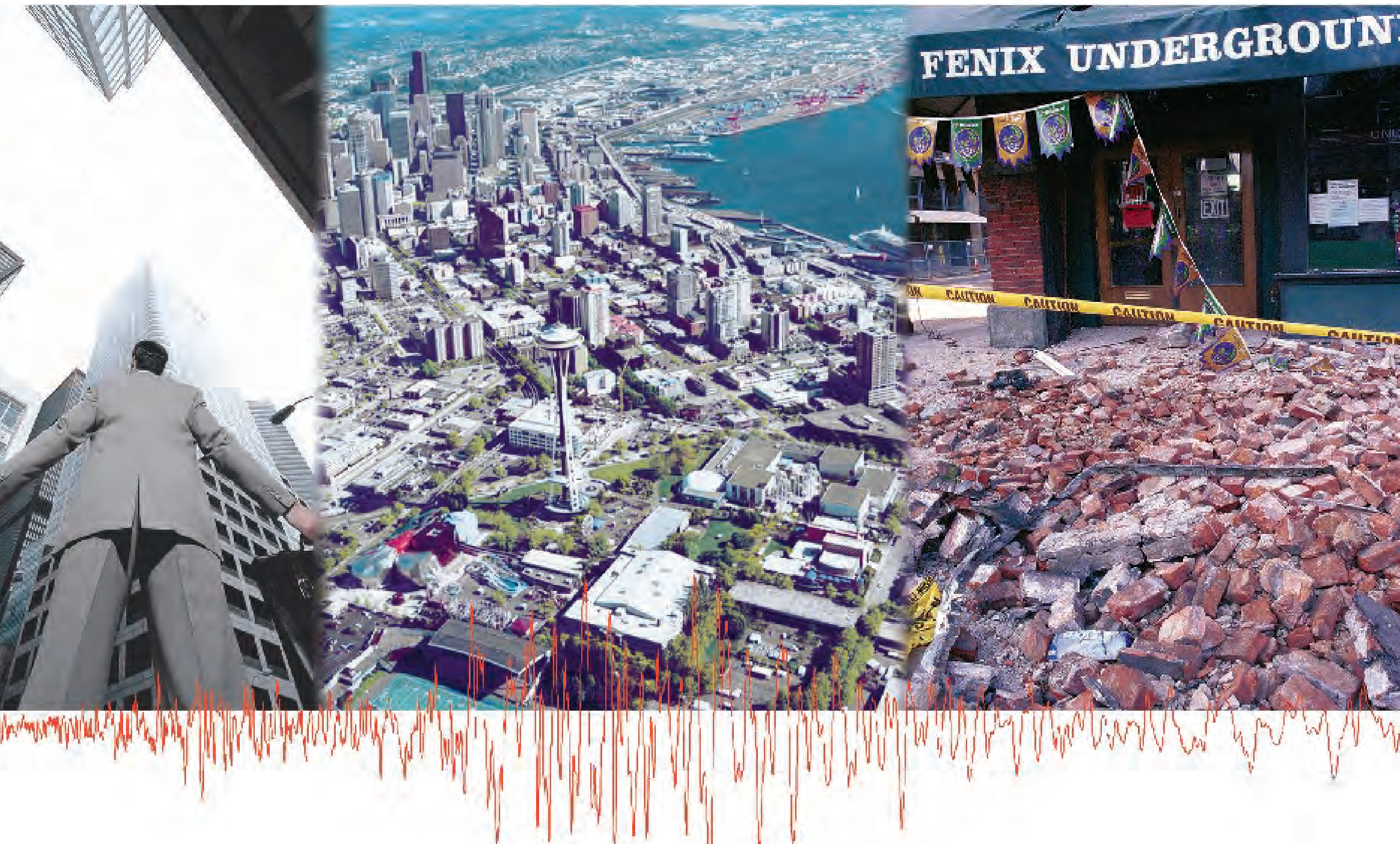
Scenario for a Magnitude 6.7 Earthquake on the Seattle Fault



Earthquake Engineering Research Institute

and the

Washington Military Department Emergency Management Division

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The Earthquake Engineering Research Institute (EERI) is a non-profit, professional association with academic and professional members throughout the world who share a common interest in reducing the effects of earthquakes on society. The primary objective of EERI is to reduce earthquake risk by 1) advancing the science and practice of earthquake engineering, 2) improving understanding of the impacts of earthquakes on the physical, social, economic, political, and cultural environment, and 3) advocating comprehensive and realistic measures to reduce the harmful effects of earthquakes.

The Washington Military Department, Emergency Management Division works in partnership with federal, state, and local agencies, volunteers, and private organizations to reduce the potential effects of natural, man-made and technological hazards. The division's mission is to coordinate and facilitate resources to minimize the impacts of disasters and emergencies on people, property, the environment, and the economy.

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The Seattle Fault Earthquake Scenario project was the result of the vision and effort of professionals from various disciplines and organizations in the Puget Sound region who work daily to improve the earthquake safety of the region's communities and people.

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■ *Organizations providing significant and key contributions to the project are the:*

ASCE **American Society of Civil Engineers, Seattle, WA**

SEA **Structural Engineers Association of Washington, Seattle, WA**

EERI **Earthquake Engineering Research Institute, Oakland, CA**

USGS **U.S. Geological Survey, Golden, CO, Menlo Park, CA**

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CREW AHEAD OF THE WAVE **Cascadia Region Earthquake Workgroup, Seattle, WA**

FEMA **Federal Emergency Management Agency**

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Executive Summary

Scenario for a Magnitude 6.7 Earthquake on the Seattle Fault

A major earthquake on the Seattle Fault will have a significant impact on the communities of the Central Puget Sound region.

The magnitude 6.7 scenario earthquake and its aftermath will disrupt for weeks and months individuals, families, businesses and governments throughout the region. The disruption will be much, much greater than the February 2001 magnitude 6.8 Nisqually earthquake.

Collapsed buildings or falling debris will kill or injure thousands of people, and trap hundreds of others. Hospitals closest to the fault may be unable to provide care to the injured because of damage to their facilities. Damage to the transportation system will impede emergency responders, prevent many commuters from returning home, and impede traffic and commerce for months. Shelter space for people made homeless because of the quake will be limited in the immediate area because of damage to schools and community centers. Water for drinking and firefighting will be scarce because of pipeline breaks. Power and natural gas service will be out, and telephone and radio communications will be difficult for days. Untreated wastewater will pollute soils and waterways near sewer line breaks.

Losses will be similar in magnitude to those of the 1994 M6.7 Northridge earthquake in California, at $40 billion, the nation's most costly natural disaster to date.

Scenario earthquake losses include:

- Property damage and economic loss – About $33 billion.
- Deaths – More than 1,600.
- Injuries – More than 24,000.
- Buildings destroyed – About 9,700.
- Buildings severely damaged and unsafe to occupy – More than 29,000.
- Buildings moderately damaged whose use is restricted – About 154,500.
- Fires – About 130, causing nearly a half-billion dollars in property damage.

The economic impact of the scenario earthquake on the region and the State of Washington primarily depends upon how quickly the heavily damaged transportation system is placed back into service.

Earthquakes in Washington State

Earthquakes pose a serious threat to life and property in Washington, particularly the Puget Sound region. The most recent damaging earthquake was the 2001 Nisqually event. It caused $2 - 4 billion in damage, primarily from Olympia north through Seattle.

A 2001 study by the Federal Emergency Management Agency found that Washington

Figure E-1: Damage to roads, similar to what this Tumwater neighborhood experienced in the 2001 Nisqually earthquake, will be widespread throughout the region close to the rupture in the scenario Seattle Fault earthquake.

Photo / Washington Department of Natural Resources

has the second highest risk of economic loss caused by earthquakes in the nation, behind only California. Seattle ranks seventh among cities nationwide at economic risk to earthquakes; Tacoma ranks 22nd.

Many residents believe that the Nisqually earthquake is the largest that could hit the Puget Sound region; studies of residential and small business damage after this 2001 event provide confirmation. However, it was not the region's "big one" – an earthquake such as one on the Seattle Fault that will cause devastating damage and widespread disruption to the region and the state.

The region has a history of large, deep earthquakes of magnitude 6.5 or greater occurring every 30 to 50 years; this includes the Nisqually earthquake. Scientific research in the past 20 years uncovered six active surface fault zones capable of generating much larger, more damaging earthquakes.

One of the region's major fault zones is the Seattle Fault Zone. It runs from Hood Canal in the west, through Puget Sound and south Seattle, and east through Bellevue and Issaquah, roughly parallel to Interstate 90. An earthquake on the Seattle Fault of magnitude 7 or greater about 1,100 years ago generated a tsunami in Puget Sound, landslides in Lake Washington, rockslides on nearby mountains, and a 22 foot uplift of a marine terrace on Bainbridge Island.

The six Puget Sound fault zones are of great concern to scientists, engineers, emergency managers, land-use planners and others, because much of the region is heavily urbanized and populated. The three-county study area for this scenario – King, Pierce and Snohomish counties – is home to half the state's population, about half the state's jobs and much of the state's economic base, including nearly all its largest employers, its two largest seaports and its largest airport.

The discovery of these surface fault zones provide much of the reason scientists believe the earthquake threat in Puget Sound is much more significant than thought just a few years ago.

The Scenario Earthquake

Evidence of an earthquake discovered in a trench in Vasa Park in Bellevue is the model for the scenario event. The scenario earthquake has a moment magnitude of 6.7. The fault ruptures or breaks the surface for a distance of about 14 miles, from Harbor Island in the west to an area east of Lake Sammamish,

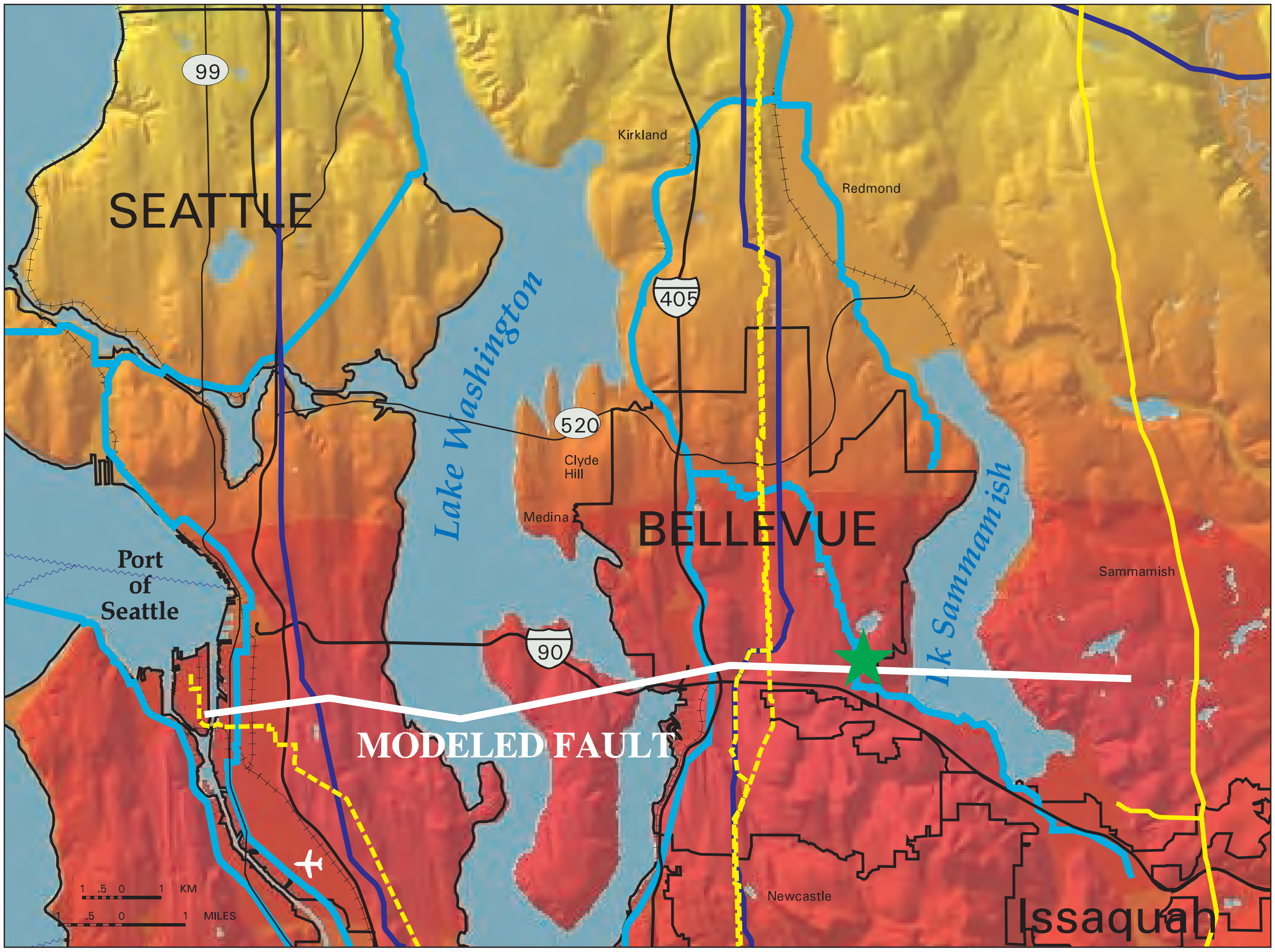


Figure E-2: Location of the surface fault rupture for the scenario earthquake. The white line shows the modeled rupture where it intersects the surface. It goes through the Vasa Park trench (indicated by the green star) where the earthquake on which the scenario event is based was found.

Graphic / US Geological Survey

passing through Seattle, Mercer Island, Bellevue, and the Issaquah area. The rupture raises the level of the ground surface on the south side of the fault by about 6.5 feet.

Ground shaking will be severe, much greater than experienced during the 2001 Nisqually earthquake. Damage will be far worse and more extensive than seen in any earthquake in the state's history.

Areas closest to the fault rupture, as well as areas of poor soils such as river valleys and steep slopes, will experience strong ground motions and the greatest damage. These areas include the Duwamish River-Green River Valley, Issaquah Creek Valley, Sammamish River Valley, Snoqualmie River-Snohomish River Valley, Puyallup River Valley, and the shorelines of Puget Sound, Lake Washington, Lake Union and Lake Sammamish.

Damage to homes, warehouses, and buildings housing small businesses will be widespread throughout the region. Damage to taller buildings such as central business district high rises and large-span bridges, while still significant, will be concentrated in areas closer to the fault rupture.

Table E-1: Comparing the scenario Seattle Fault earthquake with other recent major earthquakes

Earthquake	Damages	Est. loss (2004 $)
Seattle Fault scenario event – M 6.7 Shallow quake, with fault rupture at surface	Projected: 1,660 dead, 24,200 injured. 9,700 buildings destroyed, 29,000 buildings severely damaged and unsafe to occupy, 154,500 buildings moderately damaged with use restricted. 130 fires burn. All six major highways experience partial closures lasting months due to substantial damage, collapsed bridges. Utilities cut in areas with poor soils. Port facilities badly damaged, use restricted. Operations of businesses relying on “just-in-time” deliveries disrupted by collapsed supply warehouses, transportation closures, communication outages.	**$33 billion**
Nisqually, 2001 – M 6.8 Deep quake at 36 miles depth, NE of Olympia, WA	One death, 320 injured. Most severe damage found in downtown Olympia, Pioneer Square and SODO districts in Seattle. Legislative Building, SeaTac Airport control tower, Boeing Field runways, and Alaskan Way Viaduct seriously damaged. Highway damage minor. Power outages repaired within a day.	**$2 – 4 billion**
Kobe, Japan 1995 – M 6.9 Shallow quake at 8.7 miles depth, fault ruptured into downtown Kobe *The first severe earthquake to strike the center of a modern city in a highly industrialized country.*	More than 6,230 deaths, 40,000 injured. 102,000 buildings destroyed. 300 fires burned 7,000 buildings. 300,000 people homeless. Many important public facilities damaged or collapsed, including City Hall, several hospitals, 85 percent of schools. Widespread utility outages and failures. Major highways, bullet train networks badly damaged, service cut. Much of seaport inoperable, many shippers moved operations, did not return after repairs made. Manufacturing seriously disrupted.	**Up to $200 billion**
Northridge, 1994 – M 6.7 Shallow quake at 10.3 miles depth, beneath San Fernando Valley NW of Los Angeles, CA	57 deaths, 9,000 injured, 22,000 people homeless. 7,000 buildings severely damaged, unsafe to occupy, 22,000 buildings moderately damaged, use restricted. Nine hospitals closed. Eleven major roads into Los Angeles closed due to collapsed bridges, interchanges. Some utility failures and outages. Time of earthquake – 4:31 a.m. – prevented greater loss.	**$40 billion**
Loma Prieta, 1989 – M 6.9 Shallow quake at 10.5 miles depth, NW of Santa Cruz, CA	62 deaths, 3,000 injured, 12,000 people homeless. 18,300 homes and 97 businesses destroyed. Transportation system badly damaged – I-880 collapsed in Oakland, deck of Oakland Bay Bridge collapsed, and Embarcadero Freeway nearly collapsed. Power outage left San Francisco dark for first time since 1906 EQ. Several public buildings badly damaged. 27 fires burned. Tourism industry hurt.	**$9 – 15 billion**
Olympia, 1949 – M 6.8 Deep quake at 33.5 miles depth, NE of Olympia, WA	Eight deaths. State Capitol Campus buildings badly damaged. 40 percent of Chehalis damaged. Public utilities seriously damaged, services interrupted. Landslide generated tsunami in Tacoma Narrows.	**$0.2 billion**

Note: Figures rounded to the nearest billion and adjusted to 2004 dollar values.

Impacts of the Scenario Earthquake

Immediately After the Quake

The scenario earthquake badly damages homes, office buildings, manufacturing plants, schools, port facilities, utilities and transportation routes from the south end of downtown Seattle east through Bellevue and throughout river valleys north and south of the cities. Collapsed structures and highway bridges kill or injure thousands of people. Communication links are swamped or broken, making communications difficult if not impossible throughout the region. Police, fire, and medical aid units receive hundreds of calls for help, but clogged and damaged roadways limit their ability to respond. Areas closest to the fault rupture are devastated. As the initial response gets underway, mayors, city and county councils, and state officials consider the implications of the disaster decisions on rebuilding and restoring the well-being of their communities.

Among the biggest concerns facing the region immediately after the earthquake are that:

- Police, fire, and medical aid units will be overwhelmed in the initial hours after the earthquake.
- Damage to transportation systems will make movement of people and freight around the region difficult for weeks or months.
- Demand for emergency shelter, food and water by displaced individuals and stranded commuters will place tremendous demand on available community resources.
- Disruptions to transportation, telecommunications and utility systems, and damage to key facilities, will complicate the daunting task of getting the region – and the state's – economy back on its feet.

The scenario earthquake will overwhelm the fire, rescue, and emergency medical services responders of the Central Puget Sound region.

Calls to public safety agencies for help will increase dramatically. Damage to vehicles and facilities, injuries to personnel, and damage to roads and bridges will affect response times of firefighters, police officers, and emergency medical staff. Public safety radio systems will be overloaded, making communication between dispatchers and responders, and between responders, difficult.

Initially, responders address high priority problems to keep them from escalating. Emergency medical responders must adjust standards of care for the injured; it may become necessary to deliver hospital-like care from temporary facilities until air or ground transportation can take patients outside the area.

Availability of water is a key concern. The earthquake will trigger fires that burn nearly a half-billion dollars of property near the fault, and a lack of water will hamper firefighting. One third of the region's households and businesses will lose water service. Restoring service as quickly as possible is important to sustain human life, for sanitation, for business and industry, and for firefighting.

Caring for the injured will be difficult because of a shortage of health care services. A lack of supplies and inability of staff to get to hospitals and clinics will compound damage to facilities. The lack of health care services will be significant not only in Central Puget Sound, but also to people from adjacent states and Alaska who travel to the region for care because of expertise in specialty areas such as cancer care and organ transplantation, for example.

Communities will face significant problems providing emergency shelter to thousands of individuals and families with badly damaged homes and to commuters unable to return home. Many communities use schools as emergency shelters, but about 40 percent will be unusable because of damage.

Hundreds of thousands of commuters will have difficulty returning home because of damage to key transportation corridors and a lack of alternative routes. Detours will be available, but the commute will be many hours long and very slow for those able to leave. Ferries will use undamaged landings outside of the immediately impacted area; movement of ferries to other landings will strand walk-on ferry commuters in downtown Seattle.

A number of groups will require special attention and pose challenges to responders immediately after the earthquake. These include schoolchildren, the disabled, retirees, and non-English speaking people.

The earthquake will badly damage vulnerable schools and injure hundreds of children and adults. Damaged schools will be unavailable for an extended period. Districts must find ways to accommodate a significant population of displaced students by busing them to undamaged schools further away from home, double-shifting classes, or through other means. Communities that rely on schools for shelters and staging areas will have to look to community centers and other facilities.

Disabled people and senior citizens require special attention because of their special needs. Many do not work, have medical conditions requiring regular medication or therapy, and they tend to live in older or substandard housing more likely damaged by the earthquake.

In previous events of community-wide impact, culture and language barriers led to confusion about what was happening and how people should respond. This earthquake will be no different. The Central Puget Sound region is home to substantial populations of people that do not speak English as their primary language. One area badly damaged by the scenario earthquake is Seattle's International District, the cultural and commercial center for the region's Asian American and Pacific Islander communities.

Communities will have difficulty dealing with multiple environmental problems caused by the earthquake. Release of hazardous materials from factories, transfer and storage sites, and overturned trucks and trains will generate fires and explosions, cause human health hazards, and pollute the air, water, and soil. Untreated wastewater will spill in areas where major sewer lines break, or into Elliott Bay if treatment plants lose power.

Deciding whether homes are safe to remain in will be the focus of individuals and families immediately after the earthquake, which will displace about 46,000 households. Displaced people will live with other family members or relocate to temporary shelters. Family members scattered throughout the region will not be able to communicate or find one another with telephone services unavailable.

Families able to remain in their homes may not have power for lights and cooking, natural gas for heat and cooking, water for drinking, cooking and sanitation, or phone service for keeping in touch with family and friends for some time after the earthquake.

The psychological impact of the earthquake will be significant. Aftershocks, some strong and causing more damage, will rattle nerves and injure more people. Post-disaster stress will continue for months for some people, heightened by the death or injuries of a loved one, temporary relocation, making repairs to homes, and replacing cherished items and household goods.

Loss of life and housing pose the largest social burdens, as people struggle to rebuild their lives. Temporary and long-term housing arrangements will disrupt lives and may force people to relocate permanently outside of their neighborhood or community. Temporary or permanent closures of community centers, churches, schools, interest groups and social clubs will stress the community's social fabric.

The earthquake will most affect those people with the fewest social and economic resources; they will have more difficulty recovering from the event. Moreover, many of the elderly, the disabled and non-English speakers have special needs and may be more reliant on social networks and government and charity services during the recovery process.

Personal and financial stress and anxiety resulting from disruptions at home, work, school, and daycare may result in higher incidence of social and psychological problems, such as increased absenteeism, alcohol or drug abuse, and physical abuse.

Resources to help individuals and families recover from a major disaster such as the scenario Seattle Fault earthquake are limited. Most people incorrectly believe that the federal government will repay them fully for their damage and losses. Few have earthquake insurance or the savings to cover their expenses for an extended period. Government assistance following a disaster is limited to uninsured losses only. Credit-worthy individuals and families initially will be steered into low-interest loan programs. Those who do not qualify for these loans will receive grants to help repair damaged homes and take care of immediate needs. Disaster grants target those with lower incomes, but some in greatest need will not apply due to cultural issues or mistrust of the government.

The potential is great for individuals and families unable to carry the financial burden of their losses to relocate to another area, possibly with other family members.

Economic Impacts

Major urban earthquakes can cause economic loss in the tens of billions of dollars. The impacts of the scenario Seattle Fault earthquake extend beyond the cost of repairing shattered buildings and broken freeway bridges to lost business output and productivity, business failures and loss of competitiveness in the national and global marketplace.

Perhaps the most critical economic restoration initiative facing the region is repair of damaged transportation systems. A key lesson from the Northridge, Kobe, and Nisqually earthquakes is that damaged transportation and utilities infrastructure cause major economic disruption.

The 1994 Northridge earthquake was a moderate-sized event, but the costliest natural disaster in U.S. history. Small businesses – particularly those that rented rather than owned their space – were most vulnerable to long-term economic hardship or failure. Damage to transportation systems was as great a source of disruption as building and infrastructure damage; one quarter of business interruption loss was due to transportation disruption. Losses in the Los Angeles area would have been greater if not for the region's redundant freeway network – a redundancy not found in the Central Puget Sound region.

Following the 2001 Nisqually earthquake, small businesses in highly impacted areas were most economically vulnerable. Damage to roads, bridges and buildings made it hard to conduct normal business in some locations for months; damage to local airports caused significant impacts to aviation-related businesses that lasted for weeks.

Kobe's experience provides the best example of what to expect following the scenario Seattle Fault earthquake. The 1995 Kobe event was the world's first experience of a large earthquake striking a modern urban economy. Economic sectors in decline before the earthquake were vulnerable to structural change that accelerated after the event. For example, the Port of Kobe's

Figure E-3: Repair of damaged transportation systems will be the most critical economic restoration initiative facing the Central Puget Sound region after the scenario Seattle Fault earthquake. The quicker transportation systems are repaired, the quicker the region will recover from the earthquake. Photo / Washington Department of Transportation, Aerial Photography

ranking among world container ports dropped from number 6 to number 17 after the disaster. It took two years to repair the port and the region's transportation systems; this resulted in cargo traffic cut in half as shippers moved permanently to other ports outside the disaster area. The same thing happened to the Port of Seward following the 1964 Great Alaska earthquake; much of Seward's business went to the Port of Anchorage.

Similar infrastructure vulnerabilities will yield serious economic disruption in the Puget Sound region from the scenario earthquake.

