200,000 average daily passengers. In a future Hayward earthquake, the parallel section of roadway will experience multiple hazards across parallel links.

event has the added dimension of fault rupture and landslides along Hwy 17 and fault rupture across US 101 just south of the Santa Clara County border.

The North Bay will also be impacted by these two events. In a Hayward event, strong shaking is limited to the roadways that hug the north shore of the San Francisco Bay, San Pablo Bay, and Carquinez Strait. If the Hayward and Rodgers Creek faults rupture at once, severe shaking would extend north along the same path as the Hayward fault with MMI 8 shaking as far north as Santa Rosa. The Rodgers Creek fault runs parallel just east of US 101 in Sonoma County. Considering just a Hayward event, Highway 37 which runs east-west connecting I-80 and US 101 is likely to be exposed to liquefaction.

The rail systems are also vulnerable. Unlike roadways which generally have some parallel local roads that provide some trip diversion capacity, the passenger rail lines are series systems and a single failure of the track could interrupt an entire system. BART expects the majority of their system to be operational very soon after a large earthquake. Figure 6 shows their expected system restoration after a M7.0 Hayward event both before and after their mostly completed seismic retrofit program, which began in 2002 (BART 2002a). The other rail systems are primarily at grade lines that should be quickly repairable. Altamont Commuter Express, Amtrak, and Caltrain all have at-grade platforms, and for the most part have fewer bridges than most of the highways. In a Concord event, the rail bridge that crosses parallel to the Benicia – Martinez Bridge is only two miles from the Concord fault. In a Concord event, the shaking and/or liquefaction could cause significant or complete damage to the rail bridge.

Over the past twenty-five years since Loma Prieta, the region has seismically retrofit all bridges that cross the Bay (see Table 1). The Bay Area Toll Authority (BATA) with Caltrans have had joint oversight over all bay crossings except for the Golden Gate Bridge. In 2013, BATA and Caltrans completed all planned seismic retrofits of bay crossings, including the replacement of the eastern span of the Bay Bridge.

> *"Each retrofit is designed to a level that, at a minimum, will ensure that the bridge will remain standing in an earthquake. The California Legislature has designated the San Francisco-Oakland Bay Bridge and Benicia-Martinez Bridge as "lifeline structures" since they are located along*

Slope failure on Route 160 in Lota, Chile following the M8.8 2010 Maule, Chile earthquake.

transportation corridors determined to be crucial to both emergency relief and economic revitalization of the region following a major earthquake. Based on this distinction, the retrofit strategies for these two bridges incorporate some design elements that exceed standard seismic bridge design," (BATA, 2013).

In addition to the major retrofits that have occurred, Caltrans has learned from the Loma Prieta event and successfully executed emergency contracts in the Northridge earthquake (Yashinsky, 1998) and the MacArthur Maze Fire, reducing the repair time of major highway bridges.

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CHAPTER 5

Fuel System

KEY FINDINGS

- Fuel refineries are likely to have correlated performance, if one is damaged it's likely others are damaged too. A conservative restoration estimate of damaged refineries is months.
- Damage to the fuel transmission system would severely impact counties beyond Solano and Contra Costa where most refineries are located. Transporting the normal fuel demand by truck after a disaster simply is not feasible.
- Damage to pipes that cross the Bay, or an inability to pump fuel east would cause fuel supply interruptions across Northern California and Nevada.

There are four stages of the fuel system that could be impacted in a Bay Area earthquake: (1) crude oil import, (2) refinement, (3) fuel transmission export, and (4) fuel distribution. Crude oil is imported by pipeline from the east, rail from the north, and marine tankers from the west. 38% of crude oil is extracted in California, mainly in Kern County, with the remainder coming from Alaska and foreign sources (WSPA, 2013). In a few years, the crude oil profile is expected to change with a significant percentage of the fuel projected to be imported via rail from Canada and North Dakota.

The San Francisco Bay Area has five refineries which, combined, processed 235 million barrels of crude oil in 2012, a 40% share of the states total. As a state California utilizes only 87% of its total 682 million barrel capacity, meaning refineries could produce 13% more product if their was a need. The five Bay Area refineries are located along the San Pablo Bay and the Carquinez Strait. Figure 8 (page 26) shows both the location of the five refineries and their refining capacity. Once refined, the variety of fuel products are pumped and piped across the state to terminal facilities that serve all of northern California and northern Nevada. In addition to refining all of the fuel it uses, California refines 90% of Nevada's fuel and 50% of Arizona's. The refineries in the Bay Area supply 100% of the region's fuel, northern California's fuel, northern Nevada's fuel, and a portion of the central counties fuel (which is also supplied by Kern County refineries). Figure 8 outlines the state's fuel production and use, and maps the large terminals to which the region directly exports fuel. Once the product reaches terminal facilities, fuel tanker trucks distribute fuel locally using the road network. Disruption to a single phase of fuel delivery could limit fuel supply in the Bay Area; and the other regions reliant on the Bay Area fuel system.

Airport Reliance

Airports are reliant on a number of different refined fuel products. Fuel is used for ground operations, backup electrical generation, and for aircraft flights. The three international airports have jet fuel for aircraft piped directly

TABLE 2: Estimated Daily Fuel Consumption for Commercial Passenger Flights (2007)

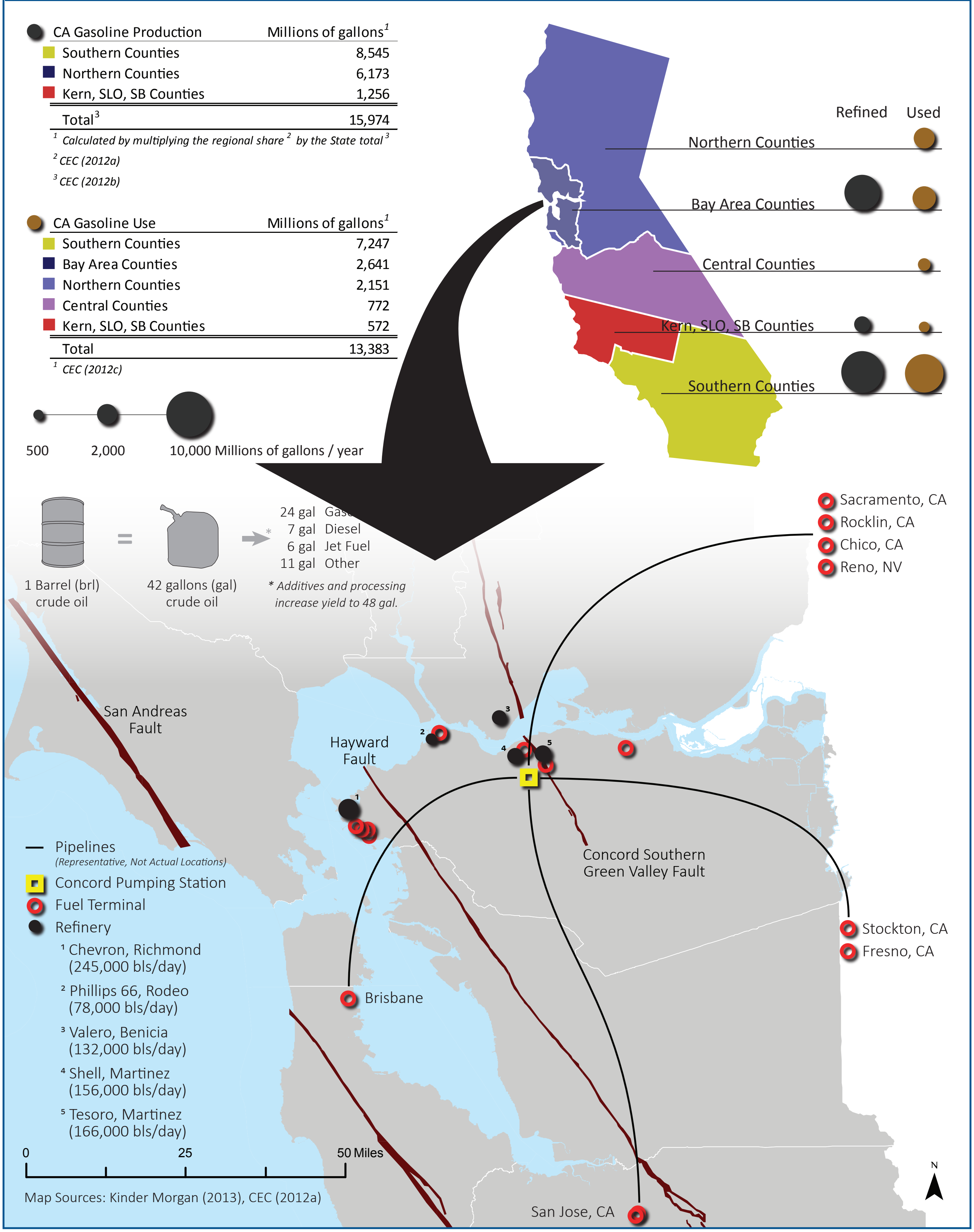
Airport	Total Daily Takeoffs	% of Takeoffs Passenger[1]	Estimated Psgr. Fuel Consumption (gal)[2]
SFO	1,022	62%	2,100,000
OAK	924	46%	1,000,000
SJC	547	48%	650,000

[1] *Not including regional jets and turbo propeller passenger trips.*

[2] *Using airplane breakdown & fuel economy, and domestic destinations.*

Data Sources: RAPC (2011).