Small businesses are more vulnerable to failure than large ones because they have fewer resources and are less likely to have prepared or planned for such an event. Marginally successful businesses will find the earthquake is the straw that breaks their financial backs. Strong businesses will fail if the earthquake hits at a moment when they are vulnerable. Businesses whose customer base is significantly disrupted may not recover.

Outages of electric power, water, sewers, and natural gas will contribute to the economic disruption. While these outages will be of shorter duration than transportation disruptions, they will affect large areas, including those with little physical damage. In two recent disasters – the 1999 Chi-Chi earthquake in Taiwan and the 1993 Great Midwest Flood in Des Moines, Iowa – utility and transportation disruptions caused greater loss of revenue and business than the actual ground shaking or flooding.

The most immediate and widespread business disruptions will result from concerns for life and safety. Many businesses will stop operations to assess structural damage and determine the condition of their employees and building occupants. Transportation disruption will affect employees, suppliers, and customers; even if buildings or alternative operation centers survive, such facilities are worthless if personnel, suppliers and customers cannot reach them.

Most businesses use just-in-time inventory practices. Limited on-site inventories and disruption to suppliers and supplies will limit functionality even of businesses that suffer no damage. Many neighborhoods and markets will not have access to goods and services because of poor transportation. Given small inventories on hand at the time of the earthquake, residents around the region will have trouble securing basics such as groceries and prescriptions.

Interrupted power and communications will leave most small- and medium-sized businesses unable to function. Small banks will not be able to obtain the cash needed for recovery. Major banks will continue operations, but branch offices, automated teller machines, and electronic banking may not.

Also important will be worker fear of re-occupying damaged buildings and a greatly reduced capability to assess damaged structures. The lack of assessment capability will interrupt business operations throughout the region.

Economic revitalization planning will be critical to the future of affected communities and the region. The scenario earthquake will create a new future that will not include many local and regional businesses. Businesses without large cash reserves will not survive. Corporate money and highly trained workers could leave. A significant number of unrepaired buildings will give the appearance that a neighborhood is abandoned. Neglected structures will affect the long-term economic viability of area businesses, neighborhood safety and crime.

Physical Damage

Ground Failures

Significant ground failures – including fault rupture, liquefaction and landslides – will occur throughout the region and contribute greatly to building damage.

Buildings on soils that liquefy will settle or tip. Liquefaction-induced settlements, sinkholes, and sand boils will disrupt pavement, such as occurred during the 2001 Nisqually earthquake at the King County International Airport (Boeing Field). Buried structures such as fuel tanks and power vaults within liquefied soil will become buoyant and rise toward the ground surface. Water ejected from sand boils could cause localized flooding. Street and basement flooding from liquefaction occurred in Puyallup during the 1949 Olympia earthquake.

The Nisqually earthquake caused about a hundred landslides throughout the Puget Sound region; the number would have been much greater if rain water had saturated soils. The scenario Seattle Fault earthquake will cause thousands of landslides over a wider area because it is shallower and its ground shaking much greater than the Nisqually event. Landslides along shorelines will generate local tsunamis as land masses rapidly slide into the water, or as underwater land masses move down slope.

Utilities

Outages of electricity, water, waste water collection and treatment, natural gas and liquid fuels, and communications will last from days to weeks depending upon a variety of factors including location of facilities to the fault rupture, ground shaking, and soil strength. Loss of utilities means some homeowners throughout the region will not have lights, heat, fuel for cooking and vehicles, water for drinking and sanitation, and communications with family and friends, for varying amounts of time. Implications for affected business operations are similar.

Few water facilities will resist the large ground motions expected in close proximity to the fault rupture. Many tanks close to the fault rupture will rip loose from their anchorages, some will burst open. Support facilities will become non-functional. North-south trunk lines will break at the fault rupture. Several thousand pipeline failures will occur. It will take weeks to restore service to areas where liquefaction causes heavy damage to old cast iron piping – the Duwamish Valley, the Sammamish Valley, and as far south as Renton and Kent. The community with the most tenuous water supply is Mercer Island, dependent on pipelines that parallel the Seattle Fault.

King County's wastewater treatment plants at West Point and Renton are vulnerable to the earthquake's ground motions, which will be larger than both plants can resist. Highly liquefiable soils in valleys will float or move sewer lines, with broken pipes spilling untreated sewage into both Lake Washington and Lake Sammamish as well as into the Green River. It will take weeks to complete repairs to some large diameter sewer lines.

The region's electrical power generation, transmission and distribution system is robust and redundant. Its most vulnerable points are high-voltage substations, many with unique components that can take months to replace if damaged. Most areas experiencing outages will have power restored within 72 hours. Outages will last for weeks in areas with heavily damaged critical substations. A critical link in Seattle's power infrastructure is the Alaskan Way Viaduct, which carries a combination of transmission and distribution lines running along and beneath the structure. The viaduct will be heavily damaged or collapse in the scenario earthquake, causing significant damage to these power lines.

Telecommunication systems performance is mixed. The wired phone system will perform well. Most switching centers are highly reliable and robust. Emergency power is common; loss of water for cooling switching center computers will be a problem. Wireless phone systems are less robust, built with less attention to reliability because of the highly competitive business environment. Many wireless facilities do not have emergency power. As a result, wireless phone service will not be dependable for a time following the earthquake. Natural gas systems will perform well. Welded-steel high-pressure transmission lines are in competent soils along most of their route south from Canada through the region. Pipeline alignment is at the eastern end of the fault rupture; if limited fault displacement occurs, these lines should perform well. Much of the region's gas service is through an intermediate and low-pressure distribution system which has seen most of its cast iron pipe replaced in recent years with more damage resistant plastic pipe. Some damage will occur in the distribution system, particularly in areas of poor soils such as river valleys north and south of the fault.

The Olympic pipeline provides liquid fuels such as gasoline and jet fuel from refineries in Northwest Washington. It runs beneath residences, schools and churches throughout the region. Although specific vulnerabilities of the pipeline are not known, the risk of failure or release of liquid fuels is highest where it passes through areas of landslide-prone or liquefiable soil. The pipeline crosses the Seattle Fault in an area where the scenario earthquake will create several feet of displacement and where liquefiable soils exist. If the pipeline ruptures, it will spill thousands of gallons of fuels that could pollute soils and nearby creeks, and catch fire.

A 1999 rupture of the pipeline in Bellingham spilled a quarter-million gallons of gasoline that caught fire and killed three people. It is more likely that broken valves at a distribution center south of Seattle, where fuel is loaded into trucks for local gas stations, will cause spills and fires.

Transportation

The scenario earthquake will inflict serious damage to the region's transportation systems – roads and bridges, airports, waterfront facilities, railroads and ferries. Damage will be widespread near the fault rupture, and in areas of liquefiable soils or slopes vulnerable to landslide.

All six major freeways – Interstates 5, 90 and 405, and State Routes 99, 167 and 520 – experience partial closures, some lasting for months or years due to major damage that includes collapsed bridges and elevated freeways. These routes carry more than 600,000 vehicles per day. A well-placed accident can shut one of these routes down for hours during the normal daily commute, forcing commuters onto other routes.

Following the earthquake, much of the traffic these freeways carry will move onto surface streets. These streets cannot carry the higher traffic volumes due to their size and the road surface construction. Severe traffic congestion will occur for at least a year. Commutes to work that took 30 minutes before the earthquake could take hours. For example, the day after the 2001 Nisqually earthquake, a five-mile commute from West Seattle to downtown Seattle took two hours because a safety inspection temporarily closed the Alaskan Way Viaduct. Movement of goods from ports to warehouses to final destinations – manufacturers, retail outlets, and hospitals, for example – will be much slower, with more deliveries scheduled during the night when congestion will be less.

Renton and King County (Boeing Field) airports will experience significant liquefaction to their runways and close immediately. It will take several days for them to re-open to limited traffic and a month to open to 80 percent traffic. Damage to Sea-Tac runways and control tower is unlikely to be significant although damage to terminal facilities will slow operations for a time.

Damaged port facilities will be out of service for months or years due to damage caused by ground failures along the waterfront. Part of Harbor Island may slide into Elliott Bay, reducing capacity of the Port of Seattle. A wave generated by the landslide will pound other shore-side facilities in the bay. Damage caused by other large soil movements will limit access to container terminals. Cranes at container terminals will be damaged or topple, and utilities will be disrupted. In many cases, docks will be of very limited use, except as temporary berthing for emergency supply ships, until damaged piling are replaced and access restored. Because of extensive damage to port facilities in the region, many shippers will move their operations to undamaged facilities; some will not return for years, if ever.

Seattle-based ferry routes from the Seattle and Fauntleroy ferry terminals will shut down for at least a week due to damage from ground failures and failure of the seawall. Vessels will be rerouted north and south to undamaged landings to help with post-earthquake emergency transportation. Significant damage to the vessels is unlikely. Temporary equipment and facilities will help ferries move passengers and vehicles around blocked land routes.

Railroads move more than 200,000 tons of freight in and out of the region every day, along with thousands of long-distance passengers and short-haul commuters. The earthquake will shut down rail operations until inspections and repairs are complete to ensure safety of the tracks and associated facilities. Rail lines close to the seawall in Seattle will distort and become unusable. Landslides and severe ground shaking will derail freight, passenger or commuter trains where rails run below slopes or in areas of poor soils; landslides could sweep trains on shoreline tracks into Puget Sound. Undamaged lines will return to service within hours, while lines with minor damage will return to operation with speed restrictions. In cases of major track damage, temporary repairs will allow restricted operation; liquefaction-induced damage will take a week or longer to repair. Damage to rail yards, container and trailer handling facilities, passenger stations, and locomotive and car servicing facilities will take weeks to repair and transfer some operations to alternate, less convenient locations. The increased cost of rail operation with damaged facilities and lost revenue during the recovery period could exceed the cost of repairs.

Buildings

Modern structures built on firm soils will survive with various degrees of damage in the scenario earthquake. Unretrofitted, older structures will sustain heavy damage. Of particular concern are unreinforced masonry and reinforced concrete tilt-up structures, which have performed poorly in past earthquakes and are common in the Central Puget Sound region. The most extensive damage will be along the Seattle Fault rupture and along low-lying river valleys with liquefiable soils.

Unreinforced masonry (URM) buildings will perform poorly. Most of these buildings predate 1940 and the use of modern construction techniques and materials. There are about 2,200 URM buildings within the region; the largest concentration is in the Pioneer Square and International District neighborhoods of Seattle near the fault rupture. URM building damage was common during each of the last three significant earthquakes in western Washington – 1949, 1965, and 2001. Unless seismically retrofitted, most URM buildings close to the fault rupture or in poor soils will sustain extensive damage or collapse, resulting in significant economic loss, injuries, and loss of life. Moderately damaged URM buildings in historic districts will present additional challenges to historic preservation boards during the recovery period.

Pre-1973 reinforced concrete tilt-up structures are another class of structures highly vulnerable to the scenario earthquake. Constructed in the region since the 1950s, the industrial area south of downtown Seattle is home to the majority of older tilt-up buildings. The expansion of tilt-up construction followed population growth into the suburbs and throughout the Central Puget Sound region. These structures primarily house light industrial and manufacturing facilities, supply warehouses, and retail stores. Many tilt-up buildings in low-lying areas near the fault rupture will partially collapse; those located along river valleys in Bothell, Redmond, Kent, and Auburn will suffer similar damage.

Performance of low- and mid-rise structures depends upon their age, construction type, location, and soils. Structures built before 1970, unreinforced masonry buildings and pre-cast reinforced concrete parking structures are most vulnerable to damage. Extensive damage will close indefinitely half or more of the businesses, offices, restaurants, and retail in these buildings in the South of Downtown District, International District, Pioneer Square, and along the Elliot Bay waterfront. Newer retail and office structures will close for two to four weeks, primarily due to less damage and a lack of utilities. Damage to low- to mid-rise structures and building closures in other areas of the region will be a function of distance from the fault rupture and whether they are in areas of severe ground shaking or on liquefiable soils. For example, more than half of these structures in Renton, Kent, Auburn, Sumner and Puyallup will experience extensive damage because of soil liquefaction. Businesses in low- to mid-rise structures in Mercer Island, Bellevue, and Issaquah's Old Town will close for up to a month for inspections and repairs.

High-rise buildings in Seattle and Bellevue central business districts will experience very strong ground motions, exceeding levels recorded in downtown San Francisco and Los Angeles during the 1989 and 1994 earthquakes, respectively. Nearly all high-rise buildings in Seattle and Bellevue will have visible structural damage and shattered windows, with about half of the pre-1975 high-rise building stock extensively damaged; collapse of a few older buildings is expected. Nonstructural damage will be widespread. Damage will be less in high rises in Tacoma and Everett central business districts due to less severe ground shaking there.

About one-third of residential structures in areas of severe ground shaking will be extensively damaged and unsafe to occupy. The most significant impact on residential structures will be structural damage, such as collapse of unretrofitted unreinforced masonry buildings and buildings with large openings at ground level. Unanchored structures will slide off foundations, and masonry chimneys will collapse and fall onto homes. Ground failures will damage foundations. Nonstructural damage will be common; broken gas pipes will create a fire hazard, and fractured water pipes will result in loss of potable and firefighting water supply.

Structures of some industrial facilities predate modern seismic design, and many are in areas subject to liquefaction-caused damage. Vulnerable facilities will experience structural damage, loss of manufacturing equipment, prolonged downtime, loss of production, and loss of market share. Facilities within a mile or two of the fault rupture have a high probability of experiencing at least moderate damage, as will more distant facilities on poor soils. Damage to industrial facilities resulted in indirect losses in previous major earthquakes; such impacts include release of hazardous materials, which can have long term environmental effects.

Essential Facilities

Hospitals care for patients from Washington and Alaska, and provide specialty care to patients from throughout the nation. Harborview Medical Center in Seattle is the state's only Level I trauma center. Immediately after the scenario earthquake, the Central Puget Sound region will have a shortage of hospital capacity because of damage to facilities and increased demand. Structural damage will vary depending on the building type, age of construction and building location; much of the damage will be nonstructural, consisting of dislodged equipment, broken pipes and ducts, fallen ceilings, and water damage from sprinkler systems.

Field hospitals will care for some of the injured on a temporary basis. Hospitals will rapidly reconfigure their facilities and operations to provide continuity of care. Staff will triage patients to focus on the highest medical needs and establish special care areas to provide services outside of the traditional patient room. Essential staff will extend their shifts and use in-house lodging until replacement staff arrives. Hospitals will delay non-essential or elective procedures until resuming normal operations and restoring staffing levels.

The loss of essential utilities such as power, water, sewer, and city-supplied steam and of just-in-time delivery of medical supplies, gases and pharmaceuticals will impede the ability of the hospitals to sustain safe operations.

Fire station performance during the scenario earthquake will depend on the level of ground motion at the station location and the age of the structure. Fire stations most at risk are those stations that are older, closest to the fault rupture, or in poor soils. This situation poses a significant challenge to post-earthquake response and suppression of fires given that these areas will experience the highest level of damage and pose greatest demand for service. Delaying response will be digging out of apparatus trapped in damaged stations and unavailability of some units because of damage. Fire stations with heavy structural damage will be unusable. Units returning to these stations will be homeless, requiring temporary quarters for apparatus and personnel while still providing for timely response within a specific area.

Most of the region's police stations are relatively modern construction or seismically retrofitted. Police stations in smaller cities, however, are located in city halls typically not designed as essential facilities. Police response following the earthquake depends on deploying officers to the field. Performance of the transportation infrastructure is important to overall performance of police response; damage to major bridges and roadways will hamper police response significantly.

Schools, typically not considered essential facilities, have unique characteristics that set them apart. School buildings have one of the highest occupant densities of any building type, and society places a high value on protecting children. Communities also look to schools for temporary shelter and distribution points for emergency supplies following disasters. Until the Nisqually earthquake, schools sustained a disproportionately high level of damage from previous earthquakes primarily because of their age, design and construction materials used. Damage to school buildings from the Nisqually earthquake was limited because of ongoing seismic strengthening, non-structural mitigation, and the number of schools built in recent years to modern building codes.

The scenario earthquake will cause the greatest damage to unretrofitted older schools and buildings on poor soils. Immediately after the scenario event, schools will have difficulty sheltering and feeding children, and connecting them with parents; many parents will be unable to reach schools to pick up their children immediately after the earthquake. Schools with slight to moderate damage will be repaired and useable within a few days or weeks; those with extensive damage will be demolished and rebuilt.

School districts will restart classes as quickly as possible. Temporary solutions include busing students to repaired or undamaged schools, some far from home. Crowded schools will double-shift students and bring in portable classrooms as space allows. Districts will use facilities such as community centers and churches as temporary schools, and explore on-line teaching after restoration of telecommunications systems.

Also of concern is the Seattle campus of the University of Washington. Daily, the university is home to 39,000 students, 23,400 faculty and staff, and hundreds of visitors and patients in hospitals and clinics. The university, one of the top research institutions in the nation, has significant holdings of irreplaceable research and research specimens in laboratories, as well as valuable artifacts in museums and art collections. The average age of the university's buildings is 43 years; some seismic strengthening has taken place in recent years. While the campus is outside the area of greatest ground shaking, the impact of the scenario earthquake could cause serious damage to buildings and infrastructure and compromise the university's ability to function as an educational and research institution.

Call to Action

Priority Recommendations

1. Establish a funded state-level seismic safety board or commission, reporting directly to the Governor to recommend polices and programs to reduce the earthquake risk in Washington.
2. Identify critical public facilities statewide that have a high seismic risk and establish long-range plans to improve their safety in an earthquake.
3. Develop local and state funding and legislation requiring mandatory seismic retrofits of high-risk buildings, such as unreinforced masonry and tilt-up structures.
4. Establish and implement a strategy to quicken the pace of protecting seismically vulnerable critical transportation infrastructure.

Other Recommendations

5. Continue to expand and improve information and maps on earthquakes and related geologic hazards, and require their use as best available science for state building codes, local land-use planning and development decisions, and local and state emergency response, recovery and continuity plans.
6. Develop financial and other incentives to increase the level of seismic safety in public and private buildings through structural and non-structural mitigation measures.
7. Develop innovative programs to educate the public, public agencies, and the business community that both appropriately communicates the risk posed by earthquakes and generates action by individuals and organizations so they are self-sufficient for at least 72 hours following an earthquake.
8. Provide adequate funding to upgrade the region's seismograph network to make it more robust and to enhance its capabilities.
9. Establish an earthquake information clearinghouse to improve access to best available science and best practices for earthquakes and related geologic hazards in Washington for the public, government agencies, businesses and other organizations.

Nisqually earthquake 2001. Photo / Federal Emergency Management Agency

Introduction

Earthquakes pose a serious threat to life and property in Washington, particularly the Puget Sound region. A 2001 study by the Federal Emergency Management Agency found the state has the second highest risk of economic loss caused by earthquakes in the nation, behind only California. Seattle ranks seventh among cities nationwide at economic risk to earthquakes; Tacoma ranks 22nd.

The most recent significant event to strike the state was the February, 28, 2001 moment-magnitude 6.8 Nisqually earthquake. It caused $2 - 4 billion in damage, primarily from Olympia north through Seattle.

Many believe that the Nisqually earthquake was largest that could hit the Puget Sound region, and that they are prepared for the next large seismic event.

However, the Nisqually earthquake was not the region's "big one," an earthquake that would cause devastating damage and widespread disruption to transportation systems, utilities, the economy, and (at least temporarily) to the region's way of life, as earthquakes in the past 15 years have in the San Francisco Bay Area, Los Angeles, and Kobe, Japan.

Research in recent years has uncovered active surface fault zones capable of generating major earthquakes in the Puget Sound region. One, the Seattle Fault Zone,[1] runs through the Central Puget Sound region, from Hood Canal in the west, through Puget Sound and south Seattle, and east through Bellevue and Issaquah, roughly parallel to Interstate 90.

This project examines the consequences of a scenario M6.7 earthquake on the northernmost strand of the fault zone, which has the potential for generating the most damaging earthquake seen to date in the United States. It also provides recommendations to local and state policy makers for improving the region's – and the state's – earthquake safety.

A 12-member multi-agency, multi-disciplinary team spent the past three years developing this project. The project team's goal was to prepare a credible description of earthquake damage and impacts that would help elected officials, building owners, engineers, architects, emergency managers, land-use planners, and others prepare a response to such an event, as well as serve as a basis for reducing earthquake risks to life and property.

Describing Damage, Impacts of the Scenario Earthquake

The damage and impacts described throughout this document represent the consensus of project contributors and reviewers of what will happen following the scenario M6.7 earthquake. In all, about 100 individuals with expertise in civil and structural engineering, local and state emergency management, land-use planning, seismology and geology, geographic information systems, and other professions, participated in the development of this project. All were volunteers who received no funding for their efforts.

[1] The terms Seattle Fault Zone and Seattle Fault are used interchangeably throughout this document. The fault zone has a number of strands. The scenario earthquake occurs on the northernmost strand of the fault zone.

An actual fault rupture on the Seattle Fault found in Bellevue in the late 1990s provides the model for the scenario earthquake. The time of day the scenario M6.7 earthquake occurs – 11:37 a.m. – is the worst for human casualties, because most people are involved in activities outside their home – working, at school, shopping, for example – and are more likely to be in buildings that do not perform as well as their wood-frame residential structures.

The descriptions in the text of the effects of the scenario event may differ from those generated by an actual earthquake of similar magnitude on the Seattle Fault. The timelines provided in the narrative for facility closures and reduced-service periods are estimates that depend in part on the commitment, organization, funding, and sheer will of the responding organizations.

In developing this project, participants used existing studies, information developed by regional and national experts in engineering, earthquake science, and emergency management, and modest additional studies, including a loss-estimation projection produced by HAZUS, short for Hazards US, a computer-based loss-estimation model developed by FEMA and the National Institute of Building Sciences. (For more on HAZUS, see page 21.)

Table I-1 - Probabilities for Earthquakes from Various Sources

Earthquake Source and Example Events	Estimated Probability of Occurrence in 50 Years	Approximate Recurrence Interval
Deep / Benioff Zone *Nisqually 2001, M6.8* *Seattle-Tacoma 1965, M6.5* *Olympia 1949, M6.8*	84 Percent	35 - 50 Years
Cascadia Subduction Zone *January 1700, M9 (est.)*	10 - 14 Percent	500 - 600 Years
Shallow Crustal / Puget Basin		
Random M6.5 or greater	15 Percent	333 Years
Seattle Fault M6.5 or greater	**5 Percent**	**1,000 Years**

Source: US Geological Survey, October 2003

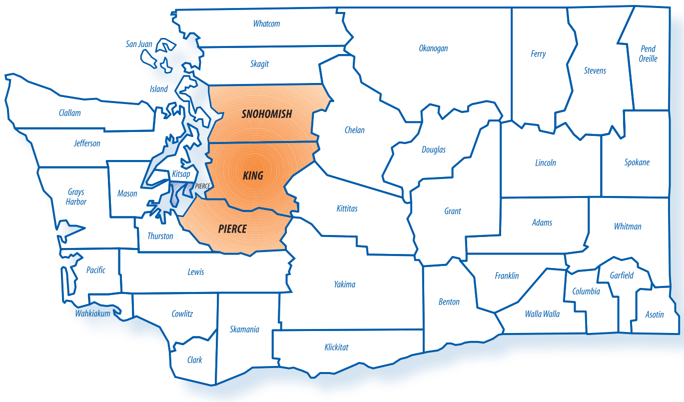
Why Study the Seattle Fault Zone?

The U.S. Geological Survey last developed an earthquake risk assessment for the Central Puget Sound region in 1975. Since that time, understanding of the earthquake risk and the region's population and economy have grown significantly. This has resulted in a much larger exposure to earthquakes than previously imagined (Table I-1).

Until the late 1980s, experts thought the greatest threat posed to the region was from earthquakes deep in the earth's crust, similar to events in 1946 (M6.4), 1949 (M6.8), 1965 (M6.5), and 2001 (M6.8). These earthquakes occur about every 35 to 50 years.

Scientists discovered the Seattle Fault in 1965 when studying gravity data for the Puget Sound region. In 1987, scientists began finding evidence of great earthquakes of M8 to M9 in the Cascadia Subduction Zone off the Washington Coast; these earthquakes occur about every 500 to 600 years. Five years later, a team of scientists discovered the first evidence that the Seattle Fault was active – a magnitude 7.0 or greater earthquake that also generated a tsunami in Puget Sound about 1,100 years ago. In the mid to late 1990s, scientists using high-resolution imaging found evidence of other surface faults. Field evidence show large earthquakes with magnitude 6.5 or greater have occurred on six major fault systems in the Puget Sound region. Scientists estimate these earthquakes occur about once every 333 years.

The project team chose the Seattle Fault Zone for examination because it cuts through the state's most heavily urbanized and industrialized area. The team wanted to explore how a M6.7 earthquake on the fault – a smaller event than occurred 1,100 years ago – would affect the people and



Seattle Fault Scenario Study Region — Snohomish, King and Pierce counties.

economy of the Central Puget Sound region. Specifically, the team wanted to know what this earthquake would do to the region's buildings and major structures, its lifeline and transportation systems, its people and communities, its emergency response and recovery, and its economy.

The Study Area

The scenario steering committee chose a three-county area in which to study the impacts of a M6.7 earthquake on the Seattle Fault – Snohomish County to the north, King County, through which the fault zone runs, and Pierce County to the south (see map above).

Together, these counties have more than half (3.1 million) of the state's 6.1 million population.

The region is home to six of the state's 10 largest cities – Seattle, Tacoma, Bellevue, Everett, Federal Way, and Kent.

Fortune 500 companies headquartered in the region are Costco, Microsoft, Weyerhaeuser, Washington Mutual, Paccar, Safeco, Nordstrom, Amazon.com, and Starbucks.

Major private employers include The Boeing Co., Safeway Inc., Group Health Cooperative, Providence Health System, Swedish Medical Center, Bank of America, and Alaska Air Group. Major public employers include the US Army (Fort Lewis and Madigan Army Medical Center), US Air Force (McChord AFB), US Navy (Naval Station Everett), and the University of Washington.

The Ports of Seattle and Tacoma annually move more than half of all goods shipped internationally from the state ($57 billion of $107 billion in 2001).

Top exports include aircraft and aircraft parts, and agricultural and wood products. The Boeing Co., manufacturer of commercial aircraft, is the nation's largest exporter.

Seattle-Tacoma International Airport is the 15th busiest airport in the nation, moving 26.6 million passengers and 400,500 metric tons of cargo in 2002.

The median household income in each of the three counties is above the state average of $44,776 (King County, ranks #1, $55,157; Snohomish County, #2, $53,060; Pierce County #8, $45,204).

Limitations of the Scenario

The Seattle Fault Earthquake Scenario has limitations, as major studies typically do. The three major issues that this scenario document does not explicitly address are aftershocks, the generation of a tsunami or seiches, and fires.

Aftershocks

Aftershocks will occur following a crustal earthquake such as the scenario event.

Aftershocks for the scenario earthquake could reach magnitude 6.0 or greater. They disrupt impacted communities by causing additional damage to already weakened buildings and infrastructure, impeding relief efforts by making it unsafe to enter damaged buildings, causing more injuries and deaths, and placing an enormous toll on the mental health of an already shattered community.

The project team decided early in its work not to specifically address aftershocks, believing that this would complicate an already complex analysis of the scenario event without adding substantially to the information presented.

As a crustal earthquake, the M6.7 scenario event would generate significant aftershock activity, probably similar in nature to those produced by recent California, Japan, and Taiwan crustal earthquakes.

Hundreds of aftershocks occurred after the M6.9 1989 Loma Prieta event, the M6.7 1994 Northridge earthquake, the M6.9 1995 Kobe event, and the M7.6 1999 Chi-Chi earthquake in Taiwan. Both the Loma Prieta and Northridge earthquakes had a significant number of aftershocks greater than magnitude 4.0 within the first week to 10 days after the main shock (Loma Prieta – 20, Northridge – 13). The much larger Chi-Chi earthquake had a number of aftershocks ranging from M6.0 to M6.8 in the five days after the main shock.

Tsunamis and seiches

Large earthquakes can generate tsunamis, damaging waves that result from movement in the water column caused by deformation of the sea floor or lakebed. Earthquakes also cause seiches, waves in an enclosed or partially enclosed body of water that are similar to sloshing in a bathtub.

Generation of a tsunami in Puget Sound appears unlikely given that the fault rupture of the scenario M6.7 earthquake does not result in changes to the sea floor of the sound. Correspondence with staff at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Lab, however, indicates the scenario event most likely would lead to some inundation and potentially dangerous and damaging water currents along the Seattle waterfront.

Tsunamis are possible in Lake Washington and Lake Sammamish, since the fault rupture crosses the lakes, changes shoreline elevations, and may change elevations in the lakebeds.

The scenario earthquake most certainly would generate damaging seiches in bodies of water throughout the study region. Like tsunamis, seiches threaten people and structures such as marinas, bridges and structures on or near shorelines. Of particular note is Lake Union, which has a history of seiches from both local and distant earthquakes that damaged houseboats in the lake, buckled their moorings, and broke their sewer and water lines.

Despite the possibility of tsunamis and seiches, the project team did not examine their impacts. Needed is additional research and modeling to determine whether the scenario earthquake indeed would generate a tsunami and to determine the extent of seiches throughout the study area.

About 1,100 years ago, a M7.0 or greater earthquake on the Seattle Fault – much larger than the scenario event – created uplift on the floor of Puget Sound and generated a tsunami. The tsunami deposited sand sheets on West Point in Seattle, at Cultus Bay on southern Whidbey Island, and along tributaries of the Snohomish River between Everett and Marysville. Computer simulations by the Pacific Marine Environmental Laboratory show the tsunami reached heights of 10 feet or more at what is now the Seattle waterfront, inundating Harbor Island, the South of Downtown district, Duwamish Waterway, and Smith Cove between Queen Anne and Magnolia.

Fires

Fire represents a serious post-earthquake hazard; this is another area requiring additional research and study not addressed by the project team. The loss estimation model generated by HAZUS for the scenario event used by the project team indicates the earthquake will cause about 130 fires, burning structures valued at nearly a half-billion dollars and displacing about 6,000 people.

How serious is the fire hazard? Fire, and not the earthquake, was responsible for much of the devastation of San Francisco in 1906; thousands of buildings that survived the earthquake were lost to the fire. While firefighting techniques and water systems have advanced greatly in the past century, fires posed significant problems following the recent Loma Prieta, Northridge and Kobe earthquakes. Broken gas and liquid fuel lines caused many fires. For example, after the Loma Prieta event, a fuel spill caused a fire at the San Francisco Airport, and gas-fed fires destroyed many homes and apartment buildings. Following the Northridge earthquake, 35 units in a mobile home park burned from a gas leak, and a fire in the science complex at California State University–Northridge was caused by spilled chemicals. In Kobe, extreme traffic congestion, collapsed buildings, and rubble in the streets hampered the response of firefighters to several earthquake-caused major conflagrations throughout the city. Firefighters in each of these communities faced a loss of water due to damaged water systems following the earthquake.

Following a large earthquake on the Seattle Fault, local firefighters would face many of the same challenges as their colleagues have in previous earthquakes – fires in buildings of all types, port facilities and fuel depots from broken natural gas and liquid fuels pipes and spilled chemicals, a lack of water to fight fires, and poor access to fire sites.

Use of HAZUS for Loss Estimation

The project team in developing this scenario used damage estimates and community impacts generated by a computer loss-estimation modeling program called HAZUS, short for Hazards US. The team combined the information generated by HAZUS with current knowledge of structures and development trends to describe the impacts of the scenario earthquake.

HAZUS, developed by the Federal Emergency Management Agency and the National Institute of Building Sciences, used current scientific and engineering knowledge of the effects of earthquakes, information on local geology, national level databases with information on local population, building stock, infrastructure and economy, to produce estimates of damage from the scenario earthquake. HAZUS generated reports and maps that provide information on physical damage to residential and commercial buildings, schools, critical facilities, and infrastructure; economic loss, such as lost jobs, business interruptions, repair and reconstruction costs; and social impacts to people, including requirements for shelters and medical aid.

For this scenario, the project team relied upon a Level 1 analysis, in which HAZUS used default national databases and information to generate its report and maps.

Prologue

■ *Today is a typical, drizzly mid-November weekday morning in the Central Puget Sound region.*

■ *With less than an hour left in the morning, Amy King began settling down her fourth graders at Sunrise Elementary in Bellevue for their weekly spelling test.*

■ *Jerry Liu and Mark Fisher left their office in a downtown Seattle high-rise for an early lunch. Mark was very excited about the new house he had just bought on Mercer Island. Jerry decided to head home to Issaquah after lunch; he thought his wife Cynthia would appreciate help with the special delivery of her custom-made chocolates.*

■ *George Volnitzski was happy as he drove out of the truck dealer's lot in Kent with his new diesel pickup. He thought he had time to grab a burger before heading back to Volnitzski's Fresh Meat, his uncle's wholesale meat distribution business in Renton.*

■ *Lisa Bona, in Seattle on her first visit from Chicago, spent the morning walking along First Avenue from the Pike Place Market to Pioneer Square with her sister Marjorie. At Yesler Street, they decided a nice hot bowl of soup and a coffee would be a good way to get out of the rain and take the chill off. This afternoon, they would head to the hospital for a biopsy of the lump on the back of Marjorie's left hand. Lisa felt they should enjoy the rest of the morning, as tomorrow they would be back at Marjorie's place on Bainbridge Island waiting for the results.*

■ *At 11:37 a.m., all of their plans changed.*

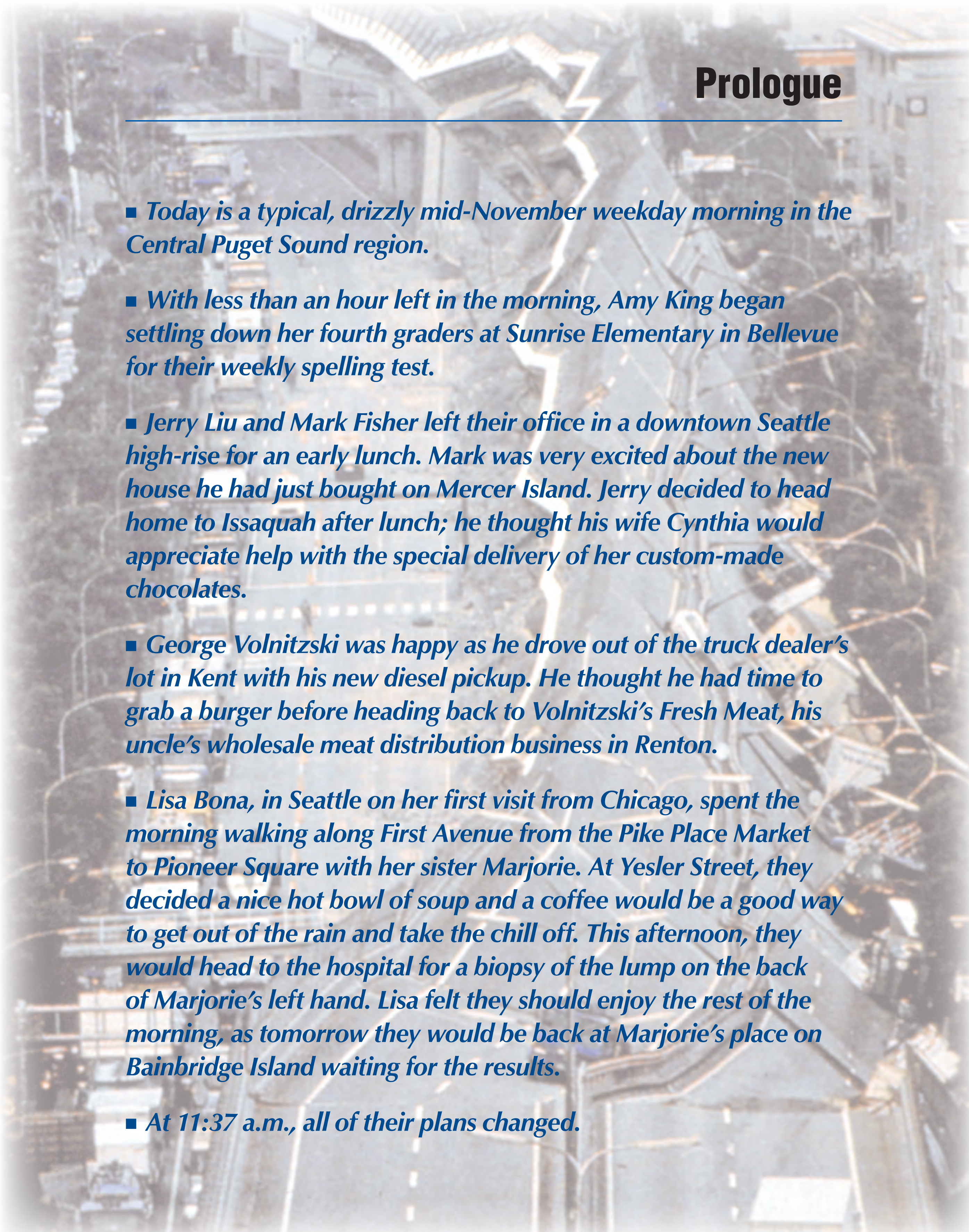


Photo / Dave Swanson

Chapter 1

The Scenario Earthquake and Ground Motions

Contributors

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■ *Bob Wilton slowly walked down Southeast 38th Street in Bellevue toward Lake Sammamish. Except for a car coming into view, he had the street to himself. A consulting engineer, Bob had a rare November day off thanks to a sprinkler leak that shorted the electrical system in his firm's small office building. Confined to the back storage area, little of importance was lost in the accident, but repairs were more efficient with employees out of the office. The gray skies were threatening, and a brisk wind stirred leaves through the air. Bob's thoughts drifted to the pump station design due next week before coming back to the incessant November rain.*

■ *At that instant, his knees buckled as the earth heaved upward. Losing his bearings, Bob tumbled to the ground, trees cracking and wires arcing around him. Somehow, he was aware of a car pitching across a lawn. His eyes caught large chunks of concrete sidewalk buckling as his face hit soft mud. As the shaking continued, Bob lay flat on the ground, covering his head. He kept telling himself that the shaking would stop.*

■ *Once the shaking stopped, Bob lifted his eyes slowly upward. In front of him, Southeast 38th Street was in two, with parts of the roadway lying in lawns on the north side of the street. The sidewalk on the south side of the street was about six feet higher than the sidewalk on the north side. He tried to focus on the two houses immediately across the street, both slid off their foundations. Turning his head, his eyes caught uprooted trees, a thick layer of mud oozing down the street, and worst of all, a fire near the power line.*

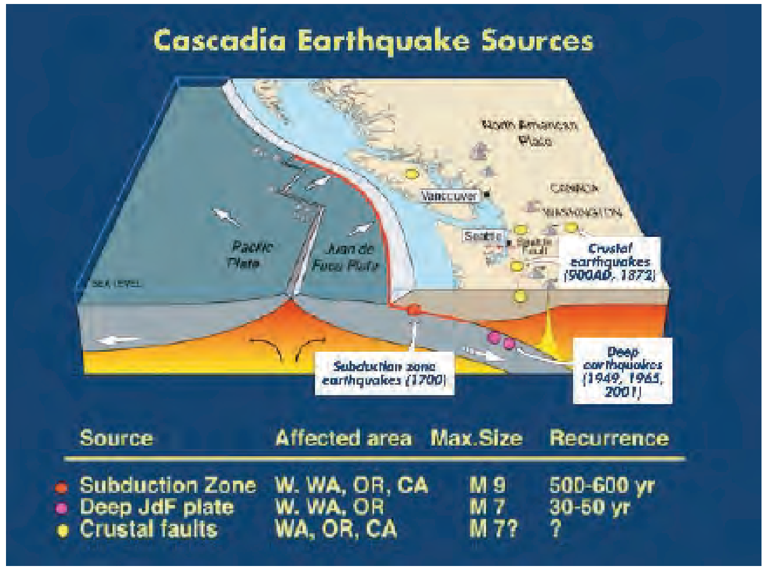
■ *Bob Wilton was at the surface rupture of a magnitude 6.7 earthquake on the Seattle Fault.*

Summary of the Scenario Earthquake

The Seattle Fault Scenario Project Team chose to model an earthquake of magnitude 6.7 on the northernmost strand of the Seattle Fault Zone. The scenario event is based on the earthquake that probably caused a mapped surface rupture on the fault in Bellevue. That event caused about 6.5 feet of surface displacement just west of Lake Sammamish in southeast Bellevue, near Southeast 38th Street. The model parameters used for the scenario earthquake are:

1. Moment magnitude of 6.7.
2. Surface rupture of about 6.5 feet (matches results from a trench excavated by the U.S. Geological Survey).
3. Fault rupture length about 14 miles, divided into 4 segments, from Harbor Island to just east of Lake Sammamish.

Figure 1-1. Simplified earthquake setting of Washington. Three distinct earthquake source zones are responsible for earthquake hazards in Western Washington.
Graphic / US Geological Survey



Puget Sound Earthquake Source Zones and Seismic Hazards

Puget Sound's earthquake hazard reflects its tectonic setting (Figure 1-1). The Pacific Northwest is at a collision boundary between two plates of the Earth's crust. This boundary, called the Cascadia Subduction Zone, is where the Juan de Fuca plate dives (or subducts) beneath the North American plate. This zone lies offshore from southern British Columbia to northern California. These plates move toward one another about 2 inches per year. Additionally, the northward-moving Pacific plate is pushing the Juan de Fuca plate north, causing complex seismic strain to accumulate. The abrupt release of this slowly accumulated strain causes earthquakes.

Because of the subduction process, Puget Sound – and the rest of Washington – is vulnerable to earthquakes originating from three sources: 1) in the subducting Juan de Fuca plate (called a Benioff zone or intraplate quake); 2) between the colliding Juan de Fuca and North American plates (subduction zone quake); and 3) in the overriding North America plate (shallow crustal quake).

A Seattle Fault earthquake is an example of a shallow crustal earthquake.

Shallow Crustal Earthquakes

Shallow crustal earthquakes occur within about 20 miles of the Earth's surface. The Puget Sound region has six known surface fault zones capable of generating shallow crustal earthquakes. One is the Seattle Fault Zone. These faults are of particular concern, as much of the region is heavily urbanized and populated.

The Seattle Fault generated a magnitude 7 or greater earthquake about 1,100 years ago. Evidence of this event includes a tsunami deposit on the shores of Puget Sound, landslides in Lake Washington, rockslides in the Olympic Mountains, and 22-foot uplift of a marine terrace on Bainbridge Island.

The state's two largest shallow crustal earthquakes observed by European settlers occurred in Eastern Washington in 1872 (magnitude 6.8) and 1936 (magnitude 6.1). A series of

Table 1-1. Measuring Earthquake Intensity and Ground Shaking

Intensity is a measure of how the ground shakes as well as the effects of an earthquake. Intensity varies from site to site depending on factors such as distance from the earthquake, and rock and soil conditions. Effects of an earthquake include potential damage, perception of shaking, and permanent changes in the landscape from ground failure.

The intensity scale used most often in the United States is the Modified Mercalli Scale (MMI), which uses Roman Numerals to represent progressively greater ground shaking and damage.

Peak Ground Acceleration (PGA) is the measure of the greatest velocity of ground shaking caused by an earthquake and the force this shaking applies to buildings. These forces are expressed as a percentage of gravity (%g), with higher numbers representing progressively greater force being applied by ground motions. Many building codes describe how much horizontal force a building should be able to withstand during an earthquake.

The table below provides a comparison of damage or impacts of earthquakes of various intensities, and levels of ground shaking. Using the table, one can compare impacts of the 2001 Nisqually earthquake (peak ground accelerations reached 30 percent of gravity) with anticipated impacts of the scenario Seattle Fault earthquake (peak ground accelerations anticipated at 70 percent of gravity).

MMI	PGA % g (est.)	Perceived Shaking	Potential Damage
IV	1.4-3.9% g	Light	Most people indoors feel movement. Hanging objects swing. Windows, dishes, doors rattle and glasses clink. Walls of wood frame buildings creak. Parked vehicles rock.
V	3.9-9.2% g	Moderate	Almost everyone feels movement. Doors swing open or close. Shutters and pictures on wall move. Sleeping people awakened. Small, unsecured objects move or topple. Liquids in containers may spill.
VI	9.2-18% g	Strong	Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Weak plaster and masonry crack. Damage slight in poorly constructed buildings. Trees and bushes shake.
VII	18-34% g	Very Strong	People have difficulty standing. Drivers on road feel their cars shake. Furniture may overturn and break. Loose bricks fall from buildings and masonry walls. Plaster and masonry crack. Weak chimneys break at roofline. Poorly constructed buildings badly damaged.
VIII	34-65% g	Severe	Drivers have trouble steering. Towers, chimneys and other tall structures may twist and fall. Houses not bolted may shift off foundations. Damage considerable in poorly constructed buildings, moderate in well-constructed buildings. Tree branches break and fall. Changes occur in flow or temperature of springs and wells. Cracks appear in wet ground and on steep slopes.
IX	65-124% g	Violent	Masonry structures and poorly constructed buildings seriously damaged or collapse. Houses not bolted shift off foundations. Reservoirs seriously damaged. Underground pipes break. The ground cracks. Sand craters form in some areas.
X	>124% g	Extreme	Most buildings and their foundations destroyed. Dams and dikes seriously damaged. Large landslides occur. Water sloshes onto banks of channels, rivers, and lakes. Sand and mud shift horizontally on beaches and flat land. Railroad tracks bent.

shallow earthquakes has occurred in Western Washington in the past 50 years, but none larger than magnitude 5.5. Despite this, scientists believe that a shallow crustal earthquake of magnitude 6.5 or greater occurs on one of the Puget Sound region surface fault zones about once every 333 years.

Benioff Zone (Intraplate) Earthquakes

Benioff Zone or intraplate earthquakes occur within the subducting Juan de Fuca plate at depths of 15 to 60 miles; the largest events typically occur at depths of 25 to 40 miles. The largest of the recorded events is the M6.8 Olympia quake in 1949. Other significant Benioff zone events include the M6.5 Seattle-Tacoma quake in 1965, the M5.8 Satsop quake in 1999, and the M6.8 Nisqually quake in 2001.

Since 1900, there have been six Benioff Zone earthquakes in the Puget Sound basin with measured or estimated magnitude of 6 or larger. Scientists believe large earthquakes in this zone occur about once every 35 to 50 years.

Subduction Zone (Interplate) Earthquakes

Subduction zone or interplate earthquakes occur along the interface between the Juan de Fuca and North American plates. Scientists have found evidence of great-magnitude earthquakes along the Cascadia Subduction Zone. These earthquakes were very powerful, with a magnitude of 8 to 9 or greater; they have occurred at intervals as short as 100 years and as long as 1,100 years. The most recent of these great earthquakes struck the state on January 26, 1700. The magnitude 9 earthquake produced a tsunami that affected both the North American coast and Japan.

Scientists currently estimate that a magnitude 9 earthquake in the Cascadia Subduction Zone occurs about once every 500 to 600 years.

Probabilistic Ground Motions

A useful representation of earthquake hazards is the probabilistic hazard map developed by the U.S. Geological Survey. This map helps determine seismic building codes and highway construction standards. The probabilistic hazard map for Washington (Figure 1-2) shows that in one year, there is a one in 2,500 chance that the peak horizontal ground motions expected on a hard rock site will be greater than the accelerations shown. The map is based on all three potential earthquake sources for the Pacific Northwest as well as the uncertainty of each source zone.

The bulls-eye of higher hazard over the Central Puget Sound region reflects the current understanding of the Seattle Fault Zone and illustrates how new knowledge of an individual fault changes hazard assessments. The projected ground motions are some of the highest in the country.

A History of Large Regional Earthquakes

The frequency of Benioff Zone earthquakes greater than magnitude 6.5 established the Puget Sound area as vulnerable to large earthquakes. However, many who live and work in the region lack a true understanding of the earthquake hazard because until recent years it was poorly understood.

Before the late 1980s, the earthquake hazard assessment did not consider the threat of events

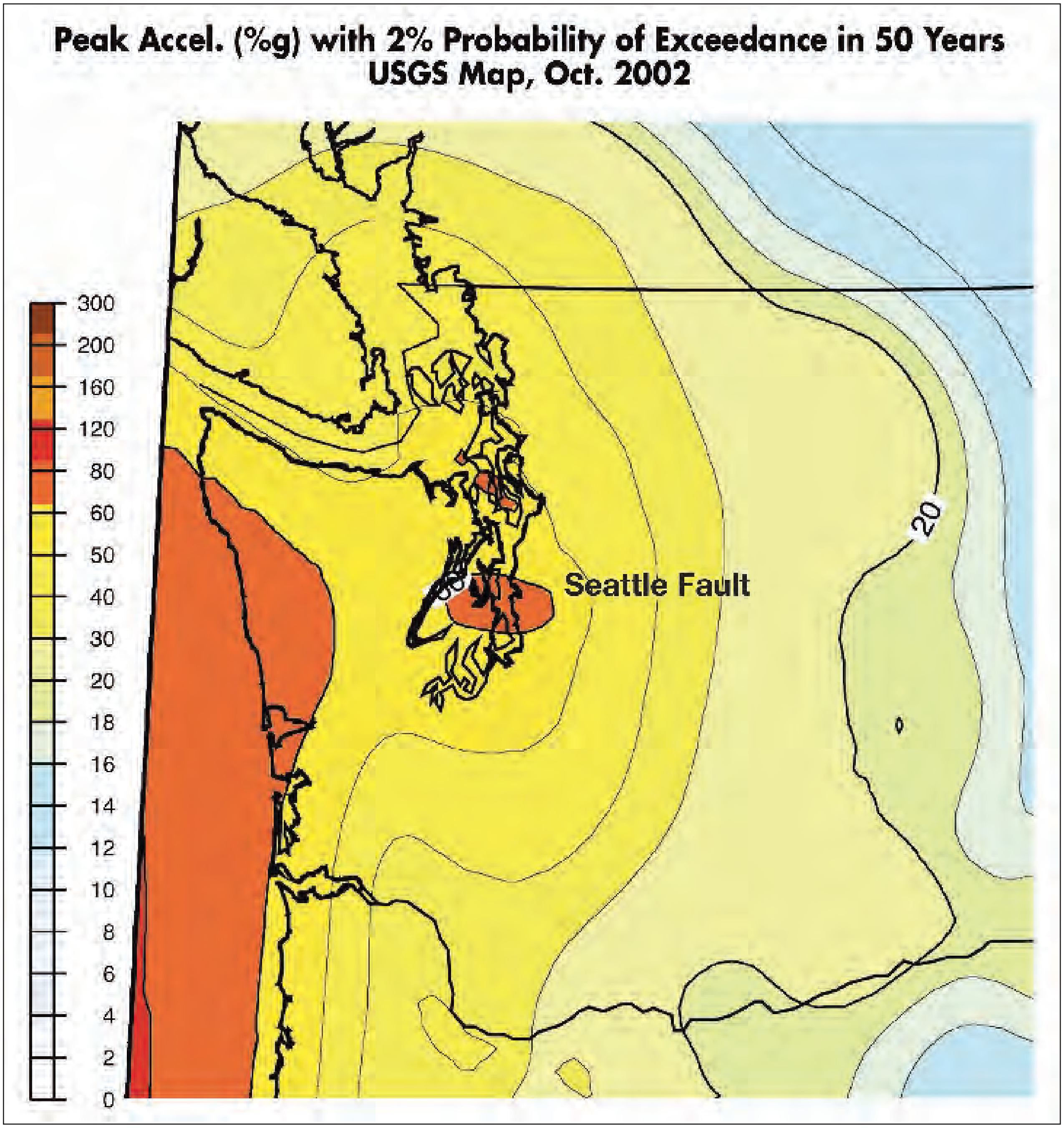


Figure 1-2. Probabilistic seismic hazard map for Northwestern Washington. The plotted values are based on estimates of earthquake magnitude, recurrence, and location from the three earthquake source zones. Note the higher hazard probability for the Seattle Fault Zone, center.