FIGURE 8:
California Fuel Production and Use, and the Bay Area's Fuel Profile



to their facility, as does Travis AFB. All other airports in the region rely on tankers to truck fuel to the site. All of the facilities are reliant on tanker trucks to supply reformulated and diesel fuel for their ground operations. The five Bay Area refineries supply jet fuel for Bay Area airports as well as airports across the northern half of California and Nevada. Outside the region, Mather, Lemoore NAS, and NAS Fallon all have fuel pipelines to their facilities.

An exact volume of jet fuel consumed by each airport was not publically available. Using a proxy between the total flight takeoffs by aircraft type, the percent breakdown of domestic destination locations, and the fuel economy of common aircraft type, Table 2 (page 25) estimates the amount of jet fuel used daily for domestic passenger flights only. In the event jet fuel is unavailable at Bay Area airports dispatchers and load planners can schedule arriving aircraft to carry round-trip fuel loads precluding the necessity to fuel at the stricken airport. If round-trip fuel cannot be scheduled, the flight can make an intermediate fuel stop at airports outside the fuel supply region. The closest airports independent of the Bay Area refinery and fuel system is Southern California.

In addition to jet fuel, the ground vehicle fleets at the airports are also reliant on reformulated gasoline. It should be noted that as a result of climate action plan adoption by airports, some are transistioning their ground fleets to be powered by alternative energy sources. As this transition is made, the reliance will shift from reformulated fuel to electricity or another source. These changes should be reflected in updated airport emergency plans. Lastly, as is discussed in Chapter 4, the median passenger trip to get from home/office to a Bay Area airports is over 25 miles for each SFO, OAK, SJC, resulting in over two gallons of fuel used for each passenger round trip to the airport. For the passenger air travel to function, passengers will on average need two gallons of fuel to get to and from the airport as well as the jet fuel for their flight.

System Vulnerability

Fuel networks are generally comprised of source facilities, pipelines, pumping stations, refineries, terminal facilities, and distribution facilities. The facilities are often above-ground and vulnerable to the same forces as any other structure. Shaking, ground failure, and fault rupture could all cause significant damage to an above-ground facility. These facilities often have intricate routing of pipes and equipment that must be designed and anchored properly.

> *"For above-ground components of pipeline systems, such as buildings and storage tanks, inertial forces resulting from ground shaking are a major concern," (FEMA, 1992).*

Pipelines are often buried underground for safety from non-earthquake hazards. In earthquakes the shaking intensity rarely damages pipelines; ground failure and fault rupture are the primary concern for underground pipelines.

> *"For buried pipelines, inertial forces are of little concern, but faulting, landslides, and liquefaction pose major problems (Hall, 1987)…. Large permanent ground movements caused by surface faulting, soil liquefaction, and landslides are the most troublesome sources of earthquake*

SIDEBAR 4:
Restoration Following the Richmond, CA Refinery Fire

On August 6th, 2012, a five foot section of pipe in the Richmond Chevron Refinery failed causing a hydrocarbon leak and fire. Investigation into the accident identified corrosive thinning as the cause of pipe failure (Chevron, 2013). The refinery processes over 240,000 barrels of crude oil a day producing 150,000 barrels of gasoline, representing 16% of the West Coast's 963,000 barrel daily use (CBS, 2012).

For eight months following the fire the Richmond facility operated at 60% capacity. As described at the start of the chapter the state only utilizes 87% of the maximum refinement capacity. It is likely that this failure was absorbed by the additional overall capacity, limiting the impact on the region. The facility did not process crude oil during this time and instead converted its operations to blend gasoline. (CBS, 2013b) *damage to gas and liquid fuel pipelines (O'Rourke, 1987, EERI, 1986, Guan-Qing, 1980, Anderson, 1985, O'Rourke and Trautmann, 1981)," (FEMA, 1992).*

In the Bay Area, there are five refineries, and one primary pumping station; study of these nodes must include assessment of the full suite of regional hazards (shaking, ground failure, and fault rupture). For pipelines, ground failure and fault rupture cause the most damage at system links. If pipeline attributes were known (material, age, eccentricities, weld type) other research reports (e.g. Palmer, 1994, FEMA 1992) could be used to further narrow where failures are more likely. Currently this information is either unknown or publicly unavailable.

Interdependency: Reliable water and electric systems are needed for fuel refinement.

The majority of academic study has focused on pipelines with limited study on refineries. Past events show potential for refinery damage resulting in long restorations. In the 1999 Kocaeli, Turkey and 2010 Maule, Chile earthquakes, refineries were in areas of very strong earthquake shaking. In both cases, damage caused by the earthquake resulted in refinery closures for three months. The refinery in Turkey was not processing its pre-event amount of fuel for 13 months after the earthquake (Johnson G., 2002). In Chile, when the refinery was brought back online after three months, it operated at 34% capacity. These restoration timelines are similar to that of the Richmond refinery following the August 6th, 2012 fire. Sidebar 4 details the recent fire.

Damage to the Izmit Refinery in the 1999 Kocaeli, Turkey earthquake. The lower part of a collapsed stack destroyed pipes and structures beneath and resulted in a fire.

©Gayle Johnson

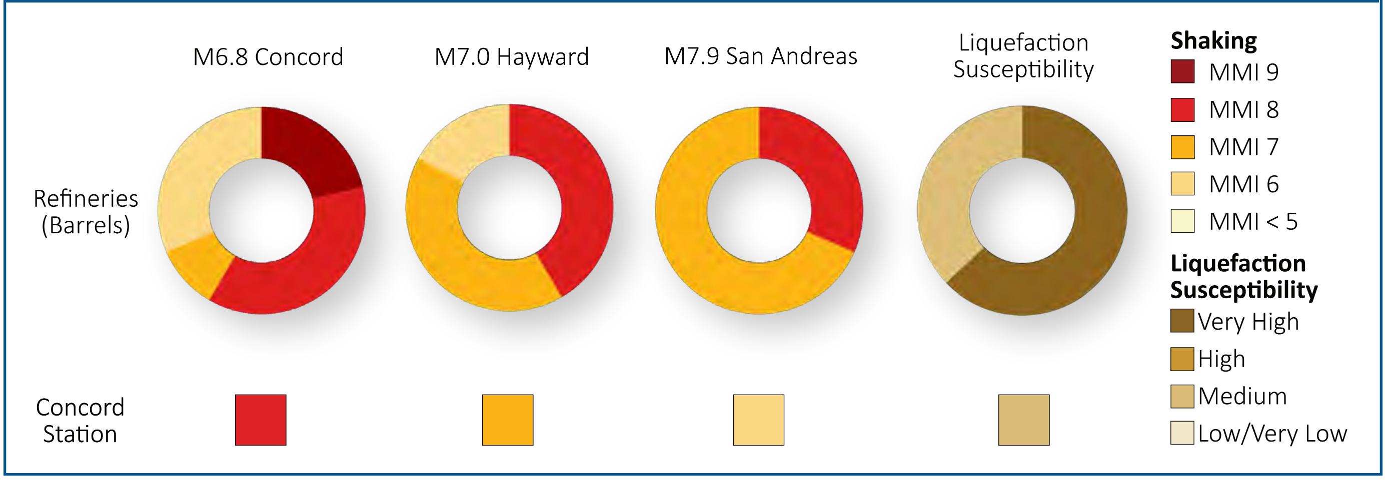
In addition to damage to the sites, fuel refineries are very reliant on other lifeline systems. Refineries require both reliable electricity and water to operate. A regional power outage in Santa Maria in June 2013, shut down a Phillips 66 refinery, requiring several days to restart operations.

BAY AREA VULNERABILITY ASSESSMENT

Fuel production and distribution in the Bay Area is likely to be severely disrupted in a San Andreas, Hayward, or Concord event with cascading consequences across the northern half of the state and into Nevada. Figure 9 (page 29) illustrates the exposure of fuel refinement and pumping to ground shaking in the three scenarios and the liquefaction susceptibility. In each studied fault scenario, a number of similar impacts could occur and will be discussed generally by stage.

(1) Crude Oil Import -- Crude oil imports occur over multiple modes with future supply over rail expected to drastically increase. Crude pipelines can be damaged by liquefaction in all events and could be disrupted by fault rupture in both Hayward and Concord events. Marine ports currently make up the largest share of crude oil import by mode. The ports attached to each refinery could be impacted by liquefaction as is common in many ports in earthquakes. All of the ports associated with the refineries are in very high liquefaction zones. Additionally, slumping of dredged channels would require the U.S. Coast Guard to complete an assessment of the shipping channels before ships could navigate. In an earthquake underwater slopes (i.e. the sides of dredged channels) can shift into the channel, possibly interrupting the channel. If indeed the shipping channels were obstructed by

FIGURE 9:
Regional Fuel Assets Exposed in Scenario Earthquake Shaking and Liquefaction Zones



slumped soil the channels would require dredging, or large fuel tankers would have to transfer their fuel to barges for delivery in shallower channels.

(2) Refinement -- Each event will cause significant shaking at all five refineries. These facilities are assumed to be extremely sensitive as seen in the 2013 Richmond refinery fire, when a single pipe failure led to a much more damaging fire. If damage occurs restoration could require months or years. In addition to shaking hazard most refineries are located in liquefaction zones, with the Richmond Chevron refinery especially susceptible.

A major issue unique to the Bay Area is that the performance of refineries in earthquakes is likely highly correlated. The refineries are:

- close to one another;
- built on similar soils; and,
- constructed with similar standards and equipment.

If there is damage to one refinery in an earthquake, it is likely other refineries are also damaged, interrupting a large percentage of the fuel refinement capacity in the Bay Area.