Graphic / US Geological Survey

on shallow crustal faults even though scientists had defined several faults; they also did not believe the huge offshore Cascadia Subduction Zone was active.

The understanding of the region's earthquake threat began changing dramatically in 1987. That is when scientists discovered estuaries on the Washington coast subsided more than three feet very rapidly and that sand, most likely from a tsunami, covered the surface of the pre-earthquake coastal marsh. The most plausible explanation was a great earthquake in the Cascadia Subduction Zone. Since then, scientists found similar evidence from Vancouver Island to northern California; in many bays and river banks, evidence supports multiple earthquakes over the last several thousand years.

In 1992, a team of scientists determined that the Seattle Fault Zone, cutting the central Puget Sound basin from Hood Canal to Issaquah, produced a very large earthquake about 1,100 years ago. (The Seattle Fault Zone consists of several nearly parallel faults. The term zone refers to all of the individual faults. Geologists have given specific names to some of the parallel faults, e.g., Toe Jam Hill fault.) This earthquake uplifted the coast of southeastern Bainbridge Island about 22 feet, generated a tsunami in Puget Sound, and caused numerous landslides from the Olympic Mountains to Lake Washington. Scientists concluded the Seattle Fault zone was active. Beginning in 1998, high-resolution topography data greatly improved geologists' ability to image faults, speeding the pace of discovery of active crustal faults.

By early summer of 2004, field evidence showed six major crustal fault systems caused surface faulting of several feet or more during the past 12,000 years. The recent discoveries clearly demonstrate that large magnitude crustal earthquakes pose a significant hazard in the Puget Sound region.

Figure 1-3: Crustal Faults in Southern and Central Puget Sound region. SFZ is the Seattle Fault zone, TFZ is the Tacoma Fault zone, SWIFZ is the Southern Whidbey Island Fault zone, OF is the Olympia Fault and FC is the Frigid Creek Fault. Triangles or dots indicate coastal marshes with geologic evidence of sudden elevation change attributed to past earthquakes, with uplift (open triangles), subsidence (filled inverted triangle), or no elevation change (filled circle). The time of last movement of the big faults indicated in the Olympic Mountains is unknown.

Graphic / US Geological Survey

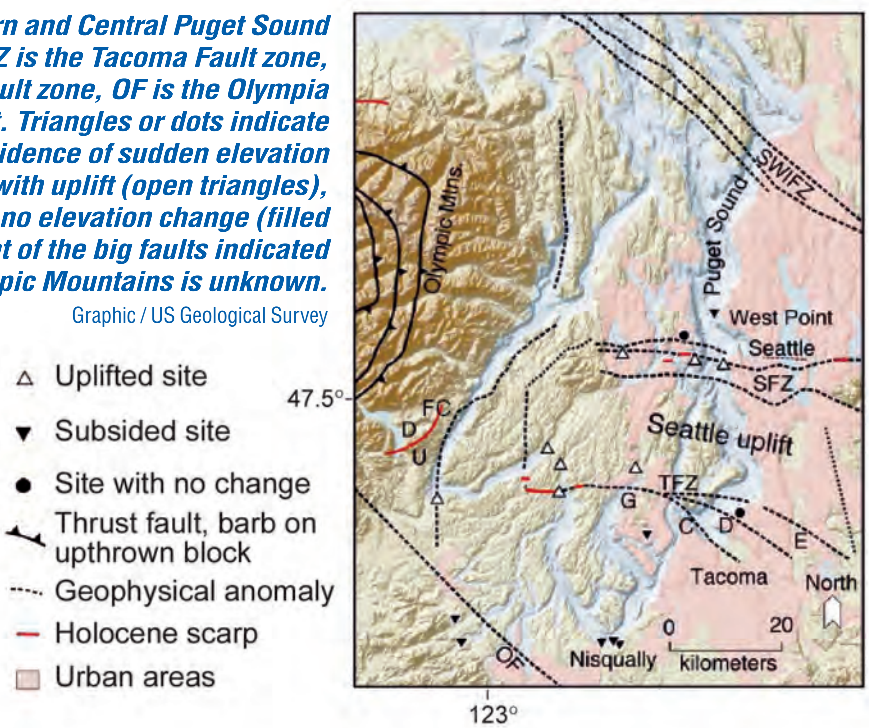


Figure 1-4: Prehistoric uplift of a beach at Restoration Point on Bainbridge Island, Washington. The beach in the foreground was uplifted about 22 feet during an earthquake on the Seattle Fault about 1,100 years ago.

Photo / Robert Bucknam, US Geological Survey

The Seattle Fault Zone and the Scenario Earthquake

Investigations over the past 10 years convincingly show that a series of large crustal faults cut across the greater Puget Sound area. These faults are complex zones that typically have several nearly parallel strands. Figure 1-3 shows the known large crustal faults and highlights locations of fault scarps studied by scientists.

Three major fault zones – Seattle, Tacoma, and Southern Whidbey Island – cut through the heavily urbanized region of Central Puget Sound. Of these, the Seattle Fault is the best studied and the most critical feature of regional hazard assessments because of its proximity to so many people and infrastructure.

The discovery of the vertical land elevation changes (Figure 1-4) sparked considerable research on the Seattle Fault Zone. One experiment suggested the location of three strands of the Seattle Fault Zone (Figure 1-5, see page 28). These strands curve from southern Bainbridge Island through south Seattle before bending more northeastward and crossing Lake Washington to the greater Bellevue area. The strands are consistent with recent LIDAR data, an earthquake sequence found on Bainbridge Island, and earlier marine work. (LIDAR is a remote sensing technique that uses laser light to

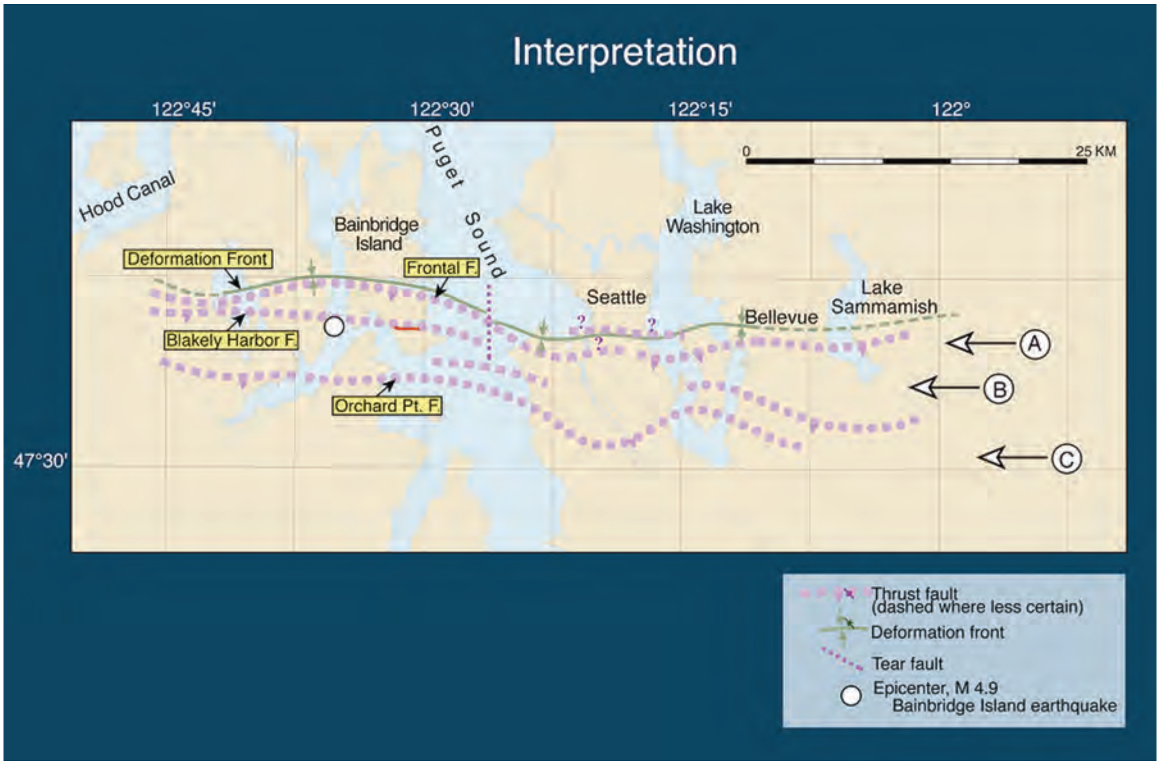


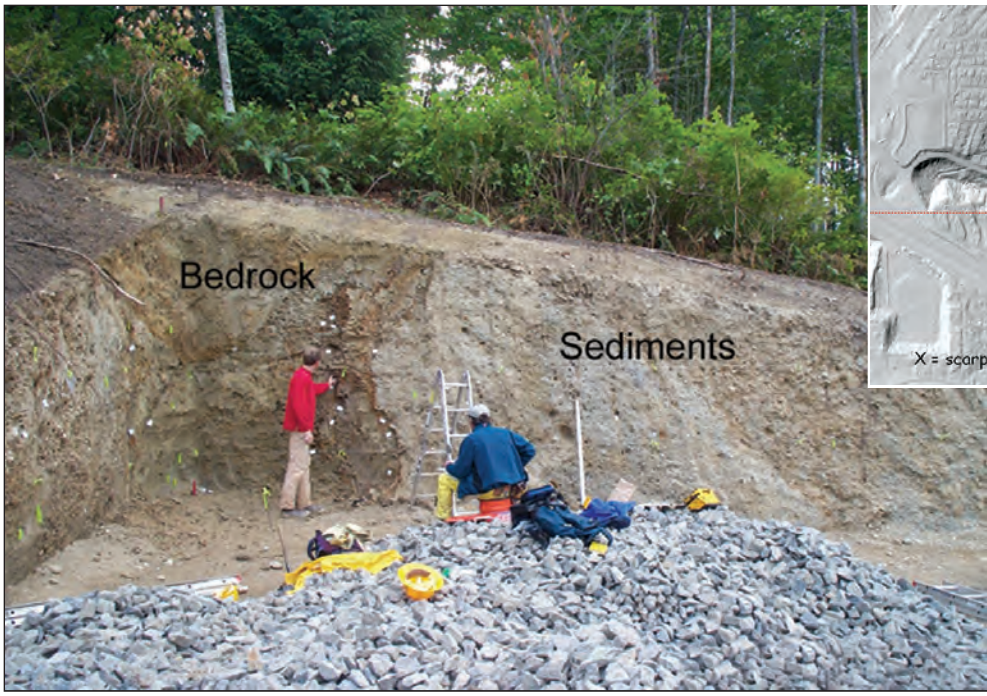
Figure 1-5: Location of strands of the Seattle Fault based on aeromagnetic, marine and land seismic studies, field geology, and LIDAR.
Graphic / US Geological Survey

probe the characteristics of the earth's surface, and is useful for finding earthquake faults.)

The availability of LIDAR data allowed geologists to find the fault in the field for the first time in 1998. Field trenching uncovered several earthquakes on the fault on and near Bainbridge Island. In Bellevue, geologists investigated features along Interstate 90 and found evidence of a scarp, a topographic feature formed when the fault broke the surface, near Vasa Park. Fortuitously, a parking lot excavation across the scarp provided geologists with good exposures of a strand of the Seattle Fault (Figure 1-6). These exposures clearly show the juxtaposition of older bedrock with younger sediments. A second site about 300 feet east of the parking lot excavation provided more clues about this earthquake. That trench revealed a very simple fault, with the south side of the fault pushing up and to the north. Geologists determined that the earth slipped about 6.5 feet at the surface. Organic material found in the trench indicated the fault in this area slipped about 12,000 years ago.

The importance of the Bellevue investigation to the understanding of the Seattle Fault is threefold. First, the trench shows that earthquakes on the Seattle Fault have occurred and produced surface faulting on both sides of Puget Sound. Second, it provides clear evidence for an earthquake unrelated to the one responsible for the large elevation changes of the beaches in Puget Sound (as shown in Figure 1-4). And third, faulting observed in Bellevue, with the south side of the fault moving upward, is different than the north side up motions on faults west of Puget Sound.

The scenario project team is interested in illustrating the problems faced by a more likely earthquake than the large event 1,100 years ago. Because the 6.5 feet of slip observed in the Bellevue trench is consistent with a smaller, but still very dangerous earthquake, the team chose to use it for this scenario.



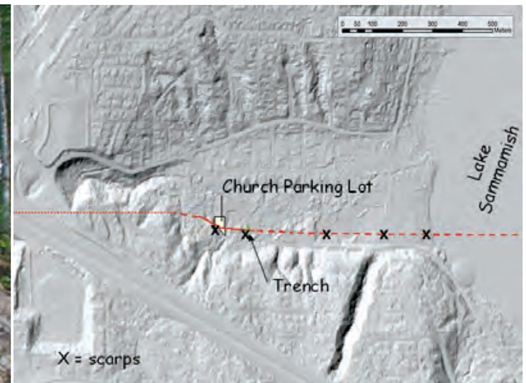
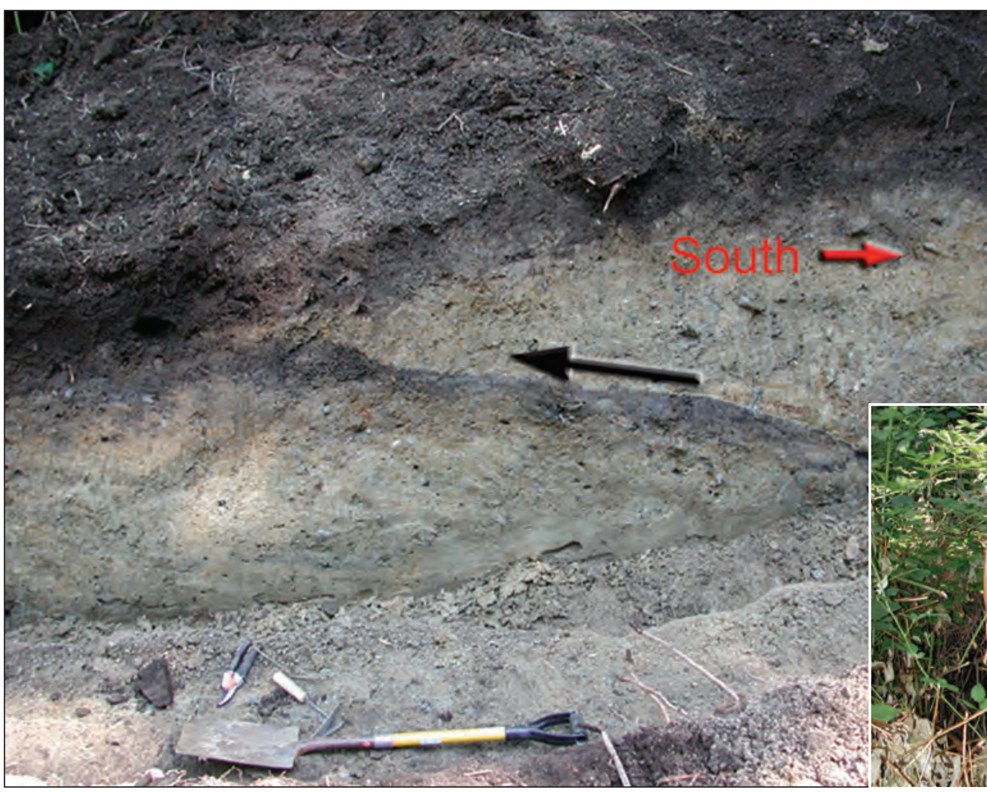


Figure 1-6: Evidence of a past Seattle Fault earthquake in Bellevue. The photo in the top right shows a LIDAR image of south Bellevue, with a lineament shown in red and scarps observed in the field marked. The white trapezoid is the location of the church parking lot. The photo at the top left shows the clear break between older bedrock and younger sedimentary deposits. The bottom left photo of the east wall of the trench shows a very distinct fault trace with about 6.5 feet of offset. The south side of the fault slipped up and over the north side. The photo at the bottom right shows the trench site before excavation.

Photos / Brian Sherrod, Graphic / US Geological Survey



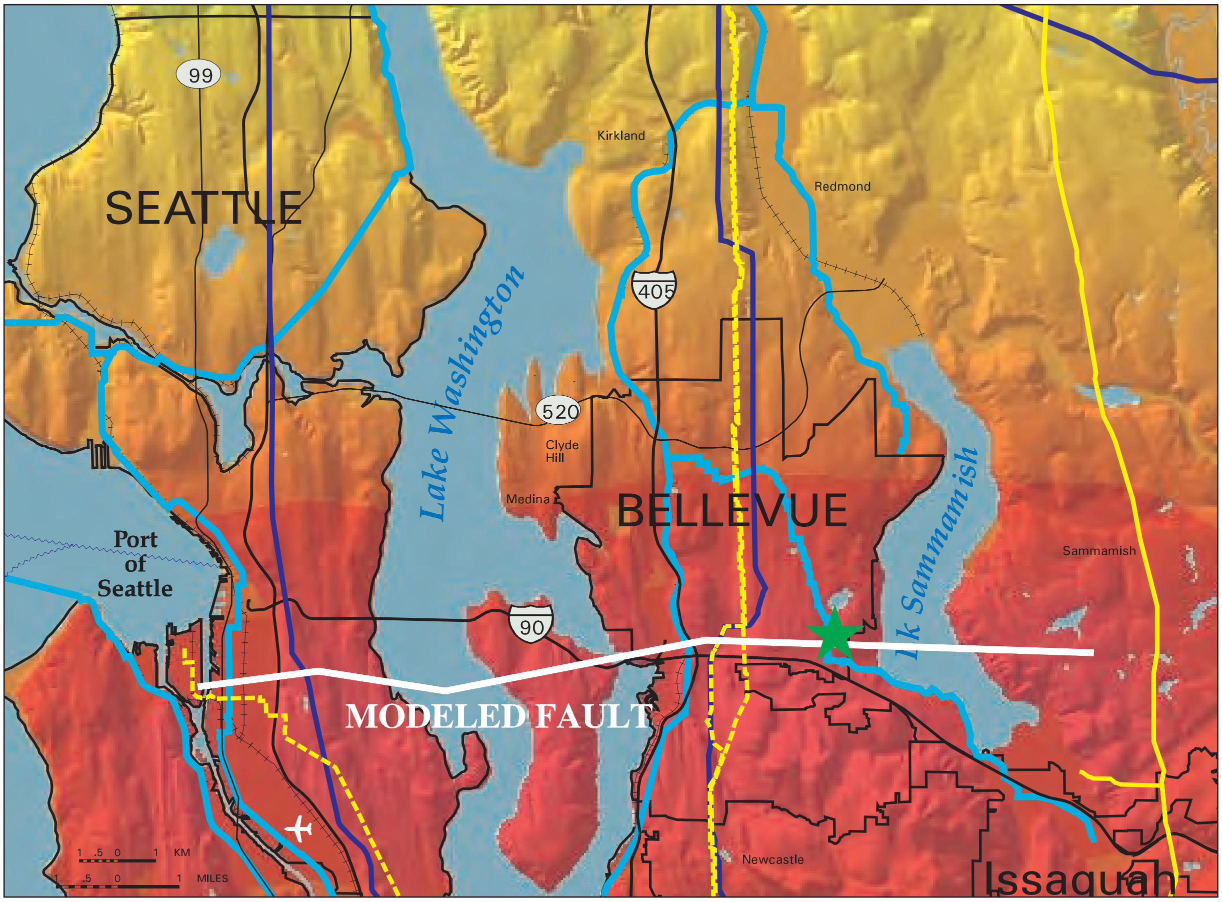


Figure 1-7: Location of the surface fault rupture for the scenario earthquake. The white line shows the modeled rupture where it intersects the surface. It goes through the Vasa Park trench (indicated by the green star). The black lines represent highways, rail lines (crossed lines) and ferry routes (squiggly lines from the Port of Seattle). The yellow lines represent regional natural gas and liquid fuels pipelines. The dark blue lines are major water transmission lines. Lighter blue lines represent primary sewer trunk lines. Graphic / US Geological Survey

Modeling the Scenario Earthquake and Calculating the Ground Motions

An earthquake scenario uses estimates of ground motion to allow engineers and planners to develop the possible effects of the event on the built and natural environments. The first step is to compute median ground motions at the earth's surface for rock site conditions.

The scenario earthquake used in this project has a magnitude of 6.7 and a surface rupture of 6.5 feet, matching the observed faulting at Vasa Park in Bellevue. The fault ruptured length is 14 miles; the rupture extends from Harbor Island to east of Lake Sammamish (Figure 1-7), passing through Seattle, Mercer Island, Bellevue, and north of Issaquah. We calculated peak horizontal ground acceleration often used by emergency managers to guide response planning, as well as spectral response values at 0.3 and 1.0 second periods typically of interest to engineers.

Taking into account differences in local site and soil conditions provides a more realistic picture of the expected pattern of ground shaking; National Earthquake Hazard Reduction Program (NEHRP) amplification factors for different soil conditions were used. A 2003 Seattle-area soils map (Figure 1-8) shows the softest soils, class E, in major river valleys and some smaller drainages. These soils amplify ground motions more than other soil types and are most prone to liquefaction. The stiffest soils, class B, are least prone to amplifying ground motions and liquefying. The other soil classes – C and D – perform in between class B and class E soils.

Applying appropriate soil amplification factors conditions results in very large ground motions for the scenario earthquake. A wide area will experience very strong ground motions in excess of 0.3g, or 30 percent of gravity. Peak ground accelerations over the modeled fault rupture exceed 0.7g, or 70 percent of gravity (Figure 1-9). In comparison, the largest peak accelerations recorded during the Nisqually earthquake were under 0.3g. The scenario event on the Seattle Fault puts ground motions that exceed those experienced in the Nisqually earthquake over virtually all of Seattle, Bellevue, Redmond, Kirkland, and Mercer Island.

Peak ground acceleration helps emergency responders understand the possible effects of an earthquake. Engineers, on the other hand, use the concept of spectral acceleration to explain the effects of strong shaking on various structures. The two ground motion maps, Figure 1-10, show spectral accelerations at 0.3-second period and 1.0-second period. The 0.3-second spectral acceleration map represents the acceleration experienced by a three-story building, and the 1.0-second map represents the acceleration experienced by a 10-story building.

The 0.3-second spectral acceleration values shown in Figure 1-10 are generally proportional to the peak ground acceleration values shown in Figure 1-9. The map of 1.0-second spectral acceleration in Figure 1-10 highlights the amplification of ground motions in areas of E-class soils. Since building damage better correlates with 1.0-second spectral acceleration than with peak ground acceleration, this map indicates that buildings on soil class E have a higher likelihood of damage from shaking than structures built on other soil types.

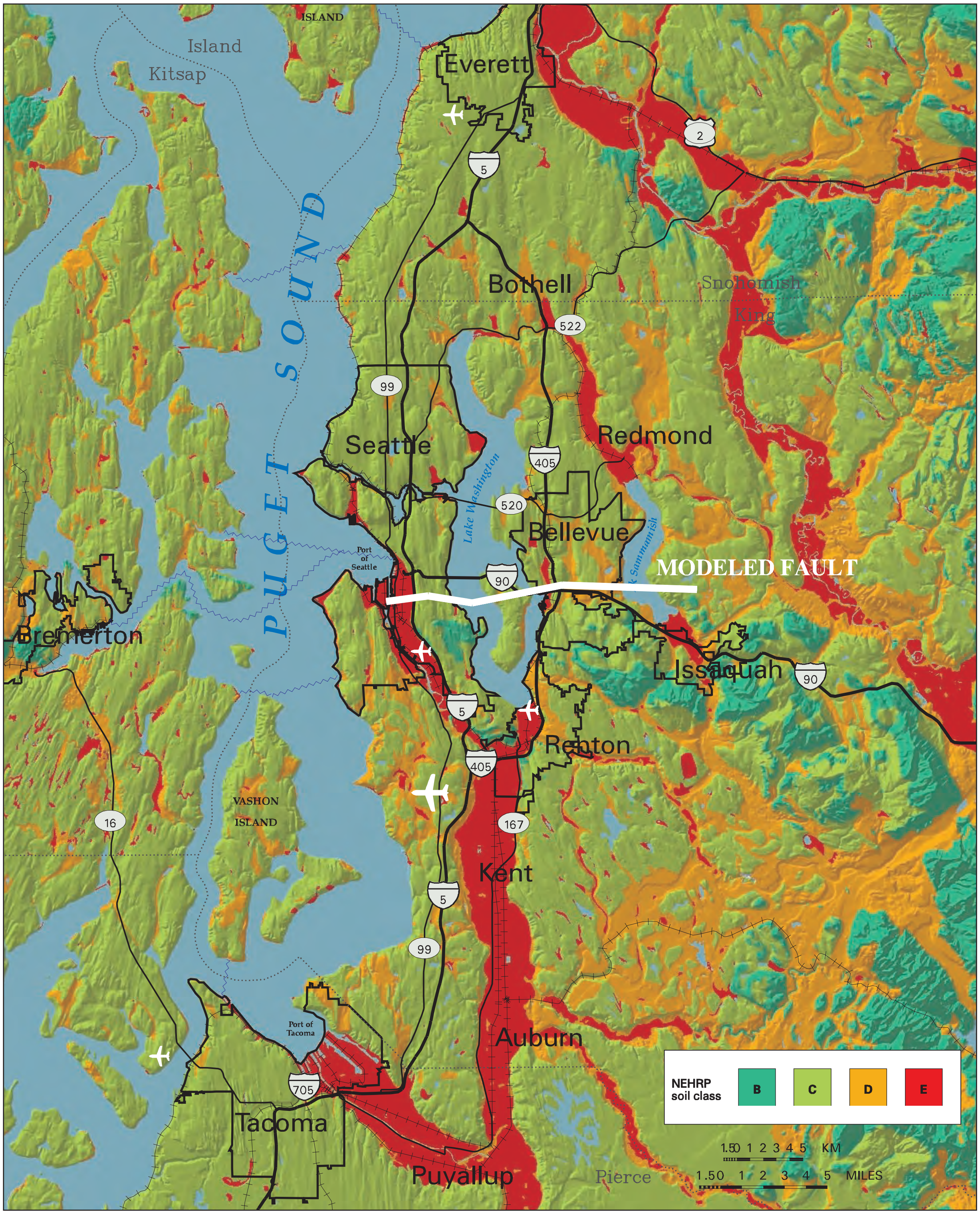


Figure 1-8: NEHRP soils maps for the study region. Earth scientists categorize the upper 100 feet into soil classes based in large part on how they amplify ground motions and their resistance to liquefaction. Class E soils amplify ground motions the most and are the least resistant (most prone) to liquefaction.

Graphic / Washington Department of Natural Resources and US Geological Survey

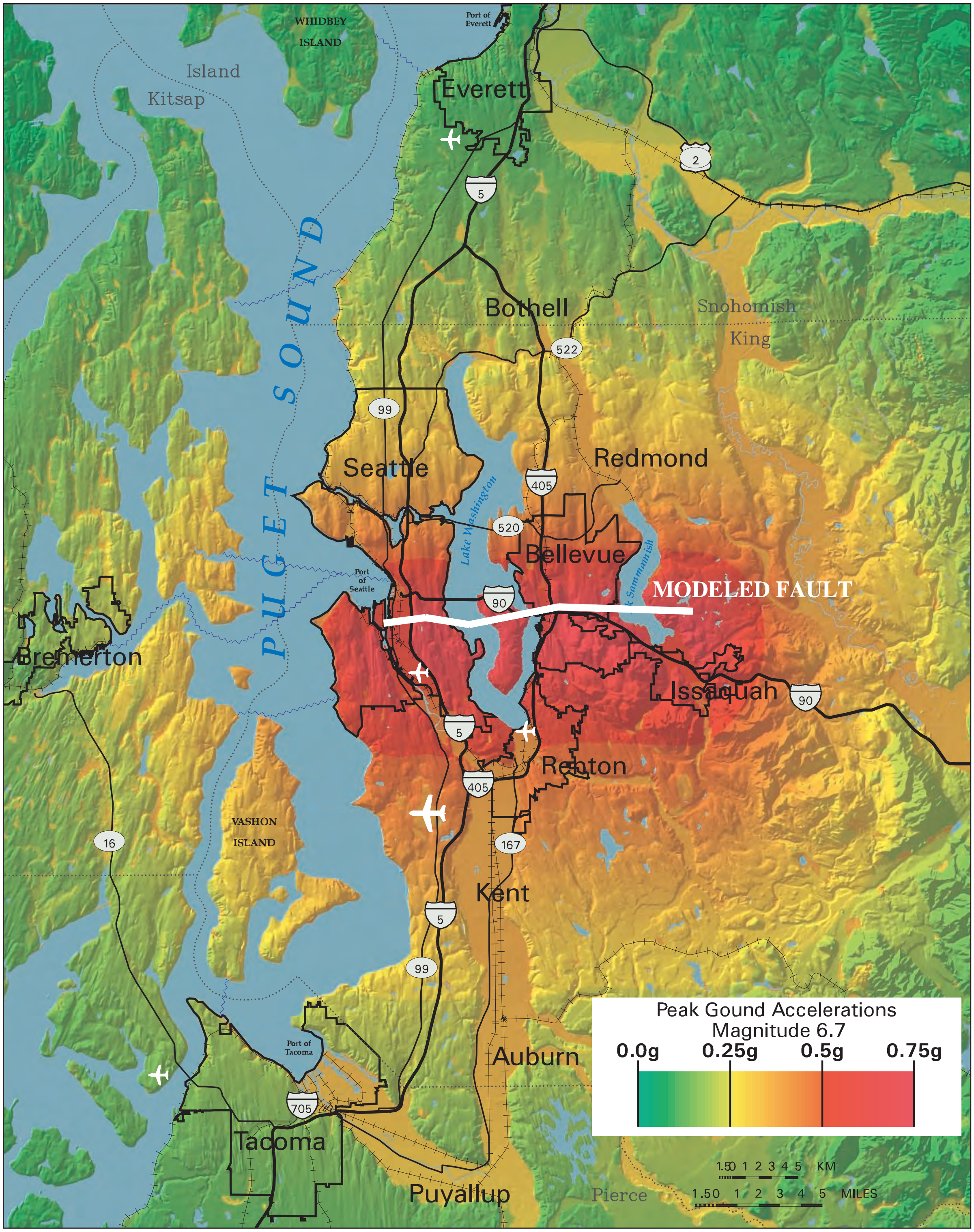


Figure 1-9: Peak ground accelerations for Seattle Fault scenario earthquake using soils map.

Graphic /US Geological Survey

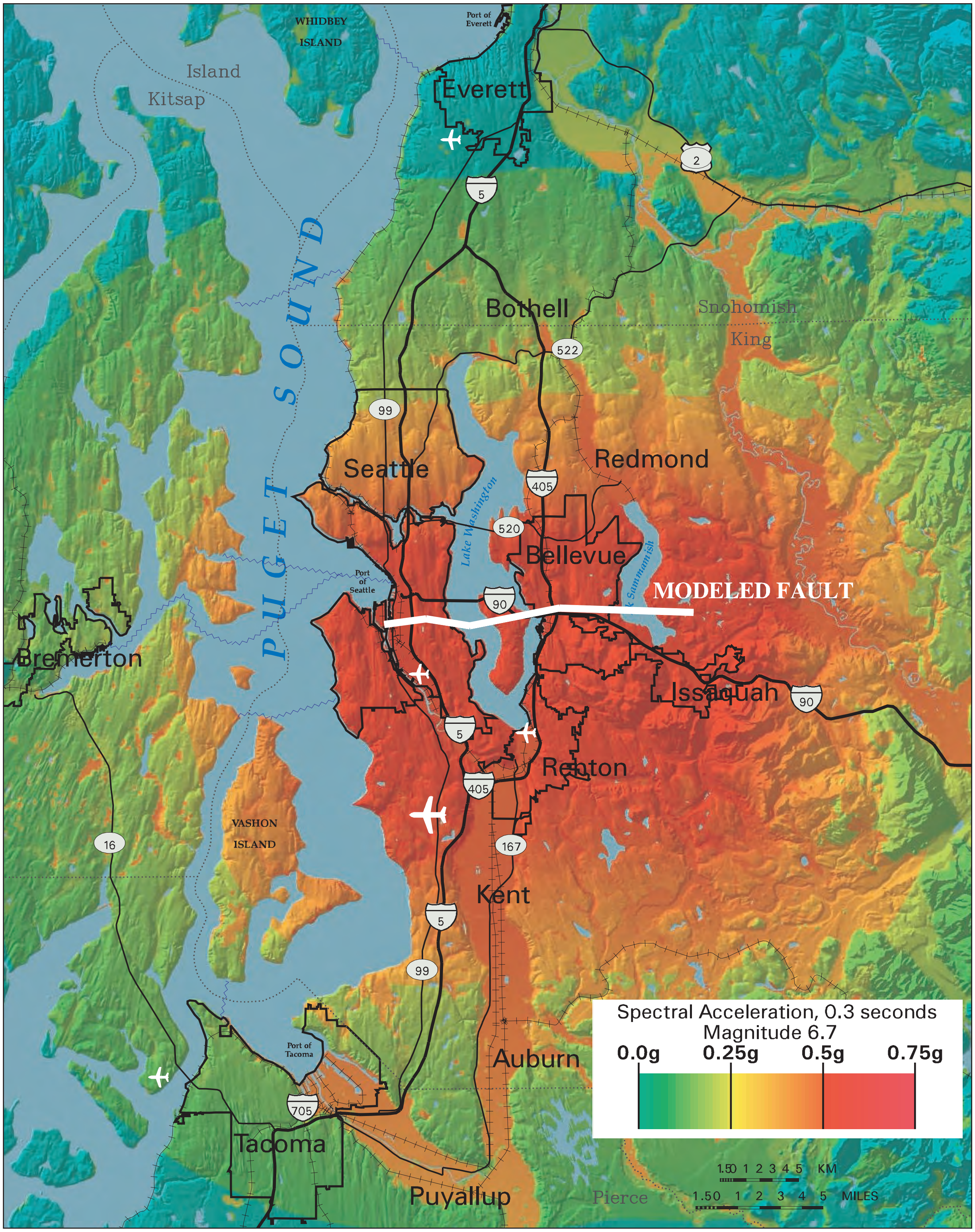


Figure 1-10a: Spectral acceleration at 0.3 seconds for M6.7 scenario earthquake.

Graphic / US Geological Survey

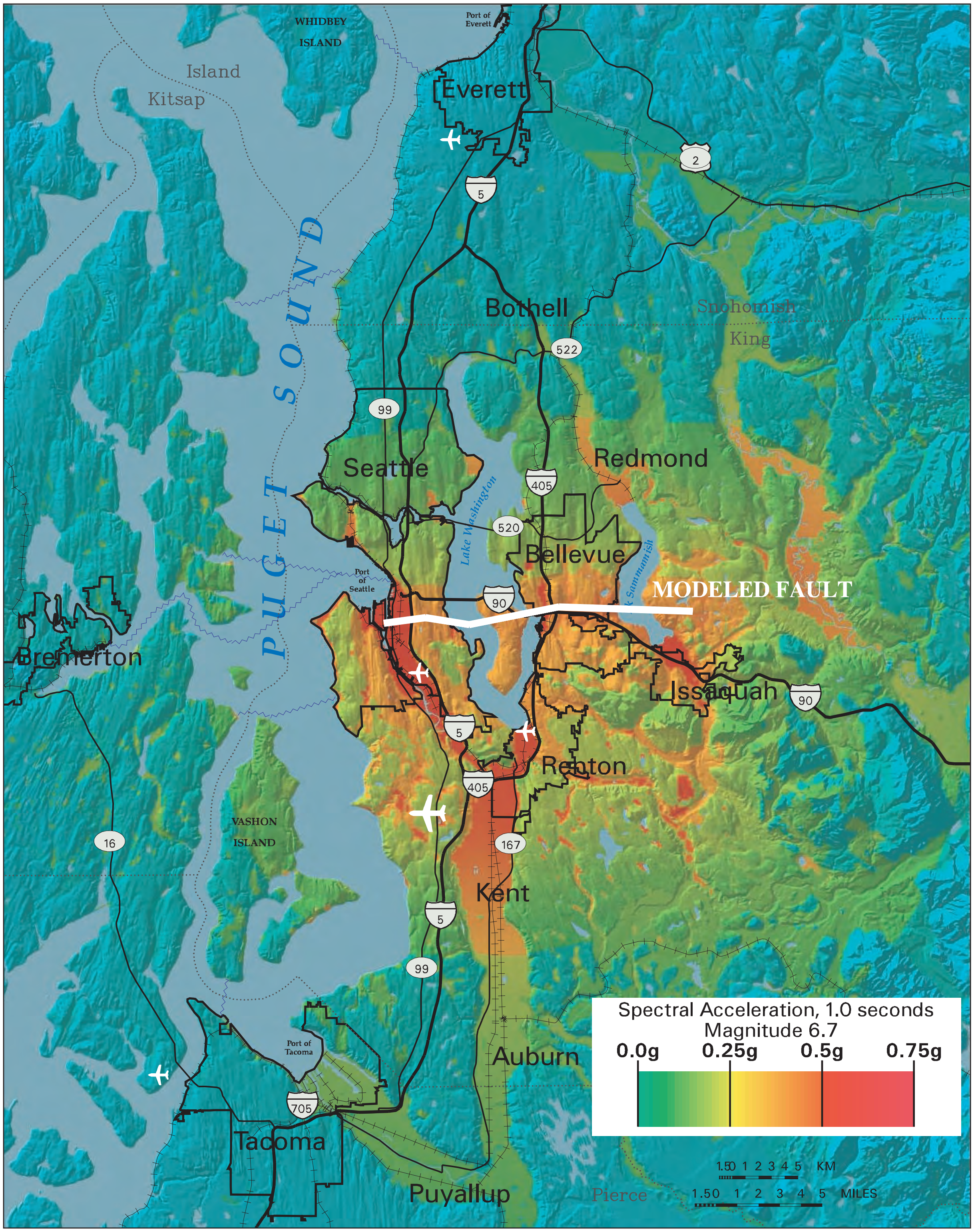


Figure 1-10b: Spectral acceleration at 1.0 seconds for M6.7 scenario earthquake.

Graphic / US Geological Survey

Nisqually earthquake 2001. Photo / Washington Department of Natural Resources

Chapter 2

Ground Failure

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- *As Lisa Bona stood at the corner of Yesler and First Avenue, she felt a sharp jolt beneath her feet. It was difficult for her to remain standing as the ground continued shaking. Small geysers of water and sand began boiling up around her feet. Then, she felt the air blast as a portion of the Alaskan Way Viaduct fell with a deafening roar and the ground began moving toward Elliott Bay.*

- *In a warehouse on First Avenue South, Dan McKenna leaped up the stairs of the basement, barely ahead of the sand and water coming through the cracks in the floor. Once the shaking stopped, he looked out a doorway to see the landscape of the industrial heartland of Seattle change in a few seconds. The ground temporarily turned into quicksand, causing some buildings to tilt or collapse. He saw that the street had split apart, and buried pipes were floating to the surface. There was a strong odor in the air, making it hard for Dan to breathe. A stream of sewage, jet fuel, and industrial solvents flowed freely into the Duwamish Waterway from broken pipes.*

- *Claire Fisher abruptly stopped when she felt her car lurch upward as if she were on a roller coaster ride. From her high perch atop the West Seattle Bridge, she saw that part of Harbor Island was disappearing beneath the water. Spans collapsed from the bridges she saw to the south. The Duwamish Waterway turned murky as submarine landslides churned up sediments, and debris from damaged waterfront structures floated on the surface. Ahead of her, she could see fresh earth from landslides on Beacon Hill. She wondered how her new house on a steep hillside of Mercer Island had fared.*

Three types of ground failure will occur during the M6.7 scenario earthquake including:

- Surface fault rupture.
- Liquefaction-induced ground failure.
- Seismically induced landslides.

This chapter describes where ground failure is expected to occur during the scenario earthquake, and the potential effects of ground failure on engineered structures.

Surface Fault Rupture

Surface fault rupture in the Seattle Fault Zone is difficult to predict, primarily because the exact locations of the fault traces are not well-defined. Based on previous aeromagnetic, gravity, offshore seismic reflection, limited fault trenching, and LIDAR data, scientists have developed at least three possible models for faulting in the Seattle Fault Zone. Although surface fault rupture might occur

Figure 2-1: In the left photo, surface fault rupture during the Chi-Chi earthquake created a 10 foot waterfall and caused a bridge collapse near Shihkang, Taiwan. In the right photo, we look directly at the fault rupture surface in which the mountains have moved upward approximately 10 feet relative to the coastal plain, lifting and tilting the buildings that straddle the fault.

Photos / Shannon & Wilson, Inc., © 1999

anywhere in the swath shown in Figure 1-3 (Chapter 1), this scenario M6.7 event assumes that 6.5 feet of movement occurs on a northern splay of the Seattle Fault Zone (Figure 1-6). South of the fault, the ground moves up; north of the fault, the ground moves down. During the last major event on the Seattle Fault, about 1,100 years ago, Alki Point moved up at least 13 feet and West Point dropped at least 3 feet.

The 1999 M7.6 Chi-Chi earthquake in Taiwan occurred on a fault similar to the Seattle Fault. Surface fault rupture from the Chi-Chi earthquake caused dramatic damage to bridges and buildings (Figure 2-1), similar to what we expect to see during the M6.7 scenario earthquake for structures located directly above the fault movement.

Surface fault rupture that occurs underwater will cause local flooding by creating water waves – tsunamis or seiches – around the rupture area. The scenario earthquake rupture zone passes beneath several water bodies including the Duwamish River, Lake Washington, and Lake Sammamish. Ground shaking, ground surface rupture, and elevation changes in the bottom of these water bodies may generate tsunamis or seiches in Lake Washington and Lake Sammamish; a seiche also may occur in Lake Union, which is sensitive to ground motions. Although the scenario earthquake does not include fault rupture in Puget Sound, some inundation and potentially damaging water currents are likely along the Seattle waterfront. Generation of smaller, landslide-induced tsunamis in Puget Sound is possible.

Geologic evidence indicates movement on the Seattle Fault caused by a M7.0 or greater earthquake about 1,100 years ago generated a 6 to 7 foot-high tsunami that washed over West Point and other low-lying areas along Puget Sound. Based on historic observations, tsunamis or seiches generated by the scenario event may damage anything located within 5 to 10 feet above the shoreline.

In addition to temporary flooding from tsunamis and seiches, permanent land level changes associated with the fault rupture will raise shorelines immediately south of the rupture and lower shorelines to the north. Lowered shorelines north of the fault deformation front along Puget Sound, Lake Washington,

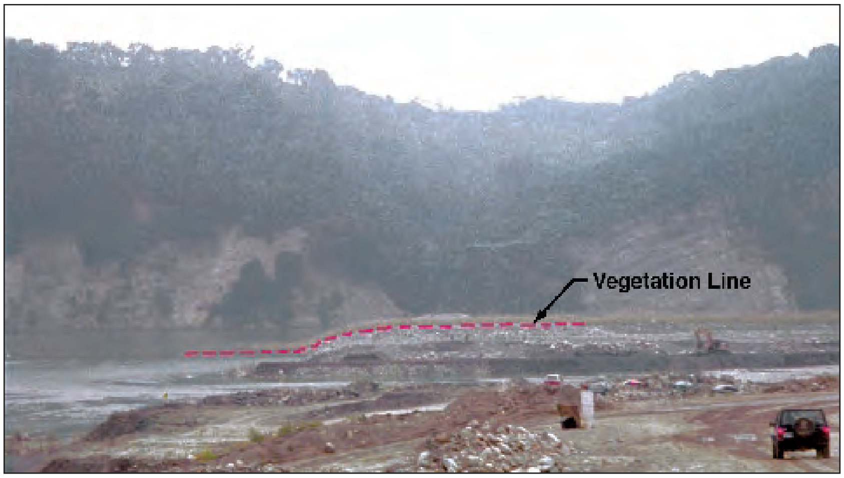


Figure 2-2: The vegetation line across the middle of the photo shows the original ground surface. Fault rupture during the Chi-Chi earthquake raised the ground and river channel on the right hand side of the photo, causing flooding upstream.
Photo / Shannon & Wilson, Inc., © 1999

and Lake Sammamish would result in flooding of buildings and other facilities located near the existing shorelines. Raised shorelines at the south end of Lake Washington or the riverbed near the mouth of the Duwamish River could result in local flooding farther upstream along the Cedar River (the Cedar River flows into the south end of Lake Washington) or the Duwamish or Green Rivers (the Green River flows from the south into the Duwamish River). Although the concept of upstream flooding due to surface fault rupture may seem far-fetched, it did occur during the 1999 Chi-Chi earthquake in Taiwan (Figure 2-2).

Liquefaction-Induced Ground Failure

Liquefaction occurs when soil grains in loose, saturated silty, sandy, or gravelly soils attempt to rearrange themselves in a denser configuration when subjected to strong earthquake ground motions. The resulting increase in pressure of the water in the voids of the soil temporarily transforms the soil into a fluid, causing the soil to lose much of its strength. As the pore-water pressure builds, groundwater and liquefied soil may find their way to the surface, creating sand boils on the ground surface. Figure 2-3 shows an example of sand boils in the Seattle area caused by the Nisqually earthquake.

Several types of damaging ground failure can occur because of liquefaction including lateral spreading, ground settlement and local flooding.

Figure 2-3: Sand boils on the main runway of Boeing Field caused by liquefaction during the 2001 M6.8 Nisqually earthquake.
Photo / Landau Associates, Inc., © 2001

Lateral spreading

Lateral spreading is one of the most damaging types of ground failure to result from liquefaction. Lateral spreading occurs when subsurface soil liquefies, and gravity and inertial forces from the earthquake cause the mass to move down slope. Lateral spreads can occur on very shallow (almost flat) slopes, and they can cause displacements of inches to tens of feet. This type of movement can damage utilities and structures supported by shallow or deep foundations (Figure 2-4).

Marine/port facilities and sewer outfalls will be particularly vulnerable to damage from lateral spreading. In unique cases, liquefaction may cause displacements of several hundred feet. The Duwamish River delta front, including Harbor Island, is an example of an area where such large displacements could occur.

Loss of bearing capacity and ground settlement

Buildings above liquefiable soils may settle or tip due to loss of bearing capacity of the soil. Figure 2-5 shows an example of damage due to settlement and loss of bearing capacity. Liquefaction-induced settlements, sinkholes, and sand boils also disrupt pavements, such as occurred during the 2001 Nisqually earthquake at the King County International Airport (Boeing Field).

Local flooding

Water ejected from sand boils could cause localized flooding. Street and basement flooding from liquefaction occurred in Puyallup during the 1949 Olympia earthquake (Figure 2-6). Buried structures such as fuel tanks and power vaults within liquefied soil could become buoyant and rise toward the ground surface. If the rising structures break the ground surface, they will damage or sever their utility connections, causing chemical spills.

During the scenario M6.7 earthquake, liquefaction will be widespread because the source of the ground motions will be close to the surface, and soils in vulnerable low-lying areas are loose, geologically young soils or fills. The ground motions will be much greater than were experienced during the 1949 Olympia, 1965 Seattle-Tacoma, and 2001 Nisqually

Figure 2-4: Damage from lateral spreading at Port Island Bridge during the 1995 M6.9 Kobe earthquake. Similar and more significant damage is expected during the Seattle Fault scenario earthquake.

Photo / Ian Austin, Dames and Moore – Tokyo Office, provided by Stephen Dickenson

Figure 2-5: Loss of bearing capacity and settlement due to liquefaction during the 1964 Niigata, Japan, earthquake caused these buildings to tip. Photo / National Geophysical Data Center

Figure 2-6: Flooding in Puyallup due to ejection of groundwater from sand boils during the 1949 Olympia earthquake.
Photo / Richard Six, provided by Stephen Palmer

earthquakes. Figure 2-7 shows areas expected to liquefy during the scenario earthquake. The map uses ground motions predicted for the scenario earthquake and a large database of subsurface information from more than 800 soil borings. Many of the low-lying areas near the fault have soils with a high or moderate to high likelihood of liquefying during the scenario earthquake. Past earthquakes demonstrated the susceptibility of these areas to liquefy.

For areas where the likelihood of liquefaction is moderate to high during the scenario event, ground failure will be significant. The most common and damaging of these ground failure effects will be lateral spreading. Figure 2-8 shows projected locations and magnitude of liquefaction-induced ground deformations that might occur during the scenario M6.7 event. The map indicates ground deformation estimates due to lateral spreading and flow sliding, without considering the benefits of engineered structures to reduce deformation.

Seismically Induced Landslides

Based on current knowledge of landslides in the Puget Sound area and theoretical studies, the severity of seismically induced landslides and related damage is dependent on the level of ground shaking and groundwater conditions at the time of the earthquake. Landslides not seismically induced in the Puget Sound area are seasonal, with a rough correspondence between monthly rainfall and reported landslides due to lag time for build-up of groundwater level in the slopes. Table 2-1 indicates the typical moisture conditions by season and the types of seismically induced landslide movements and damage that could occur.

The April 1949 Olympia earthquake and the April 1965 Seattle-Tacoma earthquake triggered scattered landslides throughout the Puget Sound region, many of which were in fill soils. The rainfall in 1949 and 1965 was below normal. Records identified 10 and 22 landslides in 1949 and 1965, respectively, between Edmonds and Tacoma. The largest of these was the Salmon Beach landslide in Tacoma that failed three days after the 1949 earthquake.

The February 2001 Nisqually earthquake generated about a hundred landslides in the region spread out over a large area; precipitation before the earthquake was meager. The U.S. Geological Survey mapped landslides as far north as Marysville and Port Townsend, west to Aberdeen, east to Leavenworth, and as far south as Highway 84 in the Columbia Gorge.

Some of the most notable landslides occurred at Salmon Beach near Tacoma (Figure 2-9), along the Cedar River drainage in Maple Valley, U.S. Highway 101 in Olympia, and Highway 302 on Bainbridge Island. The number and severity of landslides caused by the Nisqually earthquake was limited because of the depth of the earthquake. A shallower earthquake source such as the scenario M6.7 event could result in thousands of landslides in the Puget Sound region.