(3) Refined Fuel Export -- All of the refineries export their product to terminal facilities on Kinder Morgan's pipelines. Kinder Morgan's lines converge at a pumping station in Concord. This facility pumps fuel across the northern half of the state (see Figure 8, page 26). The Richmond Chevron refinery also has separate refined fuel pipelines that service Brisbane and San Jose; however, these pipelines represent a small share of the regional fuel. In all studied scenario events, liquefaction is a concern, as is typically the case with pipelines. In the Hayward and Concord scenarios, fault rupture becomes a serious concern. Fault rupture is expected along the northern portion of the Hayward fault, but it is unknown if the Concord fault will exhibit surface fault rupture. Fault rupture in a Concord scenario would interact with many fuel pipelines as well as the Concord station. Damage to the Concord station would interrupt fuel transmission across the northern half of the state.

(4) Fuel Distribution -- It is very unlikely that terminals outside of the region will have damage to their facility in a Bay Area earthquake. In San Andreas and Hayward events terminals in Richmond, Martinez, Brisbane, and San Jose will experience very strong shaking. In addition to terminal operation, roadways must be passable for tanker trucks, and service stations must be undamaged and have electricity to pump fuel.

Interdependency: Passable roadways and bridges that can handle tanker truck loads are needed for fuel distribution to service stations.

(5) Fuel Quality -- In addition to the movement of fuel, the quality of the fuel requires special consideration in California.

"With regard to fuel supply issues following a catastrophic event, re-supply of gasoline and diesel fuel that meets California reformulated gasoline (CARFG) standards from outside the state in meaningful quantities is extremely unlikely. As such, it is prudent to explore other avenues to obtain adequate supplies of gasoline and diesel fuel to make up for a reduction from California refineries and the pipeline distribution network they feed in the aftermath of a large earthquake.

Fuel waivers are one means to enable fuel to be trucked and railed into California rather quickly. Since California has its own fuel regulations, waivers would have to involve both the US EPA (for federal reformulated gasoline regulations) and the California Air Resources Board (CARB) for their California-specific gasoline regulation." (G. Schremp, personal communication, August, 13, 2013).

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CHAPTER 6
Electric System

KEY FINDINGS

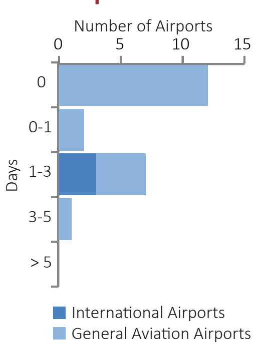
- Damage to the region's power generation facilities along the Carquinez Strait, or interruption in the natural gas system could result in long power supply interruptions.
- In the immediate aftermath, most critical facilities (including airports) plan to use fuel-powered generators to restore electric services. The interruption of fuel could limit this backup capacity and delay immediate restoration of service.

Electric power delivery is largely comprised of a four phase process: generation, transmission, substation transformation (high voltage to lower voltage), and distribution. In 2011, the Bay Area consumed 55,000 gigawatt hours of electricity, 60% of which was generated inside the nine county region (CEC, 2013a; CEC, 2013b). The remaining demand was met by power imports generated elsewhere in the state, the Pacific Northwest, and Southwest. 98% of the regionally produced power is generated at 25 large facilities with the remaining 2% generated at 44 small facilities with less than 50 megawatt capacity. The 25 larger facilities are mapped in Figure 10 (page 33) and are operated by 15 different companies.

Most of the Bay Area power is transmitted on 500, 230, 115, and 60 kilovolt above-ground transmission lines by Pacific Gas & Electric (PG&E). A handful of local jurisdictions operate their distribution system, but most are reliant in some way on PG&E to supply them with power. The high voltage transmission lines distribute electricity from regional and outside generation facilities to substations. Some substations are simply nodes along a stretch of transmission lines, while others drop the high voltage transmission lines to lower voltage distribution lines. From the substations, distribution lines route power at a lower voltage to the end user. While these lines are rarely mapped at the regional level, they can be assumed to be along all local streets.

Electrical performance is often measured by the number of customers with service. Because electricity is vital for organizations and other infrastructure systems, consequence can also be measured by the number of key facilities impacted (hospitals, pumping stations, airports, etc.). In past earthquakes, the electric grid has been sensitive to initial disruptions, but it is often the first restored system. Loss of power can be caused when there is damage to a number of generation facilities, transmission lines, substations, or distribution lines. Protective measures to shut down non-damaged components to prevent cascading electrical failures or fires are also responsible for outages.

Days of Stored Fuel for Backup Electrical Generation at Bay Area Airports



AIRPORT RELIANCE & CAPACITY

In the 2013 Airport Emergency Plan Survey, 50% of Bay Area Airports reported having no backup electric generator (Caltrans Aeronautics, 2014). Airports with generators have a wide range of operations they intend to power in the case of an outage. The general aviation airports with generators primarily planned to use backup generators for the air traffic control tower, runway lights, navigation instruments, as well as their fuel pumps. If, due to lack of electricity, the tower is not in operation, the airport may still function as a non-towered airport. If navigational aids do not function, the airport may still operate in visual flight rules. Without

Interdependency: Backup electrical generation and fuel.

runway lights the airport may function during daylight hours. At the three international airports, backup generators are intended to run all of the above listed systems as well as offices, and in the case of SFO and SJC, the airport terminal.

The generators at all airports rely on fuel. The amount of fuel stored at the airports ranged from 0.5 days to 4.7 days supply (Caltrans, 2014). The graph on page 31 shows the distribution of stored fuel for electrical generation at the Bay Area airports.

SYSTEM VULNERABILITY

Failures to electric generation facilities are possible, but have not occurred in past earthquakes. There have been few published studies of power generation vulnerability, as there is such a wide variety of generation facilities (natural gas, nuclear, hydro, wind, geothermal, solar, etc.). Most research has focused on the risk of nuclear events similar to Fukushima in 2011. This research is focused on the secondary radiation hazard, rather than the ability of facilities to generate electricity.

Transmission lines are often not impacted by earthquakes:

> *"[The] low vulnerability of towers is probably related to the fact that the wind forces on the tower and the supported wires, which transmission towers are designed to resist exceed the forces generated by earthquakes. Thus failures that do occur are mostly related to foundation instability," (FEMA, 1990).*

The few examples of transmission line failures have occurred in areas of severe ground failure. Transmission line damage was reported in the 1923 Kanto, Japan and 1964 Alaska, and 1999 Chi-Chi, Taiwan earthquakes. The damage was due to landslides and soil liquefaction. Transmission lines near ground failure areas were undamaged (FEMA, 1990).

Under seismic loadings, substations have historically been the most vulnerable component of electrical networks. Substation damage also often results in longer repair or replacement times compared with other system components. Damage at substations can be caused by fragile porcelain components failing, large heavy transformers shaken off their footings, or by the interaction of components caused by shaking (FEMA, 1990). Porcelain components are often rapidly repaired and can be obtained quickly; while breakers and transformers on the other hand, can require six to twelve months to replace. Utilities do stockpile some resources to replace damaged components, but system components are expensive; transformers range from $1-5 million.

Distribution lines are more vulnerable to damage than transmission lines because they are generally not as highly engineered as transmission

SIDEBAR 5:
2013 Rim Fire Impact on Electrical Generation

On August 17th, 2013 a fire began in the Stanislaus National Forest, 150 miles east of San Francisco. The fire grew rapidly from 16,204 acres on August 21st to 201,795 acres on August 30th. In total, the fire burned 257,314 acres surrounding San Francisco's water and power facilities. The fire was not considered contained until October 24th (SFPUC, 2014).

There were initial fears that the fire and future runoff would contaminate the Hetch Hetchy watershed. Because the fire was largely outside of the Hetch Hetchy watershed there were no serious water quality issues; however, the power system was impacted. Two of the three hydroelectric powerhouses were taken offline on August 19th, because the facilities as well as the transmission lines were threatened by the fire. The rooftop of the Holm powerhouse caught fire and sensitive equipment inside the building suffered smoke damage. During the disruption in generation, San Francisco purchased energy on the open energy market, amounting to $860,000 (2013 dollars). During the event, there was enough capacity on the open market to meet the demand.

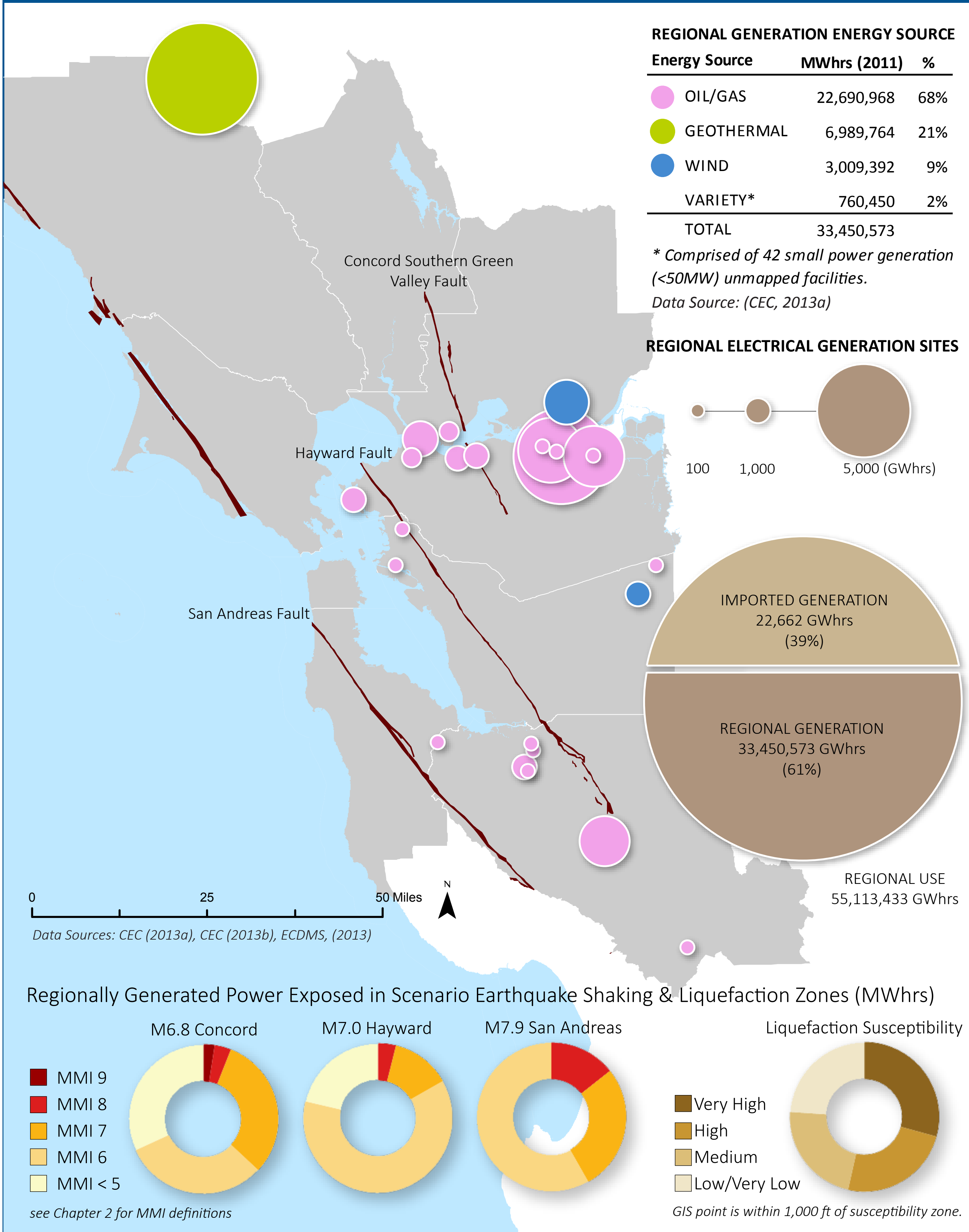
RIM FIRE IMPACT ON SFPUC GENERATION FACILITIES

Facility	MW[1]	2012 MWh[1]	Days Offline[2]
Holm	165	410,430	28
Kirkwood	118	395,840	15
Moccasin	100	314,642	0

[1] *CEC (2013a)*

[2] *SFPUC (2014)*

FIGURE 10:
Electric Generation for the Nine County Bay Area Region and Exposure to Seismic Hazard



REGIONAL GENERATION ENERGY SOURCE

Energy Source	MWhrs (2011)	%
OIL/GAS	22,690,968	68%
GEOTHERMAL	6,989,764	21%
WIND	3,009,392	9%
VARIETY*	760,450	2%
TOTAL	33,450,573	

** Comprised of 42 small power generation (<50MW) unmapped facilities.*

Data Source: (CEC, 2013a)

Data Sources: CEC (2013a), CEC (2013b), ECDMS, (2013)

see Chapter 2 for MMI definitions

GIS point is within 1,000 ft of susceptibility zone.

Interdependency: Electrical generation and natural gas.

systems. In addition to failures caused by ground failures, such as liquefaction or landslides, lines can be damaged by collapsed or partially collapsed nearby structures landing on the lines (FEMA, 1990). There are likely to be extensive failures to distribution networks, but components of these systems are readily available, and individual failures impact smaller subsets of a community.

BAY AREA VULNERABILITY ASSESSMENT

Based on past earthquake damage and technical report documentation, only the energy generation and substations are likely to cause disruptions for a significant amount of time. Two areas of concern are underground transmission lines in San Francisco and Oakland that cross over very high liquefaction susceptibility zones. Unlike above ground transmission towers, below-ground lines are likely to require longer restoration times. Plans are in place to restore these lines with temporary above ground lines while underground lines are repaired.

Distribution line damage is likely due to ground failure as well as collocation with damaged/collapsed structures, and cascading damage caused by fire, gas leaks, and water leaks. Distribution line failures may require longer times to repair due to the number of potential failures, but will impact smaller portions of the population and will be most prevalent in areas with other barriers to recovery (building damage, major damage to other lifeline systems). Power generation and substations are explored in greater detail below.

Generation -- Damage to a percentage of electrical generation facilities could limit the quantity of power available to the region. This analysis examines the facilities within the region that produce 60% of the region's energy use. While disruption in the other 40% would be significant, the sources of those facilities are very geographically dispersed and are independent from most Bay Area earthquake events. Events similar to the 2013 Rim Fire (Sidebar 5, page 32) can impact external generation sources but are outside the scope of this study.

Of the regionally-generated power, two-thirds is produced by natural gas facilities, which are mostly located along the Carquinez Strait (see Figure 10, page 33), an area that is bisected by the Concord fault. Geothermal and wind generation represent the remaining third. The geothermal facilities are clustered in northern Sonoma County and cross into Lake County. Wind generation sites are located in southeastern Solano County and the Altamont Pass between Contra Costa and Alameda Counties.

Power plants are fairly well distributed around the region. The cluster of power plants in the Pittsburgh and Antioch area have the largest single contribution of any one area in the Bay Area. In the event natural gas lines are damaged, these facilities will be unable to generate electricity. Interim solutions could be adopted to provide power on an intermittent level if the lost generation cannot be made up by outside or peak generation facilities.

Substations -- There are over 425 substations in the Bay Area with varying degrees of age. Within the bounds of this study and given that only publicly available information was used, no analysis was completed on Bay Area substations. Past events highlight substations as the most vulnerable component of the electrical system. Priority customers, which include airports, can contact PG&E directly to inquire about system reliability. Airports and other key institutional facilities can use the protocol outlined in Appendix A to contact PG&E's priority customer department.

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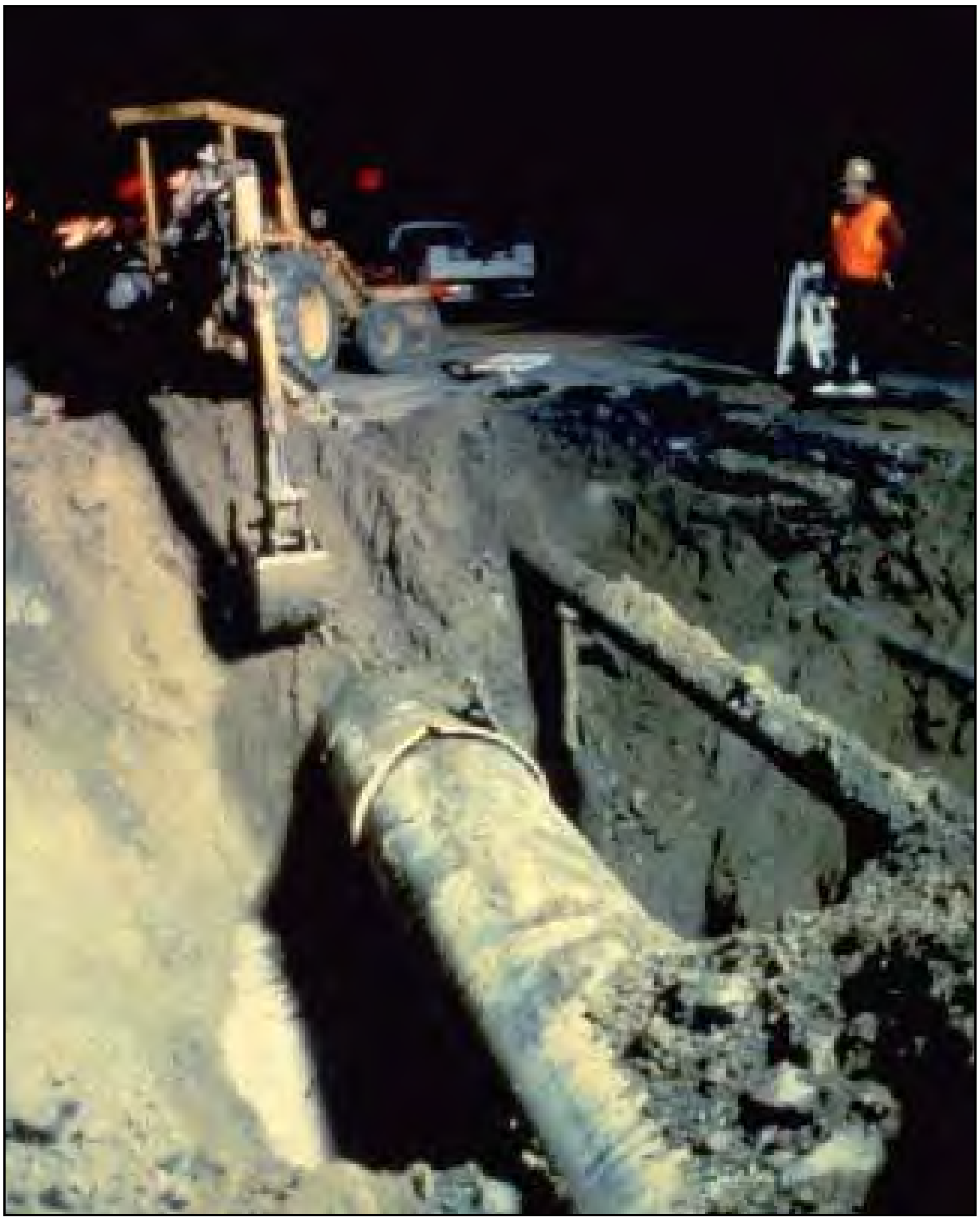


This 48-inch water line under Balboa Boulevard in Granada Hills, suffered compression failure caused by ground deformation in the 1994 Northridge earthquake.