Areas likely to experience a number of seismically induced landslides during the scenario event include:

- Slopes close to the fault where the ground motion is high. More and larger seismically induced landslides will occur in areas where ground motions are highest. The number and severity of sliding in Pierce or Snohomish Counties areas during the scenario earthquake will be less than in King County.
- Areas susceptible to landslides in the past. Figure 2-10 shows the locations of all reported landslides from the Seattle Landslide Study. Areas that would suffer damage during the scenario earthquake

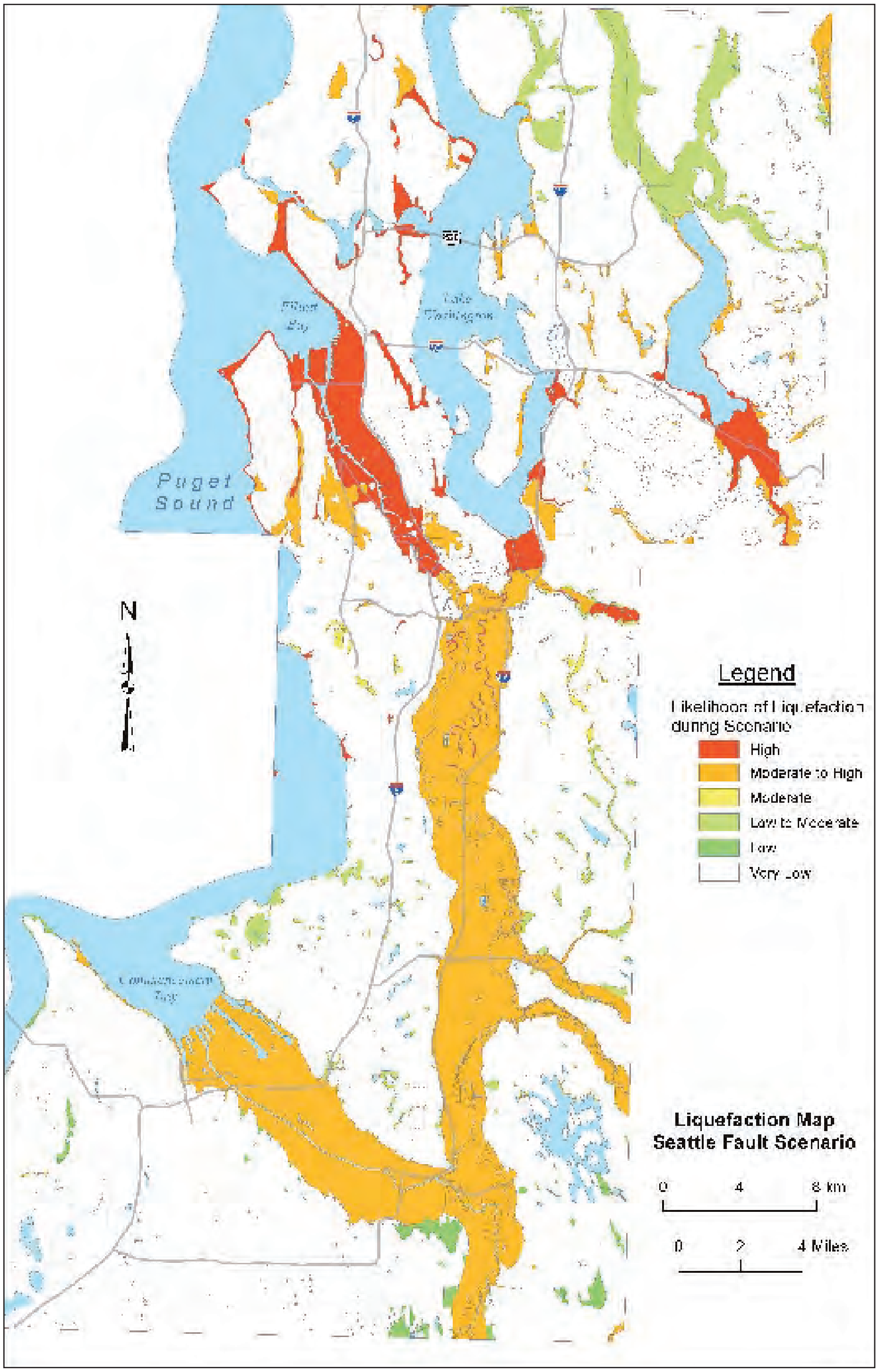
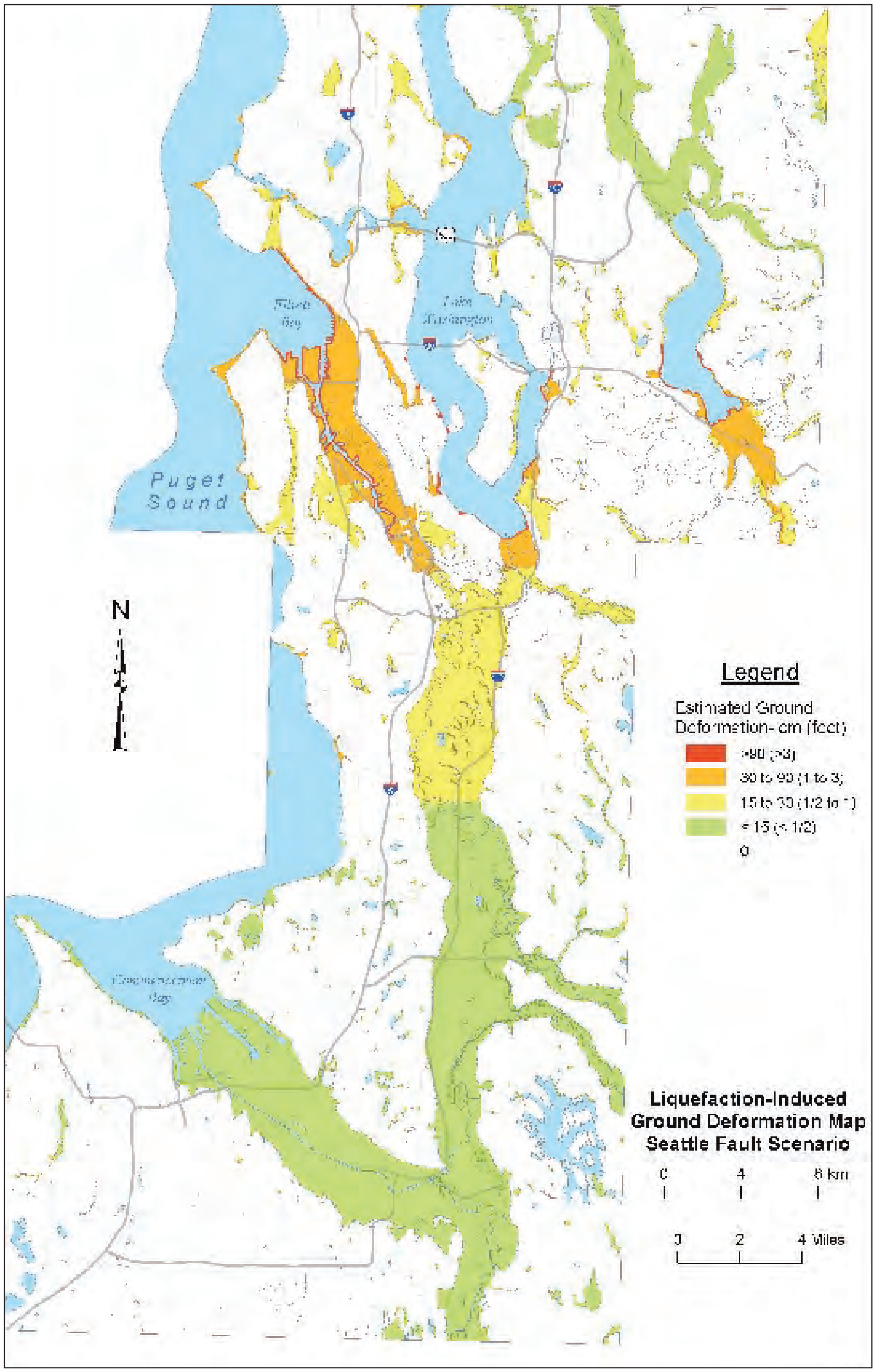


Figure 2-7: Map of areas likely to liquefy, rated by likelihood of occurrence of liquefaction during scenario M6.7 earthquake.

Graphic / Washington Department of Natural Resources and Shannon & Wilson, Inc., 2004

Figure 2-8: Map of estimated lateral spreading during scenario M6.7 event.
Graphic / Zipper Zeman Associates, Inc., 2004



1894 Commencement Bay Submarine Landslide

At 11:10 PM on November 28, 1894, a large, rapidly moving submarine landslide occurred on the Puyallup delta at Commencement Bay, the port area for Tacoma. The landslide head scarp extended from the Northern Pacific Railway dock area to the Commercial wharf, a distance of about 1,170 feet. A 9 to 14 foot- high water wave generated by the landslide inundated the port, causing damage to a number of moored vessels. Two people were lost in buildings carried into the water during the landslide and ensuing water wave. An earthquake did not trigger this submarine landslide; rather, it was a static failure that occurred immediately after a low tide.

This event highlights the potential hazard to the Seattle waterfront from earthquake-induced submarine landslides, such as those that occurred in Valdez, Seward, and Whittier during the 1964 Great Alaska earthquake.

are places with concentrations of past landslides such as Alki Point, Perkins Lane West, Madrona, east and west sides of Mercer Island, east and west sides of Queen Anne Hill, and the Burlington Northern Santa Fe railroad corridor on the Puget Sound shoreline between Seattle and Everett.

- Areas with slopes greater than 40 percent. In general, the potential for landslides during the scenario event is most significant where slopes are steepest. Areas of slopes greater than 40 percent have been mapped as critical areas as part of local planning under the Growth Management Act.

Table 2-1. Correlation Between Soil Moisture and Landslides

Moisture Condition (Months)	Expected Type of Seismically Induced Landslides and Damage
Dry June through September	■ Many small failures on steep slopes but not debris flows ■ Fill failures ■ Rock falls ■ Local sidewalk and partial road blockages ■ Large, deep-seated movement unlikely
Wet and Intense December through April	■ Movements of deep-seated, rotational slides, but not total collapse ■ Buildings in proximity of slide-prone slopes could be damaged ■ Colluvium mobilized on many slopes ■ Many roads blocked at toes of steep slopes ■ Debris flows travel far from slope toes
Wet and Prolonged December through April	■ Large, deep-seated rotational landslides; whole hillsides collapse ■ Other effects same as described for wet and intense rainfall
Moderate April, May, October, and November	■ Intermediate between dry and wet ■ Depends on antecedent precipitation and recent weather

Figure 2-9: Aerial view of Salmon Beach landslide caused by the 2001 Nisqually earthquake.
Photo / Brian Sherrod, U.S. Geological Survey

- Areas identified by LIDAR mapping. Recent LIDAR maps of Seattle and Mercer Island show numerous large ancient landslides, which are vulnerable to new seismically induced catastrophic landslides. Sunken forests in Lake Washington below the eastern and western slopes of Mercer Island and amphitheater-shaped landforms in Madrona, West Seattle, Magnolia, Queen Anne Hill, Beacon Hill, northeast Seattle, Blue Ridge, and Broadview indicate ancient landslides, some seismically induced. Some of these areas have offshore debris deposits from past catastrophic landslides.

Seismically induced landslides along shorelines – expected to be significant during the scenario event – will generate a number of tsunamis as land masses rapidly slide into the water or as underwater landslides move down slope. The landslide on the east side of the Tacoma Narrows at Salmon Beach caused by the 1949 Olympia earthquake occurred three days after the quake and created a 7- to 8-foot-high tsunami on the opposite shore.

Figure 2-10: Mapped landslides in Seattle and Mercer Island.

Data from Seattle Landslide Study [Shannon & Wilson, Inc., 2000] and City of Mercer Island, 2002

Mitigation of Ground Failure

The most important aspect of mitigation for any type of ground failure is to identify the potential locations and the type of ground failure that might occur.

There are challenges in designing for a surface fault rupture during a major event on the Seattle Fault because the expected movements are large and the zone over which the displacement occurs can be so variable. As engineers and planners, we can do our best to avoid building structures that cross known active faults. In cases where this is not possible, various mitigation measures can be taken, such as:

- Stiff frames and foundations can be used for structures that may be in potential rupture areas. While stiff frames and foundations do not prevent rupture or movement of the structure, they do reduce the potential for the structure to be pulled apart and collapsed by the rupture.
- Bridges can be designed to accommodate some movement by increasing the length of bridge seats and by using cable restrainers.
- For utilities and other lifelines that cross the rupture zone, we can minimize the effect of potentially damaged facilities in the rupture zone. For example, it may be possible to strategically locate shut-off valves on either side of the area to minimize the impact on the overall system and allow for faster repairs within the rupture zone. Other methods of minimizing damage include using more ductile steel pipe and welding joints. In some locations the depth of pipe burial and orientation of the fault crossing can be changed to minimize the potential for damage.

Mitigation of liquefaction, lateral spreading and associated effects is commonly done through either ground improvement or a structural solution. Ground improvement methods typically involve some sort of soil densification or improvement in drainage so that high pore pressures that would cause soil to liquefy do not occur or are dissipated. Structural solutions typically involve installing larger and/or deeper foundation systems to penetrate below the liquefiable soils and withstand downdrag and lateral forces from the liquefied soils. Fortunately, areas with high liquefaction potential can be identified with proper geotechnical investigations, and ground improvement techniques have proven effective based on numerous case histories primarily outside of the Puget Sound region.

Seismically-induced landslides can be mitigated in a number of ways. Some mitigation strategies include the installation of subdrainage (either with deep groundwater interception trenches or drilled horizontal drains), retaining walls, earth and rock buttresses, or avoidance of the area. Even if the mitigation does not prevent the landslide during a large seismic event, it may lessen its damaging effects.

Examples of ground improvement for mitigation of liquefaction and lateral spreading.
Photos / Shannon & Wilson, Inc., © 2003

Chapter 3

Lifelines

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■ *George Volnitzski received an urgent call from his uncle at Volnitzski's Fresh Meats – a wholesale meat distribution firm in Renton. "Get into your truck and head south, I'll locate a generator and call you when I find one," his uncle yelled into the phone. Little did George know that he would make a four-day, round-trip drive. His only assignment was to save inventory—and probably his job.*

■ *Jake Jacobson was almost back to his construction site in Kent when his truck lurched and bounced. When the shaking stopped, a relieved Jake decided to drive slowly for the remaining blocks. As he rounded the first corner, he saw flames shooting from a broken gas main to his left. He saw water gushing out of a hydrant up the street to his right. It would be several hours before anyone realized that not only had numerous water lines broken, but that raw sewage was pouring into Lake Washington from broken sewer lines.*

■ *Betsy Mann knew that without light or heat she would not be able to reopen her pharmacy; the building did not have a backup generator. Without power, she could not start her computer, print labels for prescriptions, or run her cash register. She would not be able to serve the many senior citizens that frequented her pharmacy; even one day without medications was a hardship for many of them.*

Lifelines are the often unseen network of public and private services and structures in a community that form the foundation of its development and are necessary for its well-being and economic vitality. Lifelines include water, sewer, natural gas and liquid fuel, electric power, and telecommunications systems (Figure 3-1). Without one or more of these lifelines, it becomes difficult for a community to function well.

This chapter addresses how the scenario M6.7 earthquake will affect the following five lifelines.

- Water
- Wastewater
- Electrical Power
- Communications
- Natural Gas and Liquid Fuels

Water

Regional Supply

The three largest water suppliers in the region are the cities of Everett, Seattle, and Tacoma. In all three cases, the primary supply comes from surface water gathered on the western slopes of the Cascade Mountains.

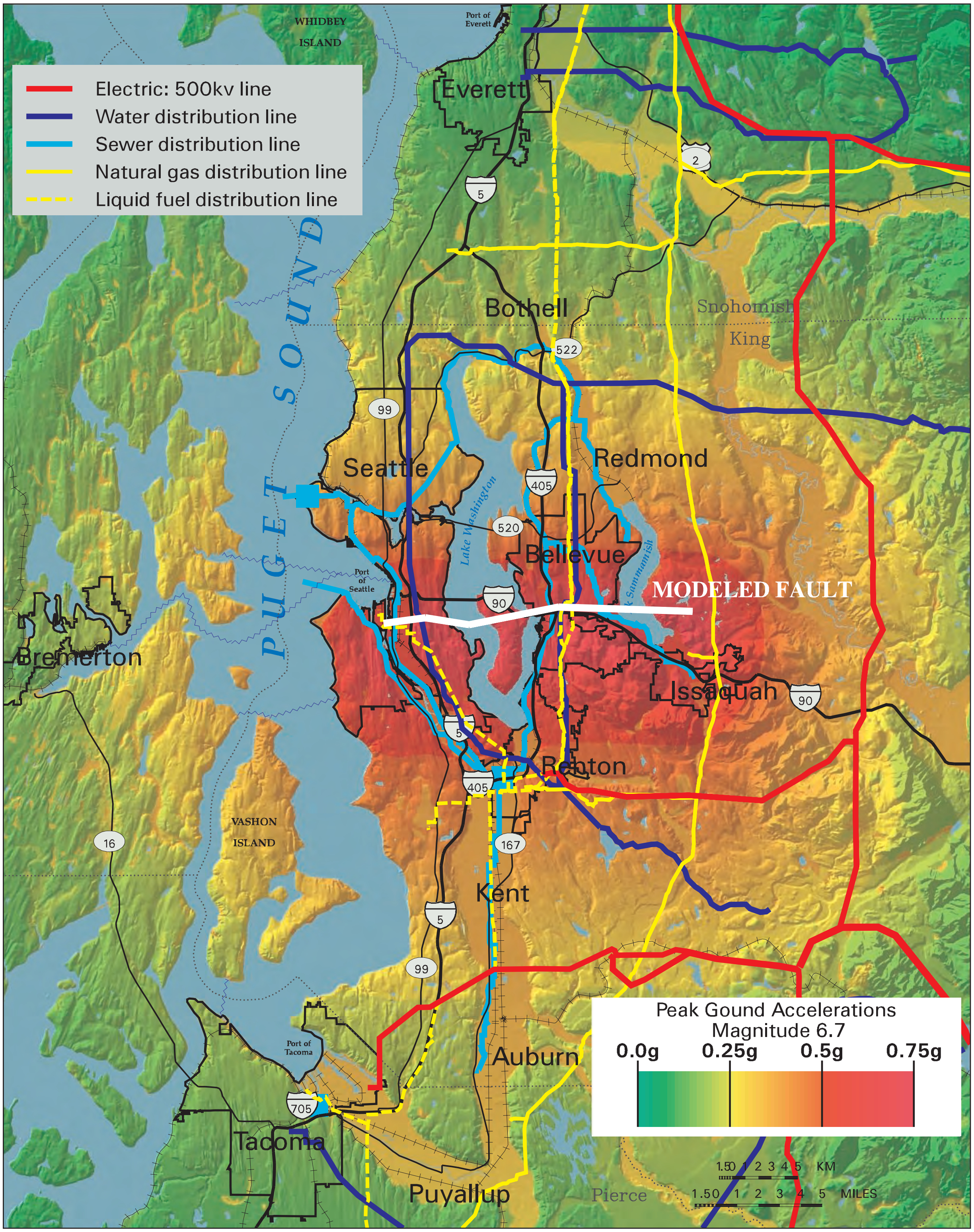

Figure 3-1. The Central Puget Sound region's lifelines.

Graphic / US Geological Survey

Seattle and Tacoma also have supplementary groundwater supplies. The three suppliers' systems are substantially independent of one another, with only small interties. These three suppliers provide both retail and wholesale service. Smaller water purveyors depend on supplies from the three cities, their own groundwater, and smaller surface water supplies.

Figure 3-2 shows the main water transmission systems. These systems generally run east to west and in all cases cross valleys with unconsolidated young soils. Some suburban communities rely both on the Seattle supply as well as on their own groundwater supplies. East of Bellevue, both Issaquah and Sammamish are very dependent on groundwater as are Renton and Kent to the south.

The water systems are made up of the source (surface water or wells), pipelines ranging in size from several inches to more than seven feet in diameter, treatment plants, tanks and reservoirs, and pump stations. Each of the three regional supplies includes one or more dams. Treatment facilities inject chemicals into the water; Seattle's Tolt River supply is filtered and ozonated while the Cedar River supply is disinfected by ozonation and ultraviolet light.

Earthquake Vulnerability

Water facilities are vulnerable to the strong ground shaking and permanent ground deformations due to fault rupture, liquefaction, lateral spreading and landslides. The number of pipeline breaks may compare to both the 1994 Northridge and the 1995 Kobe earthquakes, both of which caused several thousand pipeline failures.

Many communities have seismically upgraded some of their facilities to resist ground motions specified in current building codes (30 or 40 percent of gravity). Seattle Public Utilities is building new or upgrading existing facilities to withstand ground shaking motions equivalent to 40 percent of gravity, when feasible – sometimes with a 1.5 importance factor which brings it close to ground accelerations expected in the scenario Seattle Fault earthquake. Only a few facilities have designs that resist the large ground motions expected in close proximity to the fault rupture of the scenario earthquake. As a result, many of water tanks within 5 to 10 miles of the fault rupture will rip loose from their anchorages, damage connecting pipe, and in some cases, rupture. Tanks owned by Seattle, Bellevue, Issaquah, Mercer Island and Sammamish are closest to the fault. Also damaged will be buildings housing chemical feed facilities and pump stations. Unanchored electrical equipment will topple, making some facilities non-functional.

Pump stations and wells are dependent on electrical power that may be unavailable in the days following this event.

Ground shaking may damage some pipelines but permanent ground deformation will rip many apart. Seattle's trunk lines running north-south through Seattle and Bellevue likely will break at the fault rupture. Other than damage caused by fault displacement, pipelines in competent soils should perform well. The valley crossing through Renton is one possible exception. If damage is localized, repairs could be made within a few days.

Although located outside of the fault rupture area, the Tolt River pipelines pass through several areas of possible ground failure caused by liquefaction and landslide and may not be functional. The Cedar River pipelines, capable of supplying most of the system, are much more likely to remain functional when planned upgrades to one or two vulnerable areas are completed. Areas cut off from the Cedar River supply would be dependent on storage until the Tolt River pipelines are repaired or the pipelines connecting distribution areas to the Cedar River supply are restored.

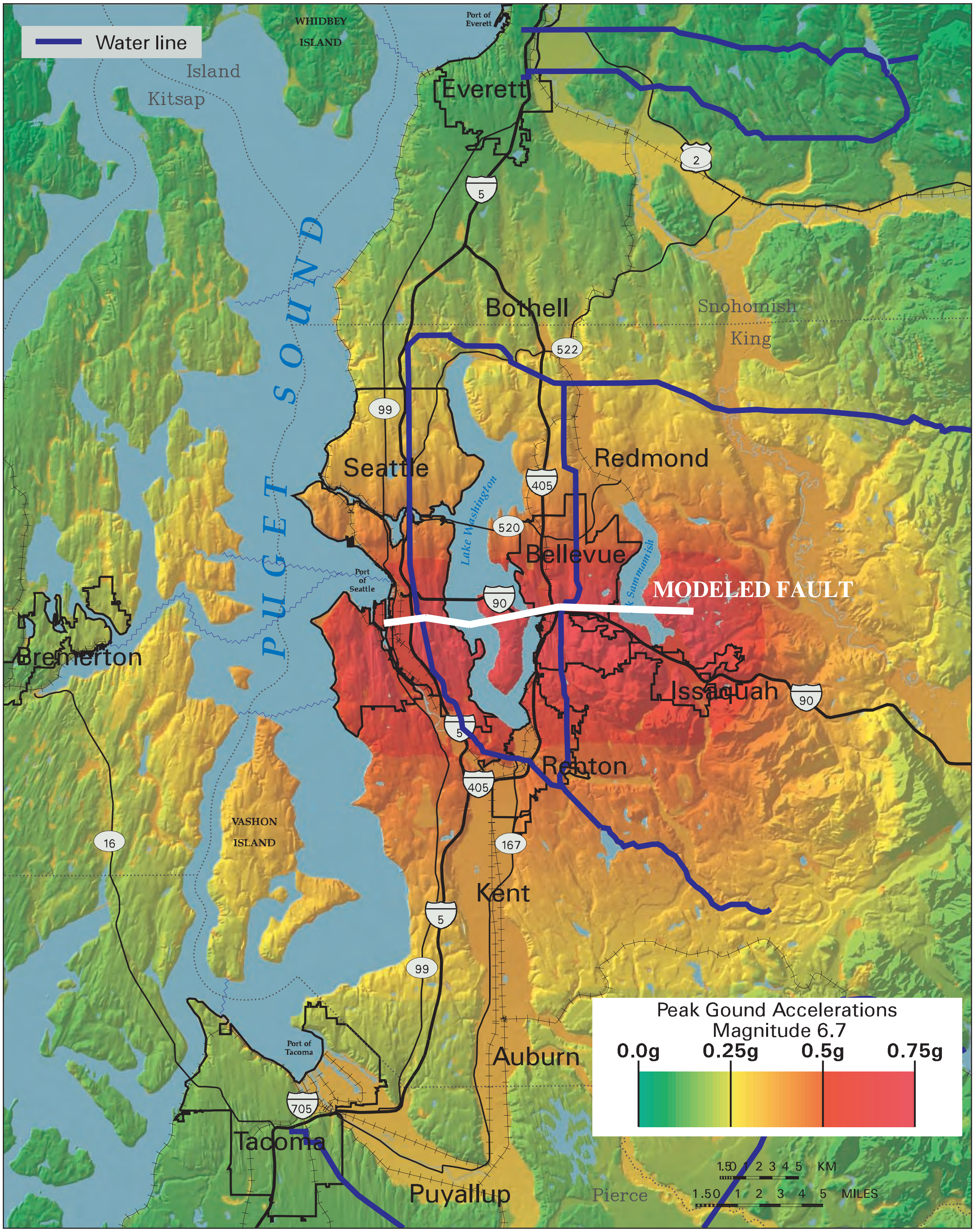

Figure 3-2. Regional water pipelines.

Graphic / US Geological Survey

Pipeline damage due to liquefaction-induced lateral spreading will cause heavy damage particularly to the old cast iron piping in the Duwamish Valley, Issaquah, and potentially as far south as Renton and Kent. It may take weeks to restore water service to these areas. In addition to affecting water availability in areas with damaged pipes, water leakage through the breaks may drain reservoirs and affect water availability in other areas unless the pipeline breaks can be quickly isolated.

Mercer Island may have the most tenuous water supply. The city is dependent on pipelines connecting it to Bellevue that are nearly on top of the Seattle Fault and that pass through an extensive peat bog, where large displacements and possibly liquefaction are expected. Additionally, a seismically vulnerable bridge supports one of the Mercer Island pipelines. The city could be dependent on emergency water supplies – storage, alternative sources, temporary feeds through portable pipelines – for an extended period. Permanent ground movement may damage wells that supply water to Issaquah and Sammamish.

Figure 3-3: Floating manhole, from 1964 earthquake in Niigata, Japan. Damage such as this will be seen following the Seattle Fault scenario earthquake. Photo / NOAA, National Geophysical Data Center

Wastewater

King County operates a wastewater treatment system with plants at West Point and Renton, both of which are moderately vulnerable to the scenario earthquake (Figure 3-4). This system collects and treats sewage generated by the Seattle, and many of the suburban communities surrounding Lake Washington and south through to Auburn. While both plants were either originally built to resist earthquakes (West Point secondary treatment system) or seismically upgraded (West Point primary treatment system and Renton plant), the ground motions expected in the scenario earthquake are larger than considered in the plants' designs. Piping and equipment damage is likely.