CHAPTER 7

Water System

KEY FINDINGS

- Most of the 11 Bay Area water districts studied have multiple water sources or have invested in robust, redundant, and repairable systems that contribute to system resilience. When reservoirs and groundwater reserves are above half full there is significant regional water storage to tap if regional systems require repair.
- Restoration of distribution systems in areas of liquefaction can require weeks to months. The regions three international airports, and a number of general aviation airports located on the bay margins, are in liquefaction susceptibility zones.
- Agencies dependent on Delta water would be significantly impacted if levees failed, causing flooding and salt water intrusion.

The Bay Area's water supply is distributed by 89 different water providers (districts, agencies, and cities). Eleven providers distribute water to 93.7% of the Bay Area's population; Table 3 breaks down the served population and water demand for the 11 studied districts (Note: Bay Area Water Supply & Conversation Agency (BAWSCA) represents 24 water districts that purchase water from SFPUC). These 11 districts distribute water locally, while some also operate or coordinate intra-regional or inter-regional transmission water supply systems.

TABLE 3: Current & Projected Population Served & Water Demand

	2010		2035	
Water Agency	**Population**	**ac-ft/day**	**Population**	**ac-ft/day**
MMWD	191,000	53	207,000	55
Sonoma CWA[1]	411,000	143	528,000	224
City of Napa	87,000	37	94,000	40
Solano CWA	280,000	535	350,000	614 [2]
CCWD	495,000	445	635,000	611
EBMUD	1,340,000	663	1,750,000	703
Zone 7	220,000	181	291,000	209 [2]
ACWD	340,000	130	411,000	159
SCVWD	1,782,000	912	2,431,000	1,159
BAWSCA	1,719,000	307	2,097,000	439
SFPUC	856,000	219	955,000	226
Total	7,721,000	3,626	9,749,000	4,438
BAWSCA Overlap	842,400			
Total 11 Agencies	6,879,500			
Total (Bay Area)	7,342,000			

[1] *Wholesale agency. Populations based on cities that purchase from Sonoma CWA.*

[2] *Estimate based on 2030 projection*

Data Source (IRWMP, 2013) (2010 Urban Water Management Plans)

Airport Reliance

As an operational facility supporting staff and customers, airports require water for hydration and sanitation services. The take off and landings of airplanes is not impacted by water interruption.

System Vulnerability

As with most other buried infrastructure, liquefaction is the hazard that causes the greatest percentage of pipeline failures. Water systems consist of a range of pipe diameters and materials, all of which are vulnerable to damage due to liquefaction and subsequent ground displacements. The systems are also reliant on a number of above ground components: water treatment facilities, pumping stations, and water storage (tanks and reservoirs). These components of a water system can be damaged by shaking and liquefaction and may take many weeks to restore. Sidebar 6 (page 37) explores the restoration of water systems following earthquakes that resulted in thousands of pipeline failures and the near failure of an above ground intake pumping facility.

All of the major water districts rely on reservoirs to collect local watershed runoff and store imported water. A number of reservoirs were created using earthen dams, often constructed on top of liquefiable soils and were themselves unstable under seismic loads. Large dams have failed in past earthquakes as recently as the 2011 Tohoku Japan earthquake when the Fujinuma dam failed, killing at least four people. In California, the 1971 San Fernando earthquake left only a thin dirt wall between 15 million tons of water and 80,000 people in the San Fernando Valley of southern California (USGS, 2012). The near catastrophe in the M6.7 San Fernando earthquake resulted in many dam retrofits and reconstructions across the state to address their seismic vulnerability. The remaining dams with high seismic risk often have their storage capacity significantly reduced, which can be a difficulty in drought years when storage is at a premium. Eight of the region's 39 largest dams have had their capacities restricted until they are studied further or improved. The Calaveras dam, the largest on the restricted list, is in the process of being replaced by a new dam that will be completed by 2018. In addition to water supply concerns, water quality could also be impacted.

Precautionary measures are often taken after large earthquakes to boil water due to potential contamination with damaged wastewater pipes. Service interruption or contamination can occur at the source (reservoir/watershed, ground aquifer, desalination plant), transmission system (pipelines, aqueducts), or distribution system. The collocation of water and wastewater pipelines can present contamination issues, as can the ability of users to treat water on their own if there are also interruptions in energy supply systems necessary to boil water.

Lastly, beyond using water in homes and businesses, water is needed to limit damage caused by fire following earthquake. Gas, fuel, and electrical breaks can result in multiple fires that can cause greater damage than the earthquake itself. Some jurisdictions have invested in completely separate

SIDEBAR 6:
Water System Failures in Urban Earthquakes

Kobe, Japan (1995)

The M6.9 earthquake resulted in severe shaking and liquefaction in the urban area of Kobe. The extensive ground failures resulted in 134,000 service pipe fractures, and 3,600 distribution main breaks. Nearly all of the breaks were to old, more brittle pipes (which also exist in the Bay Area); new higher performing pipelines performed well with minimal failures even in areas of large permanent ground deformation. Forty days after the disaster 10% of the population was without water, and complete restoration of water service required 82 days (Kameda, 2000).

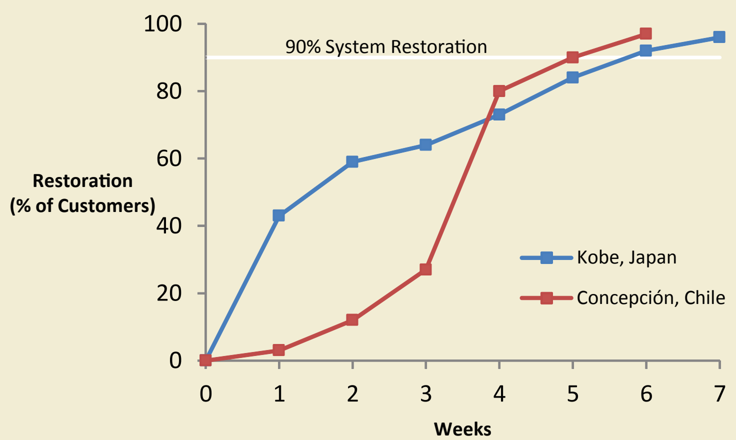
Concepción, Chile (2010)

The M8.8 earthquake off the coast of Chile resulted in widespread water outages for the 300,000+ residents of Concepción. Initial pipeline repair work was hindered by interruptions in fuel, as well as civil disturbances. After a delayed start to pipeline repairs the restoration was rapid. While the repairs to pipes were delayed at the start, the water utility rushed to reinforce and protect their water intake facility. The facility, an old concrete building, was severely damaged by the shaking. The only water intake pumps for the region were housed inside the building, which had portions of walls collapse in the main event. Had the pumps been damaged it would have taken months to replace them. Impromptu steel cages protected the pumps from potential damage in aftershocks. (ESSBIO, 2010).

Interdependency: Service providers need fuel to run their equipment and mutual aid equipment, over 24 hr shifts.

Intake pumps protected by impromptu frame structures.

WATER SYSTEM RESTORATION IN KOBE & CONCEPCIÓN



Interdependency: Potable water contamination by collocation with wastewater and reliance on energy source to boil drinking water.

water systems to supply water to fight fires after an earthquake.

- City & County of San Francisco -- Auxilary Water Supply System
- City of Berkeley -- Berkeley Aboveground Water Supply System

Ensuring water to combat fires is critical to prevent even more damage propagation caused by fires following earthquake shaking.

BAY AREA VULNERABILITY ASSESSMENT

This study focuses on the reliability of the region's water transmission systems and the capability of the local water storage to meet water needs if sources are interrupted. One way to think about the system is to treat the reservoirs as a fuse between the regional system and distribution system. Should a failure occur on the regional system the reservoir has storage to supply the distribution system, islanding the risk between the regional transmission systems and distribution systems.

The Bay Area's water supply comes from a portfolio of sources. Figure 11 (page 39) illustrates the source of water for 11 of the largest districts. The Mokelumne and Hetch Hetchy systems supply the Bay Area exclusively, while both the Central Valley Project and State Water Project supply water to regions across California. Local supply is primarily surface water and ground water but also includes small shares of recycled water and desalination. Interruption to any of these five primary water supply systems could have severe impacts to certain water districts. CCWD, EBMUD, Zone 7, BAWSCA, and SFPUC all rely heavily on a single source of imported water. SCVWD, on the other hand, has four main sources of water increasing the odds that at least a portion of their supply will remain intact in a single event. For all districts reliant on imported water supplies if interruption of their source(s) were to occur, local sources and storage would be relied on until repairs were made to restore the transmission supply.

Over 200 reservoirs store water in the Bay Area all with varying owners and operation goals. The 11 main water districts rely on 39 larger local reservoirs with a maximum storage capacity of 3 million acre-feet. More than half of the region's reservoir capacity is behind Monticello Dam in Lake Berryessa. In addition to surface storage; SCVWD, ACWD, and Zone 7 rely on local ground water for a large percentage of their storage and emergency supply. Some agencies have years of supply stored behind reservoirs even when reservoirs are only half full, while others have only a few weeks of normal demand stored. Those with only a few weeks of reservoir storage do also have groundwater aquifers which should increase the length of time they can supply water in an emergency. Figure 12 (page 40) shows the relationship between a district's average weekly water use and how much water is available when reservoirs are at 50% their total storage capacity. It also includes the addition of local groundwater reserves for the four districts with large aquifers.

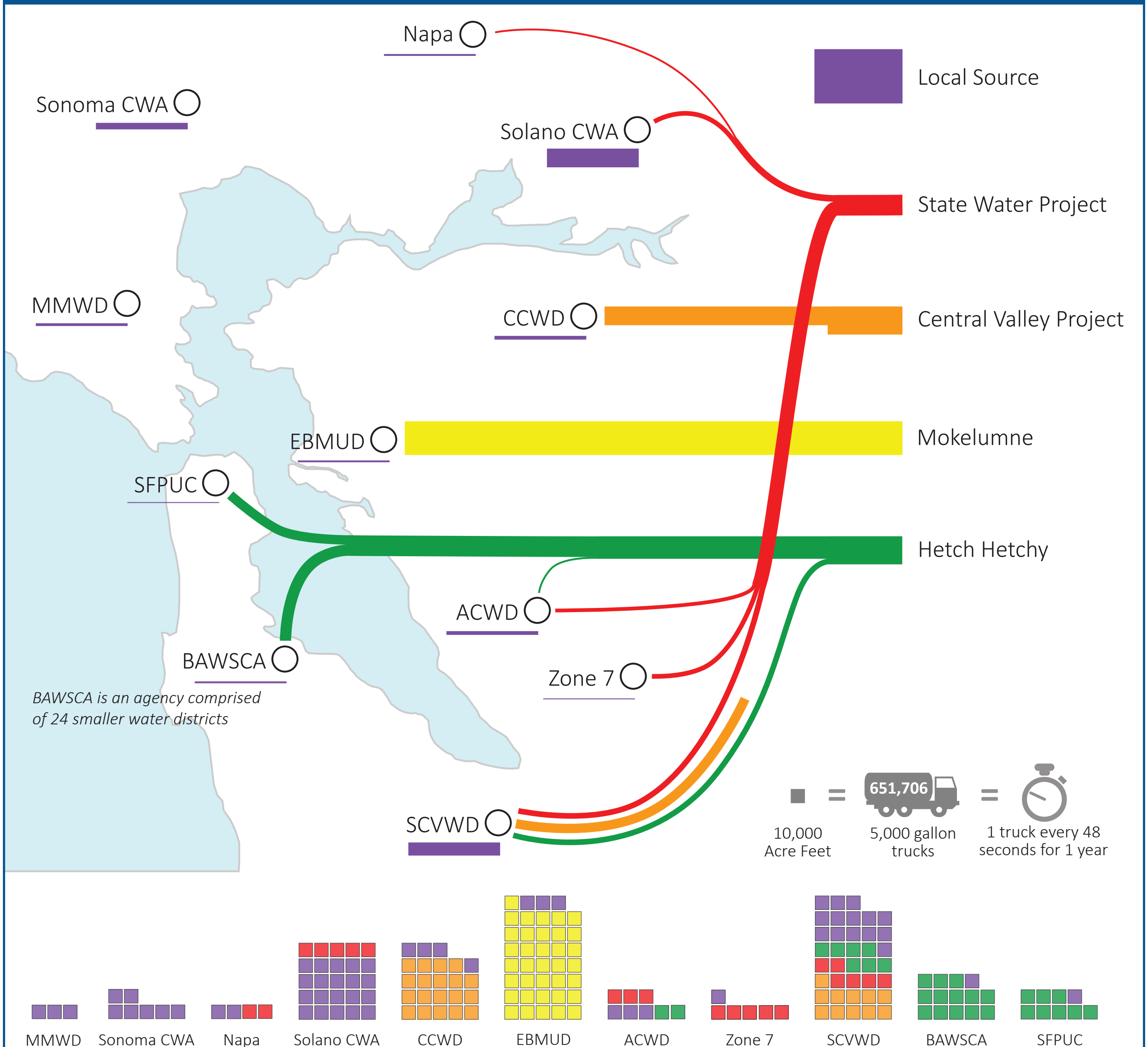
To increase redundancy, many agencies have constructed interties, or links, between systems. An interties table in Figure 12 lists the known interties between systems and each interties sharing capacity. In the event that one system has lost its sources while others are unaffected, the interties can be used to share water during the interruption. The capacity of these interties supplies a fraction of the providers normal demand, but could be used effectively to provide emergency water, or redistribute water among intertied agencies.

Water from the Delta and Sierra are gravity fed and pumped through pipes and aqueducts from large reservoirs outside the region. Some systems have a single pipeline or aqueduct while others have multiple pipes and multiple routes through the region. SFPUC's and EBMUD's supply systems have been assessed through internal seismic studies resulting in impressive mitigative actions to their regional water supply systems. Both systems have improved their systems to be more robust, redundant, and repairable in high hazard areas.

There is no record of the Central Valley Project (CVP) and State Water Project (SWP) taking comparable action to ensure their systems are functional in an appropriate time scale following a Bay Area earthquake. Additionally, these systems capture water from the Sacramento - San Joaquin Delta, which is subject to salt water intrusion if levees that hold back water fail, resulting in a long term shut down of the CVP and SWP systems that supply the Southern half of the state (DWR, 2008). AB1200 required the Department of Water Resources (DWR) to study the potential impacts of various hazards, to the Delta. The DWR study found:

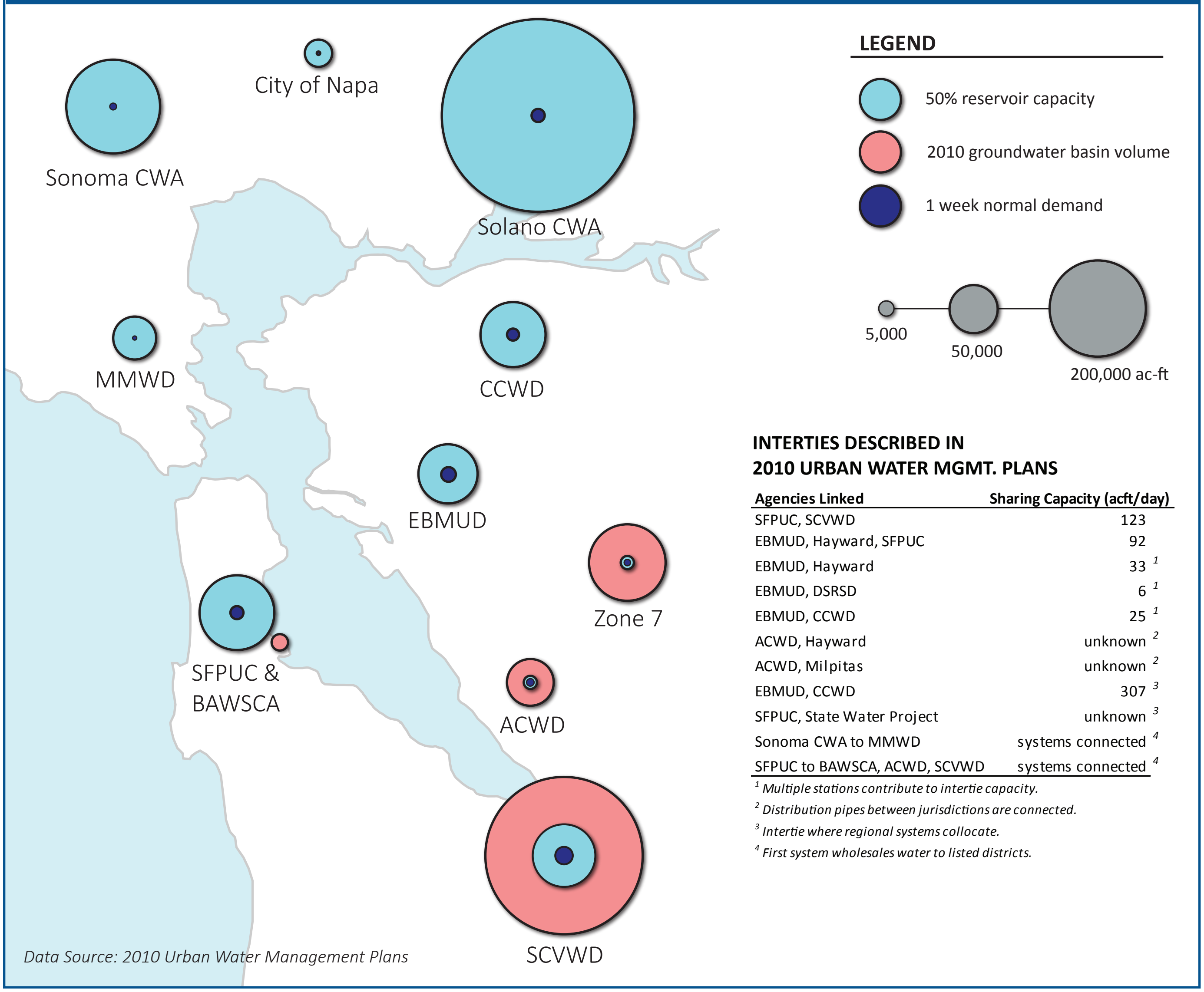
> *"A moderate to large earthquake in the San Francisco Bay region could cause major damage to Delta and Suisun Marsh levees, and could cause many of them to fail. Levee foundations could fail due to liquefaction or*

FIGURE 11:
Water System Source Portfolio (Eleven Largest Bay Area Water Districts) and Annual Normal Supply