There are smaller wastewater plants along Puget Sound north and south of Seattle, including those serving Edmonds, SeaTac, and Federal Way. These plants are on competent soils or have pile foundations. They may encounter piping and equipment damage as well. Everett operates a wastewater treatment plant along the Snohomish River, and Tacoma, and Puyallup operate plants along the Puyallup River; these plants should experience less damage because they are more distant from the epicenter.

Main interceptor sewers positioned along the bottom of valleys allow sewage to flow downhill into them for transport to the treatment plant. In many cases, these valleys have highly liquefiable soils. If the soils liquefy, many of these sewers will float or move laterally with the blocks of soil displaced by lateral spreading. Figure 3-3 shows a manhole that floated because of liquefaction in the 1964 Niigata, Japan earthquake; it is typical of the type of damage expected following the scenario Seattle Fault earthquake.

Sewage discharges resulting from liquefaction-induced sewer failures are likely into Lake Washington, Lake Sammamish and the Green

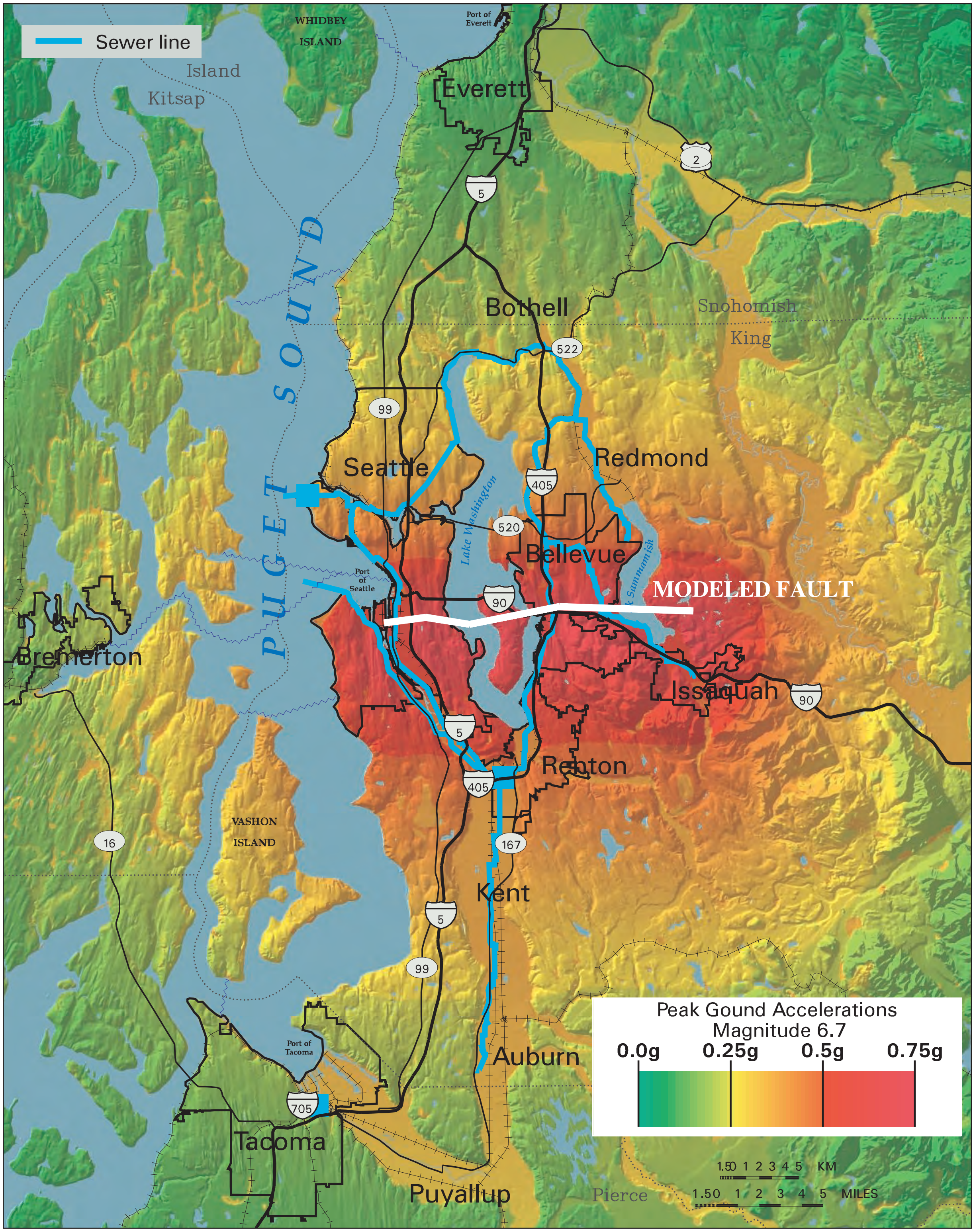

Figure 3-4: Regional sewer lines.

Graphic / US Geological Survey

River. Sewage flows may be reduced in some areas until the local water supply is restored. King County has an emergency response plan and equipment to pump untreated wastewater around damaged sections of sewers in critical locations. It may take weeks to repair some large-diameter sewers following the scenario earthquake.

Pump stations founded in the liquefiable soils will be vulnerable to damage, depending on their foundation's anchorage to stable soils below. Emergency power is available to most pump stations.

Electrical Power

Seattle City Light provides electrical power service in most areas of the city heavily impacted by the scenario earthquake. Puget Sound Energy provides service to suburban King County including Bellevue and areas east, and to suburban Pierce County. Tacoma City Light and Snohomish County PUD are on the fringes of the impact area to the south and north, respectively.

Electric utility lifelines have three subsystems: generation, transmission and distribution. The scenario earthquake will affect each of these components. Nearly all of power used in the Central Puget Sound region is generated elsewhere, and transported into the region through a system of high-voltage transmission lines (Figure 3-5).

Power transmission systems are robust. The only transmission tower failures on record have resulted from ground failures, usually in rough terrain. The longest outage after the 2001 Nisqually earthquake in the Seattle City Light transmission system was in feeders impacted by landslides, which damaged lines and disrupted access. Following the scenario earthquake, areas impacted by landslides will take two weeks to two months to restore, depending on stabilization of the slide area, site accessibility and availability of repair crews.

The systems' most vulnerable points are the high voltage (500kV and 230 kV) substations. Large porcelain insulators, bushings, and transformers are vulnerable to moderate ground motions (Figure 3-6). Damaged transformers may take months to replace. In favor of the electrical grid, however, is its redundancy. The Bonneville Power Administration can lose several substations and still maintain service on all but the coldest days of winter, when demand is the highest.

Electrical power moves from large substations via primary voltage feeder lines to numerous smaller distribution substations and overhead and underground transformers, which reduce voltage to levels required for customers.

Seattle City Light relies on power generated at its Skagit and Boundary Dam projects, which generate 70 percent of the energy sold to retail customers. The utility owns the transmission system from the Skagit facility, and relies on the Bonneville Power Administration for transmission from the Boundary Dam project. Bonneville owns and operates the transmission system serving most of the remaining area.

In the Seattle system, 11 substations distribute the power to feeders systems, which operate at 26kV to provide electricity to networks that serve more than 368,000 customers. The system uses a combination of overhead and underground electrical transmission and distribution lines. It has a combination of transmission and distribution lines running along and under the Alaskan Way Viaduct along the Seattle waterfront.

The most significant impact will be from collapse of the Alaskan Way Viaduct and the consequent loss of the transmission and distribution lines in the Alaskan Way corridor. Workers will lay emergency transmission and distribution cables on streets, but in a way that allows

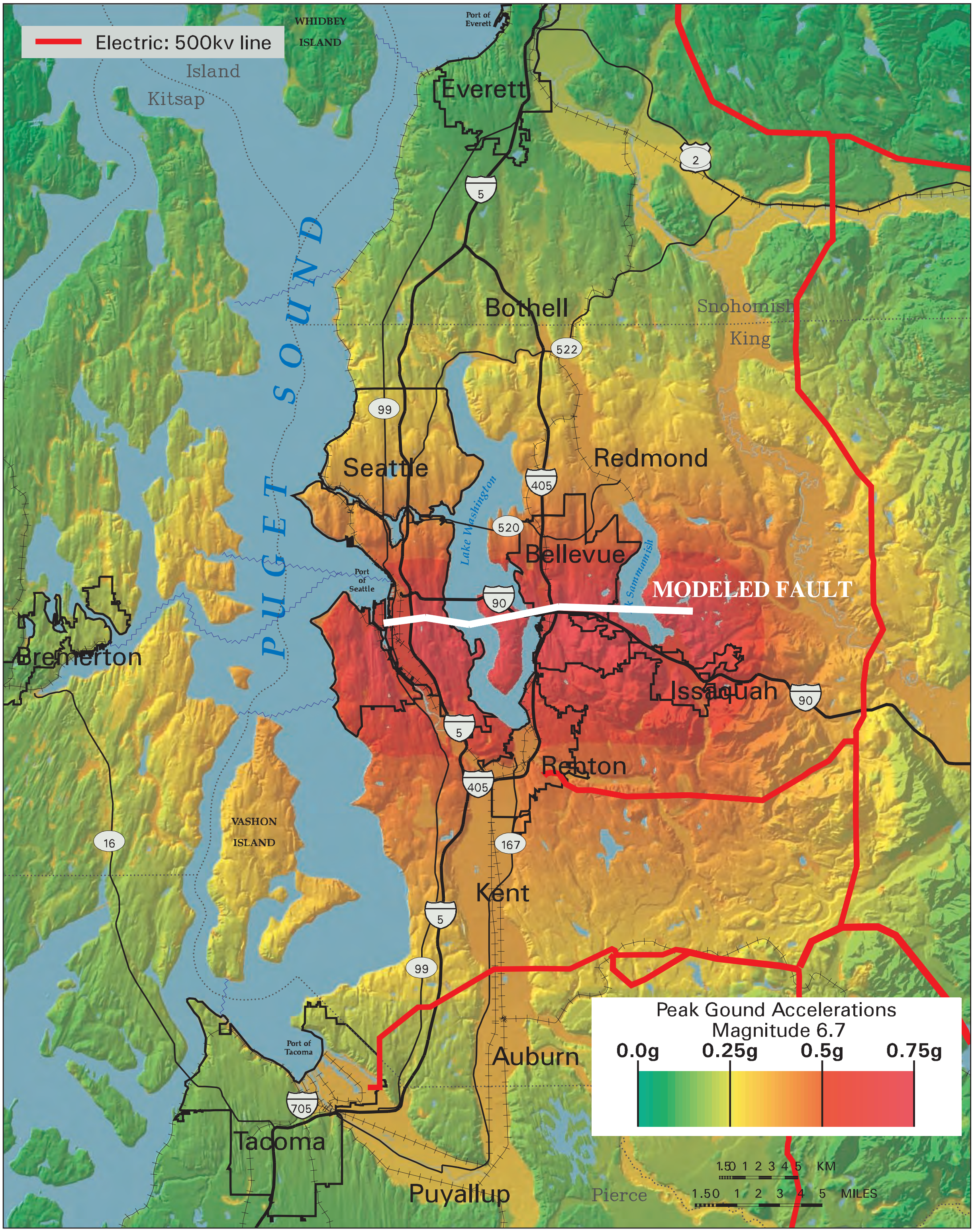

Figure 3-5. Bonneville Power Administration electric transmission system. Graphic / US Geological Survey

Figure 3-6: Electrical substation damaged by 1994 Northridge earthquake. Similar damage will occur in a major Seattle Fault earthquake.
Photo / Earthquake Engineering Research, © 1997

traffic to continue using the streets although at a reduced capacity. These cables can provide 100 percent capacity in one to two weeks.

Given the locations of and damage to substations and distribution systems, about half of the system will suffer outages in the scenario earthquake. Most areas should have power restored within 72 hours, based on experience from several California earthquakes. However, if several critical substations experience heavy damage, outages in some areas could last for many weeks.

Communications

The region's communications systems have rapidly developed over the last several decades. Such systems include hard-wired telephone and cable TV systems, wireless cellular phone systems, and 800 MHZ public service radio systems to name a few. The cellular systems are dependent on the hardwired connections between the cell towers and the land-based telephone system.

The hardwired systems are owned and operated locally primarily by Qwest and Verizon, with long distance carrier service from AT&T, Sprint, and others. A number of cellular companies provide service in the area. Police, fire, and emergency medical response agencies are primary users of the publicly owned and controlled 800 MHZ system.

Each of these systems has its own vulnerabilities. All are vulnerable to overload in the minutes and hours following a major event. The Internet provided the most reliable service following the Nisqually earthquake while other systems were overwhelmed. However, many local Internet hubs are located in buildings vulnerable to high levels of ground shaking.

Improvements made to hard-wired system switching hardware following the 1971 San Fernando earthquake in California allow them to perform well in the scenario earthquake. Most installations, made before the competitive business environment was in place, have a high degree of reliability designed in. Emergency power is common. Loss of water for cooling switching-center computers has been an issue following several major disasters. Nationwide networks are robust; if a Seattle node was lost, the system would continue to function.
A big unknown is the reliability of the nodes, for example, particularly in buildings connecting major local carriers with the long distance carriers.

Wireless phone systems are not robust. Reliability received less attention because of the highly competitive cellular phone business environment. Many locations do not have emergency power due to cost or permitting issues. As a result, cellular phone service will not be as dependable as hardwired phone service in the hours and days following the scenario event.

The 800 MHZ system owned by King County and other similar radio systems with robust designs should survive the scenario earthquake well. However, communication between dispatchers and responders, and between responders, will overload the system following the earthquake.

Natural Gas and Liquid Fuels

Williams Pipeline owns and operates a pair of high-pressure natural gas lines running south through the region from the Canadian border to Portland and beyond. Puget Sound Energy distributes natural gas in the region. The Olympic liquid fuel pipeline operated by BP Pipelines North America runs from the Canadian border and the refineries near Anacortes, south through the region to Portland. The pipeline delivers much of the gasoline used in the region as well as jet fuel used at SeaTac International Airport and fuel used for shipping at the Port of Seattle. Figure 3-7 shows these two pipeline systems.

The natural gas welded-steel pipelines are in competent soils along most of their route through the region. Spurs branch off to the west to serve the Seattle region. A large underground storage facility is located along the southern edge of Maple Valley, east of Renton. The pipeline alignment is at the eastern edge of the expected fault rupture. If limited fault displacement occurs, the pipeline should perform well.

Puget Sound Energy distributes the gas through an intermediate and low-pressure system. Over the past 15 years, it has replaced most of the cast iron pipe with polyethylene or PVC pipe. This plastic pipe is more resistant to damage from ground movement. The distribution system will experience some damage, particularly in areas of poor soils. Otherwise, the natural gas systems should perform well.

The Olympic Pipeline annually transports 4.9 billion gallons of gasoline, diesel and jet fuel in a pressurized pipeline along a 299-mile north-south corridor. The pipeline runs through all three counties of the study area. Its route takes it beneath homes, schools and churches. Although specific vulnerabilities of the Olympic Pipeline are unknown, the risk of failure or release is higher where it passes through areas of landslide-prone or liquefiable soil.

The pipeline crosses the fault in an area where several feet of displacement are expected. It continues south into Renton where it splits into three branches. Lines go to the Port of Seattle, SeaTac International Airport, and south through Kent and beyond. The area in Renton where the pipeline splits has highly liquefiable soils. If significant ground displacement occurs, pipeline rupture is expected. Consequences could be devastating – a 1999 rupture of the pipeline in Bellingham released nearly a quarter-million gallons of fuel that subsequently caught fire and killed three people. Another hazard location exists at facilities south of Seattle where fuel is loaded into trucks for distribution to local gas stations. Spills from broken loading valves could cause fires.

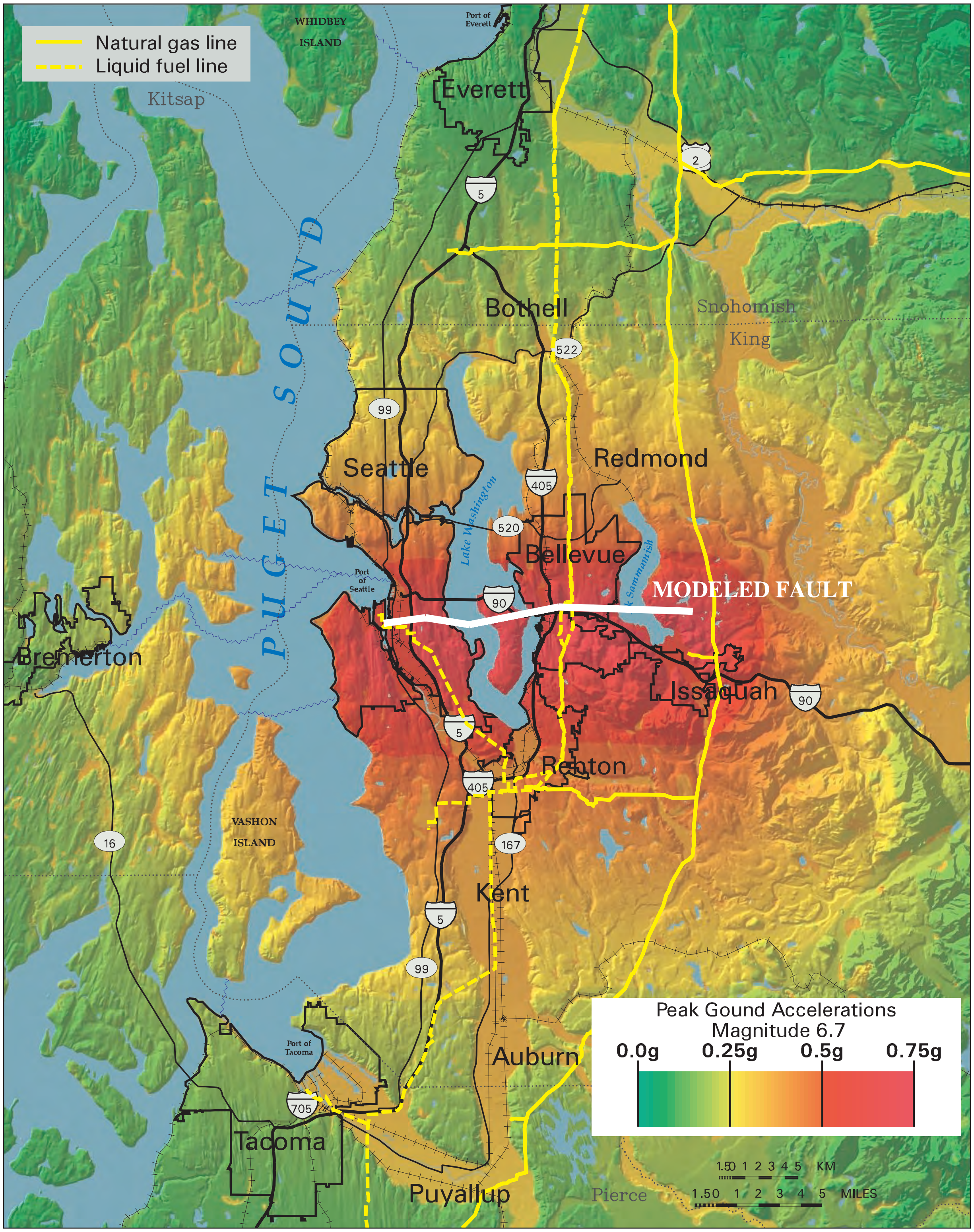

Figure 3-7: Natural gas and liquid fuel pipelines.

Graphic / US Geological Survey

A Vulnerable Cluster

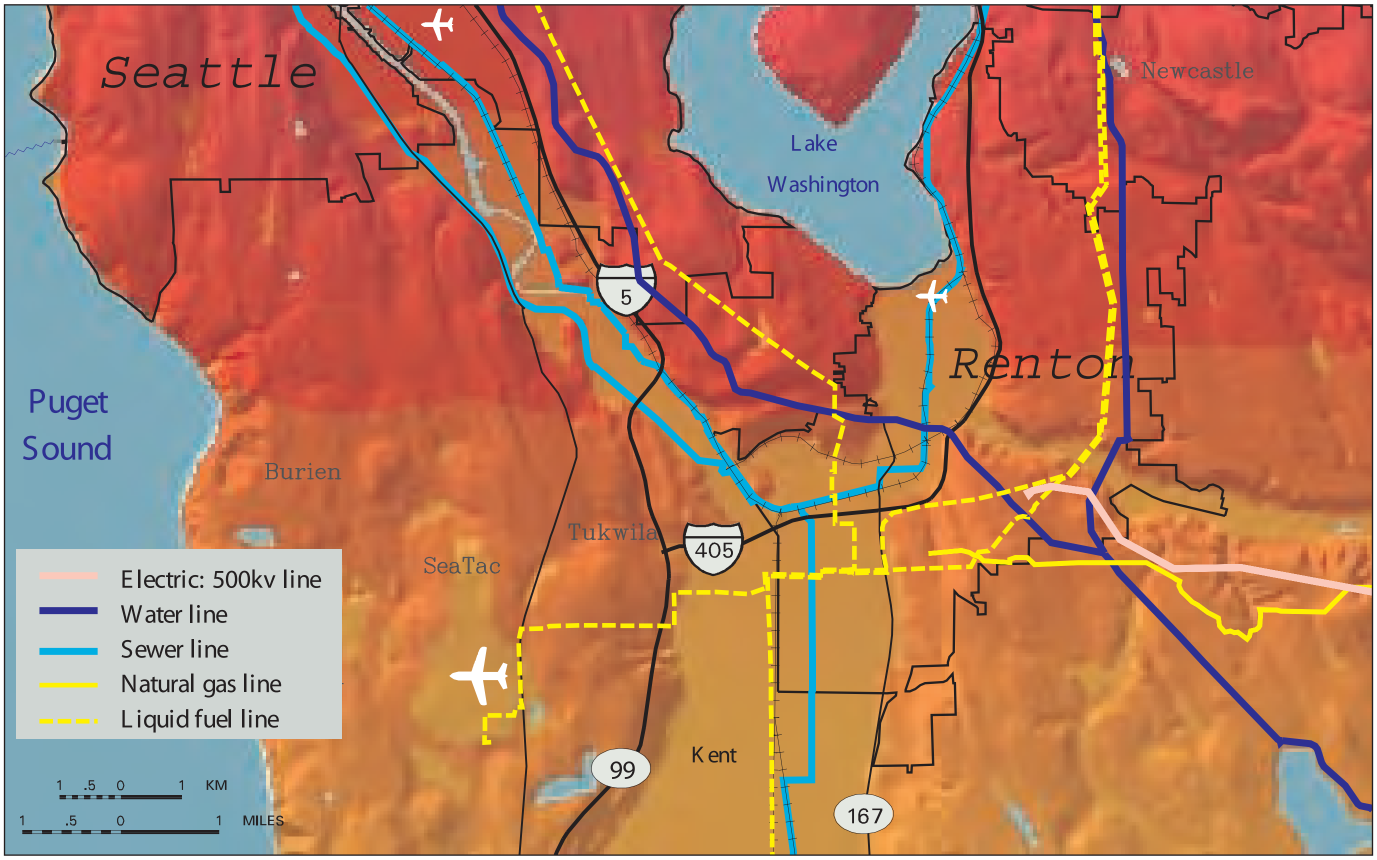

Figure 3-8. This cluster of lifelines in the Renton area is particularly vulnerable to the scenario earthquake. Most are on soils highly susceptible to liquefaction. These lifelines are critical utility structures for the Central Puget Sound Region.