Data Source: 2010 Urban Water Management Plans

FIGURE 12:
Water Storage Within Nine County Region and Normal Water Demand



INTERTIES DESCRIBED IN 2010 URBAN WATER MGMT. PLANS

Agencies Linked	Sharing Capacity (acft/day)
SFPUC, SCVWD	123
EBMUD, Hayward, SFPUC	92
EBMUD, Hayward	33 [1]
EBMUD, DSRSD	6 [1]
EBMUD, CCWD	25 [1]
ACWD, Hayward	unknown [2]
ACWD, Milpitas	unknown [2]
EBMUD, CCWD	307 [3]
SFPUC, State Water Project	unknown [3]
Sonoma CWA to MMWD	systems connected [4]
SFPUC to BAWSCA, ACWD, SCVWD	systems connected [4]

[1] *Multiple stations contribute to intertie capacity.*
[2] *Distribution pipes between jurisdictions are connected.*
[3] *Intertie where regional systems collocate.*
[4] *First system wholesales water to listed districts.*

Data Source: 2010 Urban Water Management Plans

the levees themselves could deform and fail. Seismically induced levee failures would be expected to extend for thousands of feet if not miles and impact many locations simultaneously… For example, there is about a 40 percent chance that 20 or more islands will flood simultaneously as a result of an earthquake sometime over 25 years of exposure." (DWR, 2008)

Three districts rely on the State Water Project or Central Valley Project for the majority of their water, City of Napa, Contra Costa Water District (CCWD), and Zone 7. The City of Napa has a large amount of storage for their water needs, when their reservoirs are at least half full. Half of Napa's water supply is also collected by local runoff. The CCWD is almost completely reliant on the Central Valley Project, but recently constructed the Los Vaqueros Reservoir which has a maximum capacity of 160,000 acre feet. Zone 7 is almost completely reliant on the state water project and is reliant on the 15,000 ac-ft Del Valle Reservoir which it shares with ACWD 50/50. All three could have severe water supply issues if the Delta fed water supplies are interrupted for multiple months. When reservoirs are near maximum capacity both the City of Napa, and CCWD have a significant amount of water stored within the region, while Zone 7 relies on groundwater storage to meet emergency needs.

Because of the overall distributed portfolio of sources regional water supply should be fairly reliable post-earthquake, assuming that reservoirs are at least half full, groundwater reserves are high, and damaged regional water components can be repaired in months following an earthquake. An earthquake occuring during extended drought conditions would test the systems more severely. When there is stored water within the region, there is capacity for the water system to operate in isolation from water sources outside the region. This is important if multiple months are needed to repair severe damage to one of the regional systems. In a drought, it is possible that these reserves will be less sufficient to supply water while regional systems are repaired.

This study only examines the vulnerability of the regional portions of water systems. As seen in Sidebar 6 (page 37), an earthquake can cause severe damage to aged distribution pipes, requiring weeks if not months, to restore water to all customers.

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CHAPTER 8

Interdependencies

Infrastructure system failures in an earthquake can be caused by both earthquake damage and interdependencies. Chapters 2 through 7 highlight the interaction between earthquake hazards and individual systems. In this chapter, interactions between infrastructure systems are organized and implicitly explored.

In many urban earthquakes, systems can have negative cascading effects where the failure of one system causes the failure of another (Kameda, 2000). The inclusion of interdependencies in the study of systems and their performance is critical in properly understanding the overall impact an earthquake may have on individual systems. Sidebar 7 (page 43) highlights how power restoration timelines for Southern California Edison were drastically increased after the inclusions of interdependencies.

TYPES OF INTERDEPENDENCIES

Infrastructure interdependence is the interaction of one system on another and is used to describe a number of different interactions. In this section, four common types of interdependencies are defined with a case example.

(1) Cascading outages –- the failure of one system causes another to shut down until the system is restored. Example: A cell tower without batteries loses electricity and shuts down until electricity is brought back online.

(2) Cascading failure –- a failure results in physical damage to another system. This can be caused by collocation of systems, or by an inability of systems to safely shut down in an outage. Example: A water main break causes damage to nearby sewer and gas lines as well as the roadway above, or an electrical outage causes a sump pump to fail, flooding a roadway.

(3) Influence on recovery –- a system outage slows the repair of other systems. Example: Impassable roadways prevent telecommunications repair crews from reaching damaged sites.

(4) Multi-system processes –- a process requires two functional systems, and one of the systems does not function. Example: vehicle transportation requires both a drivable road network and fuel. If roads are not damaged, but fuel is interrupted, transportation does not work.

Interdependencies can hinder function, hinder repair, or physically damage systems. The interactions can occur both within a system and across systems and is used to describe the snowball effect of one failure on all systems. In the Bay Area, these interdependencies were evident in the Loma Prieta earthquake and the 2010 San Bruno pipeline failure.

In Santa Cruz after the Loma Prieta earthquake, a 35-hour power outage at a wastewater pumping station resulted in an 800,000 gallon raw sewage release (Schiff, 1990). The wastewater facility was not damaged by the earthquake, but the dependence on electricity resulted in the sewage release. This same interdependence was also experienced in Southern California when a cascading power grid failure caused by maintenance work at a substation outside Yuma, Arizona sparked a rapid-fire 11-minute sequence of system failures where portions of California, Arizona, and Mexico lost power in 2011 (Lee, 2012). In San Diego, the electrical outage caused huge transportation delays and was responsible for more than two million gallons of sewage discharge (CBS, 2011).

In the above power outage cases, it is irrelevant if the power failure was caused by maintenance error or a large hazard event. The interruption caused by interdependencies has little to do with the initial damage and more to do with the organization and design of the system. The cascading effect starts with one small failure leading to another; very quickly the interaction between infrastructure systems can lead to multi-system outages. It is the interconnectedness of the systems that is the key to the massiveness of the final failure. While the magnitude and epicenter location of a future earthquake may be desirable predictions, the instability of the lifeline systems and their interconnection is what can lead to cascading larger failures.

Designing and operating systems below maximum capacity can provide for a surge in the system without failure. In 2010, the San Bruno Pipeline explosion demonstrated both cascading failure and surge capacity. The pipeline failure began with an error in electrical maintenance work 50 miles away, which resulted in a natural gas pressure surge and explosion of the weak portion of pipe in San Bruno. The dependence of the gas system on the electrical system and the inability of the pipeline to handle higher pressures are clear.

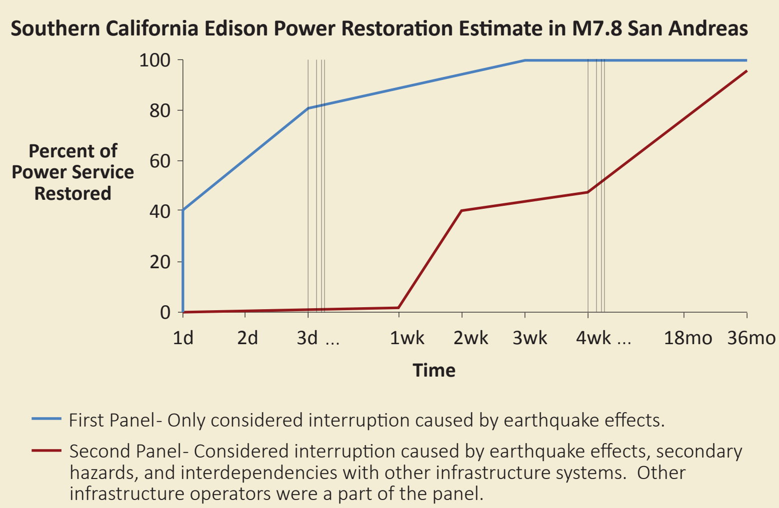
The failure illustrates how small failures can cause larger failures, and that failure propagation is enabled by coupling of systems (Lewis, 2011). A few small failures at an electrical substation led to a large failure and consequence of the coupled natural gas line. Surprisingly, soon after the explosion, natural gas was restored to all but a few blocks near the explosion despite a major natural gas pipeline being taken off line (NTSB, 2011). PG&E has three natural gas transmission lines that service the Peninsula. Had the overall system been at capacity prior to the explosion, natural gas would have been interrupted to a large swath of the peninsula and San Francisco. Because the system was running below capacity (partially due to the season) demand could be met by the remaining two lines,

SIDEBAR 7:
Influence of Interdependencies on Expected Utility Restoration

For the 2008 Shakeout exercise in Southern California, Southern California Edison (SCE), the power provider for the region held two panel discussions to estimate the restoration of their system after a massive Southern California M7.8 San Andreas scenario (Porter et al., 2011). In the first panel, operators and engineers discussed how the system would be damaged by the earthquake, and the length of time necessary to repair damage. Without interdependencies, the timeline was very optimistic with power being restored to over 90% of customers within two weeks. When SCE was provided additional information of how other systems were expected to perform and the potential for fire following earthquake, the utility took it upon itself to hold a second panel meeting with other utilities present. At the second panel SCE noted:

> *"power restoration times are strongly interdependent with other lifelines and are particularly affected by damage to the water system, natural gas delivery, transportation network, telecommunications overload, and post-earthquake fires. In revising the restoration estimates, SCE used expert judgment to consider these factors and determine the potential time frame for restoration based on damage to external dependencies," (Porter and Sherrill, 2011).*

With knowledge of other expected system performance, and a desire to manage public expectations of system performance, the restoration of the power system was drastically impacted as seen in the figure below. In the revised estimate 10% of customers in Los Angeles, Riverside, and San Bernardino Counties do not have service restored for over one year after the scenario event.



so no natural gas outage occurred.

The San Bruno and electrical outage impacts on waste water systems all highlight the independence of space – the original failure began miles away from subsequent larger failures. Interdependence can also be caused by the collocation of systems, or more simply put their close proximity. Systems are often collocated due to the environment's physical constraints. Many corridors through mountain passes bunch lifelines together; in urban environments public right of ways bunch systems together. When infrastructure systems are collocated a single failure can damage other systems unaffected by the hazard. In the San Bruno case, had the PG&E pipeline ruptured along another section where it runs adjacent to one of the other natural gas transmission pipelines, the collocation of the pipes would have resulted in failure of both pipes, and a natural gas outage for the San Francisco Peninsula. In addition to collocation causing damage across systems, it can slow restoration. Repair crews can be delayed by safety concerns, or by multiple crews working in the same area. Gas and wastewater leaks can slow the restoration of other systems. In Loma Prieta, crews were slowed when repairing damaged lifelines adjacent to buildings at risk of collapse (Schiff, 1990).

Lastly, it is important for airports and other stakeholders to consider which infrastructure systems are needed to accomplish a process. When assessing all systems within a region, studying the differences in system performance may reveal imbalances that limit the utility of resilient systems. Consider the sample process of commuting to work and the interaction between roadways and the fuel sector. For commuters that rely on personal vehicles to get from home to work, or in the case of airports, their ability to get passengers and cargo from the airport to their final destination requires both roads and fuel. The process cannot be completed unless both systems are operating. Airports and other stakeholders must understand which systems are needed to complete necessary tasks.

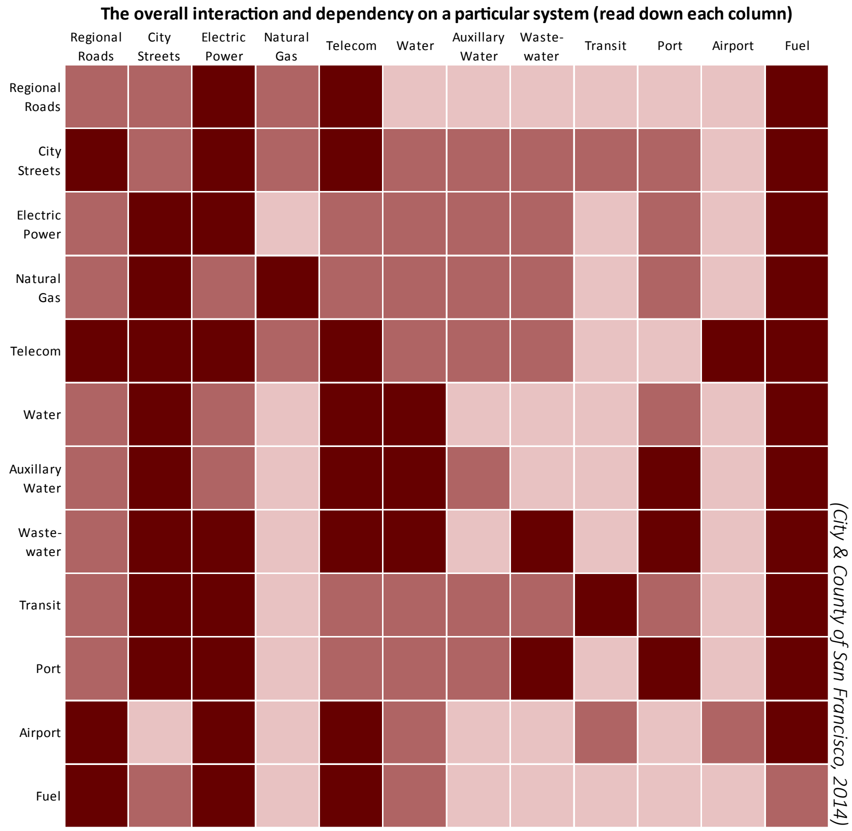
SF LIFELINES INTERDEPENDENCIES STUDY

In 2014, the City and County of San Francisco's Lifeline Council published its first Lifelines Interdependence Study. The report was generated under the umbrella of the Lifelines Council, a pioneering council made up of utility operators that service the City. For the study, past research and utility interviews were used to roughly quantify the interdependence between systems. Figure 13 (page 45) shows the matrix of interdependence between twelve important systems for the City and County of San Francisco. This information was then taken and displayed with lines. It is clear from both graphics that fuel is the system most relied on by all other systems. All other systems had a significant interaction with the fuel sector. Roads, electricity, telecom, and water were also main systems relied on by others.

The San Francisco study was completed for the City. The relationship for other cities may be different, but the overall interactions are likely to be fairly similar for the Bay Area region as a whole. The study is a testament to the work that a Lifelines Council can achieve, and should be used as a model to approach issues of infrastructure vulnerability and interdependence for the Bay Area region.

FIGURE 13:
Interdependencies of Infrastructure Systems, Specific to San Francisco - SF Lifelines Council

Reading the matrix from left-to-right shows which systems the designated operator relies on. For example, Airports have a strong interaction with regional roads, but a limited interaction with natural gas.
Reading the matrix from top-to-bottom shows which systems rely on the designated operator. For example, all systems have a strong interaction with the fuel system.

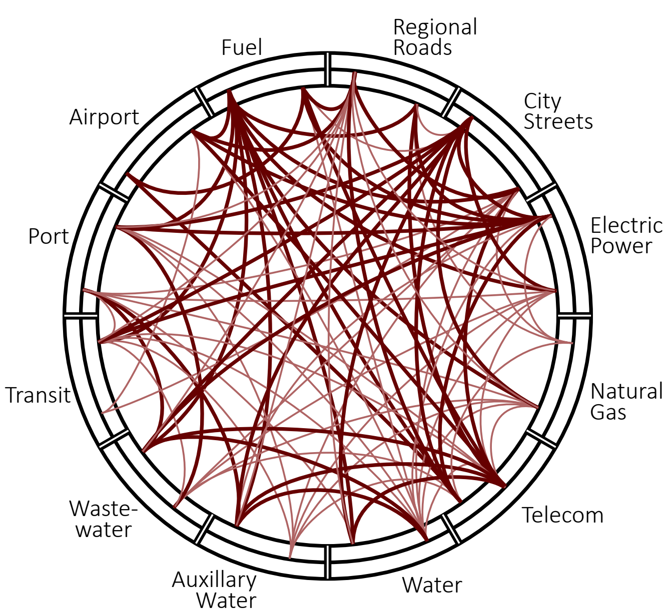


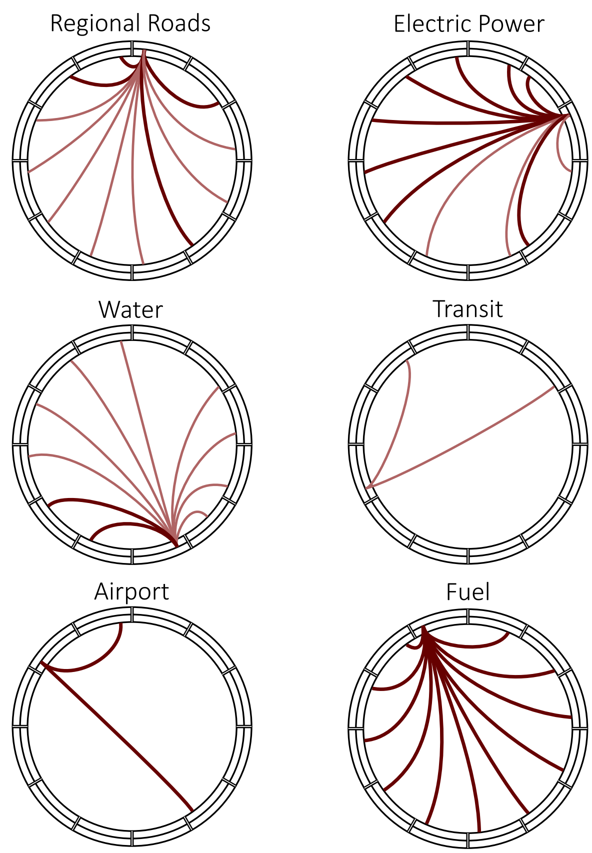
The lifeline operators' dependency on other lifeline systems (read across each row)

Strong Interaction
Moderate Interaction
Limited Interaction

Matrix Information Displayed as Scallop Diagram

The graphic below shows all moderate and strong interactions between systems. The individual systems to the right show which systems rely on the designated operator (same as reading the matrix from top-to-bottom).





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APPENDIX A

PG&E Commercial Buisness Center

The PG&E Energy Solutions and Service Department is responsible for maintaining a close working relationship with all of our large commercial customers for all of their energy needs. There is a local PG&E Major Account Manager assigned to each of the large Bay Area Airports. Below is an excerpt describing the PG&E program:

One of the most critical priorities of our large commercial customers is to obtain detailed and timely outage communications throughout an outage and restoration process. As a result, each PG&E Major Account Manager has already established an ongoing open line of communication with the local airport Director of Engineering/Facilities regarding local G&E service and reliability. This includes detailed discussions on exchanging key current 24/7 outage and emergency contact information for each airport and the local PG&E First Responder Teams. We have also established how our customers should report reliability issues, outages, emergencies, etcetera; when they occur. Additionally PG&E outage information systems will often automatically notify the assigned account manager, On Call Reps, and our local restoration leads etcetera, when an outage/service reliability issue occurs. We will then proactively initiate outage restoration and major customer outage communication services until the problem is resolved.

To enquire about this relationship PG&E's Commercial Business Center can be contacted at: 1(800) 468-4743.

ASSOCIATION OF BAY AREA GOVERNMENTS
RESILIENCE PROGRAM

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