Graphic / US Geological Survey

Chapter 4

Transportation

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■ *Jerry Liu, returning to his downtown Seattle office when the earthquake struck, immediately thought of his family in Issaquah. He decided to head for home. But cars filled the streets until they could not move. An immobilized fire engine with siren blaring could not travel three blocks to help with search and rescue efforts in a seriously damaged four-story building up the street. A police officer told Jerry that I-5, I-90, and I-405 could be out of service for a while, and that the Alaskan Way Viaduct had collapsed. Jerry returned to his office, but he could not re-enter the building. He figured that if he could get across Lake Washington, he could find transportation to Issaquah. He was right, but it took him 26 hours to get home.*

■ *Failure of the sea wall and the Alaskan Way Viaduct decimated the Seattle waterfront. Harbor Master Sam Chang wondered how fast temporary ferry berths could become operational; he hoped it would not be more than a day or two for foot passengers and a week or so for vehicles.*

■ *Peter Bigelow looked out the window of his home in Magnolia at the landslide that had struck the passenger train passing below his house at the time of the earthquake. He saw the slide buried the last few cars.*

■ *Port manager Carmen Rogers knew the region had a disaster on its hands before the shaking stopped. Luckily, the new SeaTac control tower survived and most of the repairs made following the 2001 Nisqually earthquake held. It appeared planes could land and take off safely. Whether they would have any passengers was another question, as it appeared roadways to the airport were jammed.*

■ *The seaport was another matter. The first step was to determine damage to cranes, piers, and wharves. Carmen anticipated problems at the port would be a boon to her competitors in other states. Cooperation with Tacoma and Everett would be important to keeping customers from deserting the region. Just then, Kevin Williamson from the Port of Everett called. He said his port experienced little damage and offered his help.*

The Regional Transportation System

The Central Puget Sound region's transportation system is an integral set of networks and routes connecting many locations and providing for the movement of people and products within, into, and out of the region. Highways and secondary routes allow people to commute to and from work and move people and goods to ferries, rail stations and yards, airports, and seaports. Local water ports rely upon shore-side facilities, highways, and rail to move supplies and goods in containers from ships to regional manufacturers and

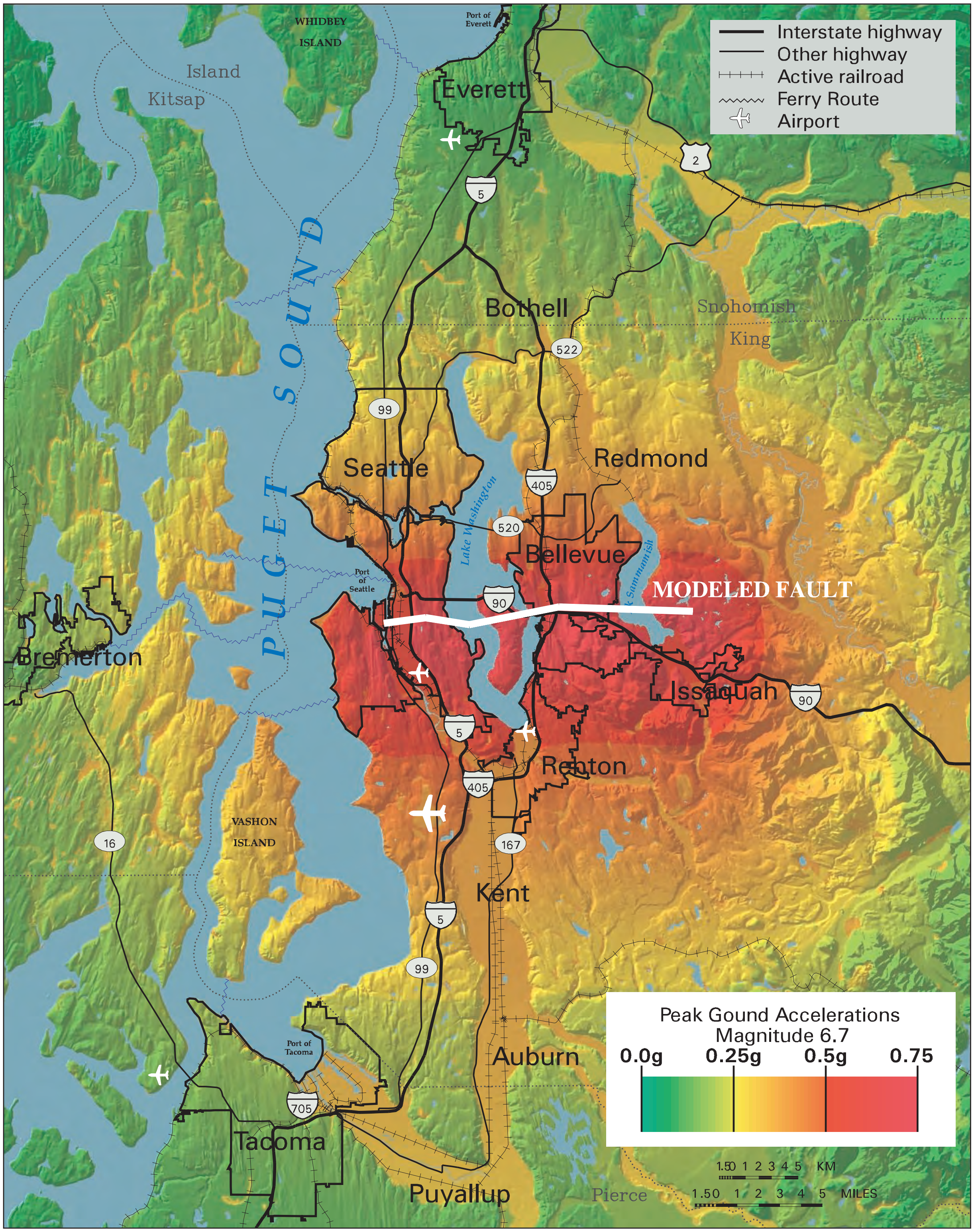

Figure 4-1: Map of peak ground accelerations beneath transportation facilities. Graphic / US Geological Survey

retailers and to end users a continent away. Seattle-Tacoma International Airport provides access to air travel to support regional, national, and international business, and both Sea-Tac and Boeing Field provide for overnight delivery of critical business documents and shipping of cargo around the world; highways and secondary routes move people and goods to and from the airports.

The region's economic well-being relies upon the smooth interconnections of its highways, ferry and rail systems, and air and water ports. A major disruption to any one of these components, such as will be caused by the scenario M6.7 earthquake, will overload the other systems, reducing their efficiency, potentially bringing them to a halt, with devastating affect on the region's economy.

Immediately after the earthquake, there will be massive congestion as bridges fail and the region's primary transportation arteries – its Interstate freeways and state highways – become saturated with traffic. Significant delays will occur. As witnessed after the Loma Prieta, Northridge and Kobe earthquakes, adaptive transportation routes and modes will emerge within the first few days after the scenario event. Use of secondary roadways and accessible waterways will increase. Transportation system inefficiencies will last from months to years; the length of time depends how long it takes to make repairs.

Roads and Bridges

The road transportation network on the east side of Puget Sound is comprised of facilities owned and maintained by the state, counties, municipalities and port authorities. The network serves a metropolitan population of more than 3 million people and has 1,600 lane-miles of freeways and 2,100 lane-miles of arterials.

Due principally to the mountainous topography and major bodies of water, the primary road transportation network is constrained to a handful of north-south and east-west corridors as shown in Figures 4-1 and 4-2. The major north-south routes in the region are Interstate 5, carrying more than 240,000 vehicles per day; State Route 99, carrying about 110,000 vehicles per day; and Interstate 405, carrying more than 148,000 vehicles per day. The major east-west routes across Lake Washington are Interstate 90, parallel to the Seattle Fault, carrying more than 200,000 vehicles per day, and State Route 520, carrying more than 100,000 vehicles per day. Normal rush-hour traffic often leads to congestion on these highways; a serious accident on one often severely restricts traffic and forces vehicles onto other routes, clogging them. The road system is not as redundant as that found in other major metropolitan areas, such as Los Angeles.

Snohomish, King, and Pierce Counties have 1,830 road bridges of more than 20 feet in length. Virtually all were built during the past 80 years, many during the Interstate System construction period from the late 1950s to the 1970s. Modern bridge design practice began in the mid-1970s after the 1971 San Fernando, CA earthquake. Significant improvements began in 1983, followed by complete incorporation into the design code in the early 1990s. Figure 4-3 shows the construction timeline for bridges in Washington. Washington State applied seismic design guidelines introduced in 1983 in all subsequent designs.

A number of unique structures cross major bodies of water, for example: the Lake Washington floating bridges (I-90 and SR-520) and the associated approaches and tunnels; the ship canal high bridges (I-5 and Aurora Avenue SR-99); the ship canal bascule (moveable) bridges (Montlake, University, Fremont, and Ballard); the West Seattle/Spokane Street bridges; and the First Avenue South bridges.

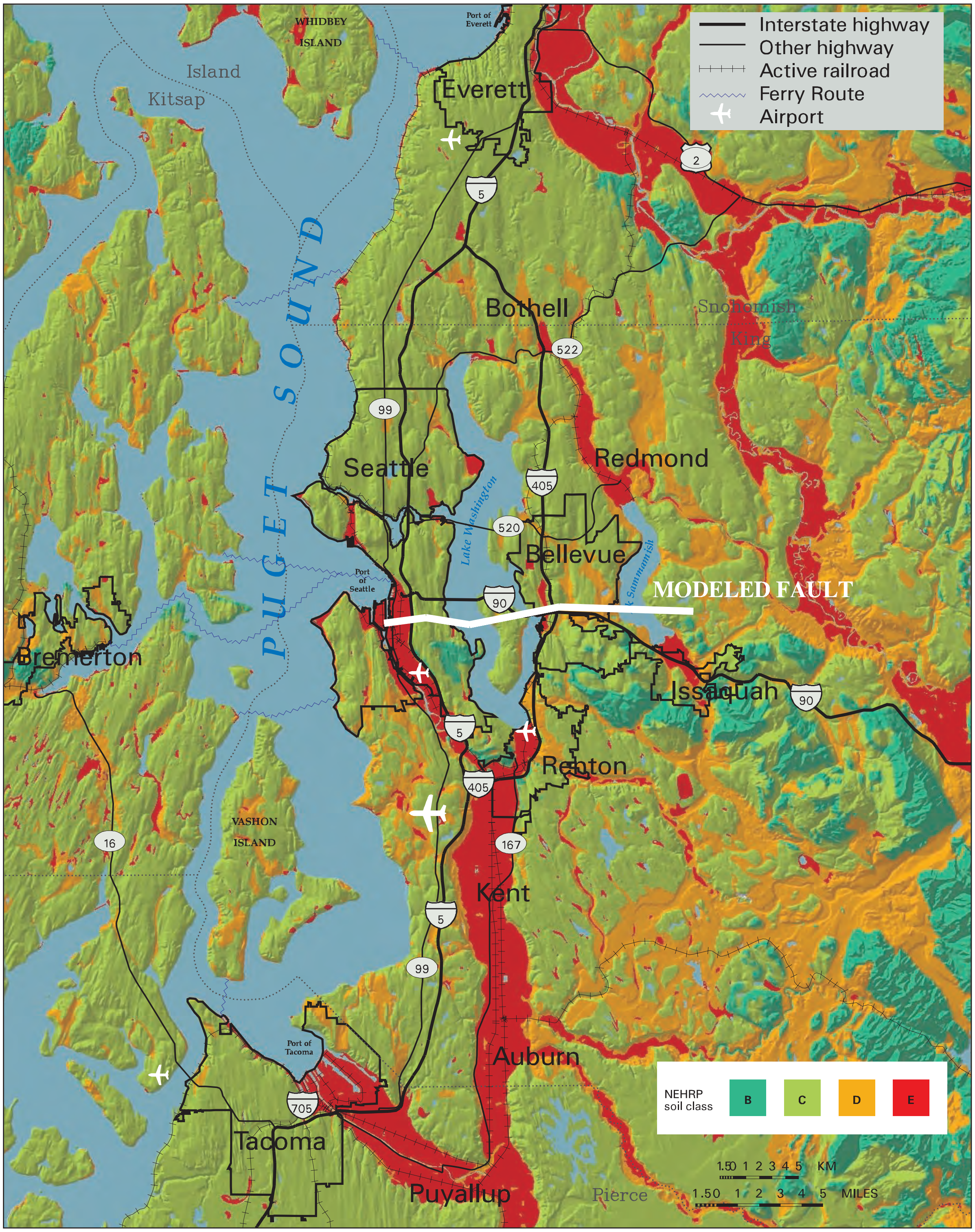

Figure 4-2: Transportation facilities located on Class E soils (red) are most prone to damage from liquefaction. NEHRP soils classes evaluate soils according to their resistance to amplifying ground motions. Class E soils amplify ground motions the most and are the most prone to liquefaction.

Graphic / US Geological Survey

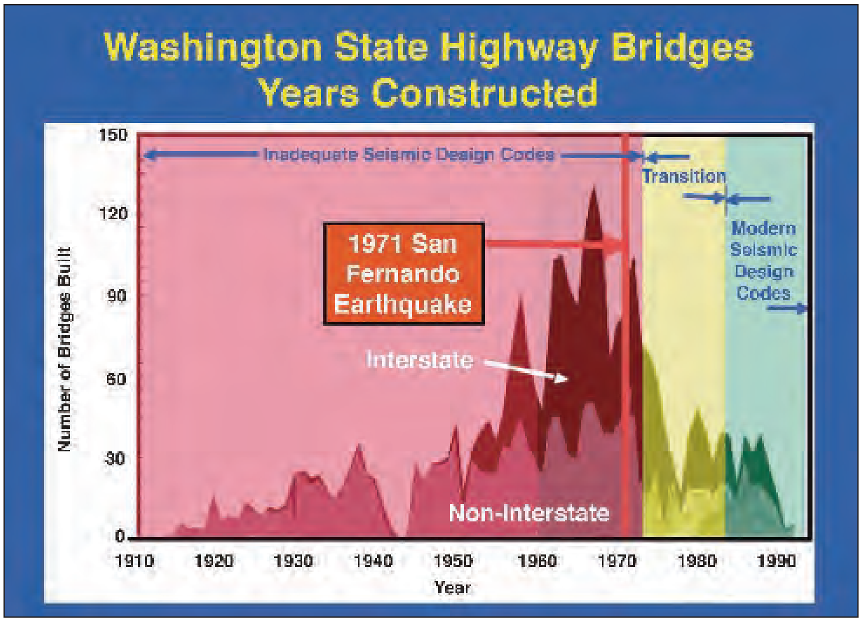

Figure 4-3: Washington state bridge construction and code changes.
Graphic / Washington Department of Transportation

These bridges range from early 1900-vintage steel bascule and masonry structures to modern concrete structures. Major structures, including the Alaskan Way Viaduct, Battery Street tunnel, and the I-5 elevated structures, complement these bridges in forming portions of the major roadway networks. Additionally, many smaller overcrossings, interchanges, and main-line bridges are part of the network.

Earthquakes that occurred elsewhere in the 1970s and 1980s showed the vulnerability of existing facilities to earthquake damage. Consequently, bridge seismic retrofit programs began in the Puget Sound region, accelerated after the 1989 Loma Prieta earthquake in the San Francisco Bay area, and continue today. State, County, and City bridge owners have used different retrofit strategies to upgrade their bridges. For example, the Washington Department of Transportation (WSDOT) is addressing state bridges in a phased approach, which allows spreading available funds over a large inventory of structures. By retrofitting the most vulnerable bridge elements first, WSDOT is providing the most protection to the greatest number of structures. On the other hand, County and City agencies with smaller inventories have chosen to implement more complete retrofits on a limited number of critical structures.

WSDOT's bridge seismic retrofit program, shown in Figure 4-4, will address 940 bridges built before 1982 in areas expecting at least moderate ground shaking. This covers most of the state structures west of Yakima, Ellensburg, and Wenatchee; 559 are in Snohomish, King, and Pierce counties. Phase I, which retrofitted simple span bridges to prevent them from falling off their supports, is complete. Phase II, which will retrofit more than 170 bridges with single columns, was more than half complete as of December 2004. Phase III, which retrofits bridges with multiple columns in a pier, has not begun. Retrofit of the State Route 99 Alaskan Way Viaduct, the State Route 520 bridges with hollow core pre-stressed concrete columns, bridges with substandard spread footing foundations, and bridges with poor soil near the foundation are not included in the WSDOT seismic retrofit program.

The Alaskan Way Viaduct, which passes along the western part of Seattle as part of SR-99, is a double-decked structure completed in 1953. It carries about one-quarter of the north-south traffic through Seattle, and operates at almost twice its design capacity. It nearly collapsed due to damage caused by the Nisqually earthquake. The viaduct and the 7,000-ft long seawall beside it, completed in 1936 without any earthquake design, are deteriorating. There is a recognized probability of 5 percent in the next 10 years that the route will be permanently unusable from a moderate-sized earthquake. Plans for replacement of the viaduct and seawall are underway, with the current preferred alternative being a tunnel costing $4 billion; even the most-quickly constructed alternative will take about six years to complete with a cost ranging from $2.7 – $3.1 billion.

If an earthquake closes the viaduct, the Washington Department of Transportation estimates that speed of traffic on I-5 at peak hours will slow to an average of 10 to 15 miles per hour. The viaduct, like many bridges in the region, also carries other services such as power and water, which will not function if there is severe damage to the viaduct.

For the scenario earthquake, high hazard locations are those along the main fault rupture, which parallels the I-90 corridor eastward from Seattle. Bridges along the corridor, as far east as North Bend, will see high ground accelerations. Additionally, bridges in geologically young and loose soil deposits or poorly compacted man-made fills will see high accelerations and high potential for ground-induced failures, such as flows and lateral spreads. An example of such damage occurred to the bridge in Figure 4-5 in the 1992 Costa Rica earthquake. Areas likely to be hardest hit are the Duwamish and industrial areas south of downtown Seattle, as well as low-lying areas of south Bellevue, Renton, Kent, Mercer Island, Factoria, and Issaquah. The peak ground accelerations in these areas may be several times greater than the current design acceleration.

In addition, the major north-south routes, Interstate 5, State Route 99 and Interstate 405, as well as portions of Interstate 90, all cross the Seattle Fault. Damage expected from the scenario earthquake will be most severe and most prevalent near the fault rupture. Unfortunately, this area contains the highest density of road and bridge inventory. Those bridges designed or retrofitted to the level of modern codes may suffer significant damage, but they are unlikely to collapse if ground displacements are small. Collapse could occur

Figure 4-4: Washington state bridge seismic retrofit timeline.

(Costs in 2004 dollars. Bridges with hollow-core piles and the Alaskan Way Viaduct are not included.)

Graphic / Washington Department of Transportation

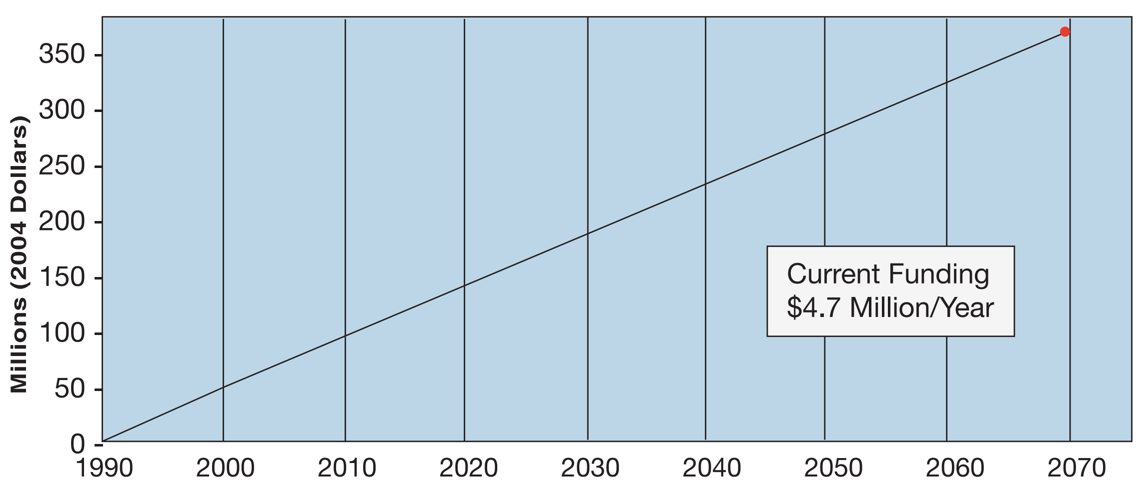

Figure 4-5: Bridge damage from the 1992 Costa Rica earthquake. Photo / Priestley

even on new bridges if supporting columns move because of the fault rupture or lateral spreading associated with liquefaction.

It is useful to recognize that the design objective for most bridges is that they will endure a design-level earthquake without loss of life, primarily meaning that there is no collapse. Design criteria historically permitted some damage – which could be significant – although collapse should not occur. Large surface fault ruptures not directly accounted for in design, however, will result in collapse of some structures.

Significant damage will occur in the bulk of the bridge inventory built before adoption of modern codes. For unretrofitted structures, such as the Alaskan Way Viaduct, partial or total collapses will occur. Damage will be worse in structures not tied together well. For example, when a bridge deck and beams sit on supports without positive connection, the deck and beams could fall off the supports. Additionally, structures with short reinforced concrete columns with steel reinforcing details from pre-1970s code criteria likely will suffer serious damage.

Fully retrofitted bridges will have much less damage. Partially retrofitted structures could experience significant damage; for example, an unretrofitted foundation may experience significant damage while a retrofitted column performs well.

Abutments of movable bridges likely will move toward each other during the earthquake due to the movement of soil embankments toward the water. Bridges that are open during the earthquake may be unable to close for vehicular traffic. Those that are closed may be jammed shut, unable to reopen. They also may experience structural damage, limiting their ability to carry traffic. A bridge with alignment problems after the Nisqually earthquake is shown in Figure 4-6.

Roadway damage will take the form of slumping of fills, such as occurred on Highway 101 during the Nisqually earthquake, shown in Figure 4-7, which are costly to repair. The scenario earthquake also will produce lateral movement of retaining walls and reinforced-earth structures. The extent of such damage will slow overall recovery of the area.

In addition to roadway damage, there will be vehicle damage, and injury and loss of life to vehicle occupants. Spills may occur from damaged vehicles carrying hazardous materials.

There will be a significant disruption to the roadway network in the region. Due to the lack of redundancy and the age of the structures this disruption may have a profound effect on the local area for many months after the event. For example, restoration and bridge replacement efforts by the California Department of Transportation following the 1994 Northridge event took nearly a year and cost about $300 million (1994$), with roughly half of that spent on replacing 10 bridges. The 1989 Loma Prieta event cost $1.8 billion (1989$) in transportation system damage, with 24 state-owned bridges closed permanently or requiring major repair.

While repairs to highways and arterial routes are ongoing, some traffic will move onto local roads. This could have an adverse impact on local roads, particularly those not designed to take the weight of large trucks nor the volume of traffic they will carry following the scenario earthquake.

Commute times to, or through, the near-fault region will increase substantially. Because life and commerce within much of the scenario region is highly dependent on the road system, the economic recovery of the region depends to how quickly repairs are completed.

Recovery will begin with inspectors from local and state transportation agencies evaluating damage and recommending closures, scheduling immediate repairs, and studying more extensive repairs or replacement. Most agencies have

Figure 4-6: Moveable bridge alignment problems after Nisqually earthquake.
Photo / Ranf et al., 2001

Figure 4-7: Highway 101 damage from ground failure caused by the Nisqually earthquake.

Photo / Washington Department of Transportation

post-earthquake plans in place and identified personnel to evaluate structures. Additionally, inspectors and contractors from other parts of the Pacific Northwest and the nation will assist in recovery efforts. Durations of service disruption will depend heavily on the commitment, organization, funding, and effort of appropriate response organizations.

Airports

Although there are numerous airports used by various types of aircraft, this project focuses on Seattle-Tacoma (Sea-Tac) International Airport, King County International Airport/ Boeing Field, Snohomish County Airport/Paine Field in Everett, and Renton Municipal Airport.

Sea-Tac International Airport, the major passenger airport in the Pacific Northwest, transported 26 million passengers in 2003. It is south of Seattle on soil not prone to liquefaction. Reinforced concrete and steel structures date from 1949. Major new additions have been made recently to terminals, concourses, office towers, and parking garages. The airport built a new control tower; it has an ongoing program to seismically upgrade older facilities.

In the 2001 Nisqually earthquake, peak ground accelerations near the airport measured about 0.20g (about 20 percent of gravity). Generally, damage at the airport was minor. However, there was considerable structural

Figure 4-8: Nonstructural damage in the old Sea-Tac International Airport control tower from the Nisqually earthquake.

Photos / Port of Seattle

damage to the control tower in use at the time caused by deformation of its steel supports. There was significant non-structural damage in the tower as shown in Figure 4-8. Extensive water damage occurred in the North Satellite from broken pipes. There was minor non-structural damage in the Main Terminal, where seismic upgrade work was only partially completed. It took more than a month to return the airport to full operating capacity.

The Boeing Co. uses King County International Airport (commonly known as Boeing Field), as it does Renton and Everett airports, for commercial aircraft operations. Boeing Field also is home to about 150 aviation-oriented businesses, and it is designated as a reliever airport, which means that it can accommodate a portion of the Sea-Tac traffic should the need arise. It is located south of downtown Seattle on highly liquefiable soil. This airport's major facilities date from 1930. Some seismic upgrade work is complete.

During the Nisqually earthquake, in which peak ground accelerations reached 0.27g (about 27 percent of gravity), minor structural and nonstructural damage occurred to the existing control tower; operations moved to a temporary facility. There was minor damage to the passenger terminal building, which closed for a few days. The most significant damage was to the runways, where large cracks appeared with evidence of soil liquefaction and lateral spreading, as shown in Figure 4-9. This resulted in runway closures for a couple of weeks until temporary repairs were completed.

Snohomish County Airport (commonly called Paine Field) is a reliever airport, located in southwest Snohomish County. Major buildings date from the 1940s and consist of a wide variety of construction. A replacement control tower is under construction. There was no damage reported at the airport in the Nisqually earthquake.

Renton Municipal Airport is a reliever airport in Renton, southeast of downtown Seattle. This airport has a control tower and various ancillary buildings, including hangars. There was some damage at the airport caused by the Nisqually earthquake. Boeing has considerable commercial airliner assembly operations at both Renton Municipal Airport and Paine Field.

The peak ground shaking at Sea-Tac from

Figure 4-9: Long cracks and liquefaction at King County International Airport runway, commonly known as Boeing Field.
Photo / Shannon & Wilson, Inc., © 2001

the scenario Seattle Fault earthquake will be close to 0.5g (50 percent of gravity), as shown in Figure 4-1. This level of shaking is greater than most modern building codes consider. Because the airport is not on liquefiable soils, no significant runway damage is expected.

A variety of structural and non-structural damage will occur due to the wide range of age of buildings and because not all facilities have undergone seismic retrofitting. The new control tower should survive without damage, although high ground accelerations may throw unattached items around the tower. Recently constructed facilities should have no more than moderate structural damage that is reparable although there is likely to be non-structural damage that may result in temporary closures. Recently retrofitted facilities should not collapse, but post-earthquake replacement of some buildings may be required due to severe damage. Older, unretrofitted structures may collapse.

If liquefaction at Renton cuts high-pressure fuel lines to Sea-Tac, trucks will have to carry fuel to the airport. In addition, aircraft whose wings are damaged by violent flapping during severe ground shaking will need to be replaced by working planes; this occurred at the San Francisco airport during the 1989 Loma Prieta earthquake. If Sea-Tac is out of service for some time, out-of-the-area passengers unable to depart will need housing.

Boeing Field and Renton Municipal Airport will experience peak ground accelerations of up to 0.7g (about 70 percent of gravity) in the scenario earthquake. Liquefaction will occur again at Boeing Field since ground shaking will be much greater during the airport experienced during the Nisqually event. The Renton Municipal Airport will experience similar liquefaction and lateral spreading, significantly damaging runways. In addition, more structural and nonstructural damage will occur in buildings at these two airports from both ground shaking and soil movement. There is a potential for structural collapse in older structures not seismically upgraded. It may take months to return to some level of operation at both airfields.

With peak ground accelerations at Paine Field of 0.15g or less (about 15 percent of gravity), there will be little or no runway or structural damage. There is a potential for temporary closure due to minor non-structural damage in older structures not seismically upgraded.

Waterfront Port Facilities

Typical waterfront facilities in the Puget Sound region include port facilities, marinas, industrial facilities, ferries, and residences. Ports within the Puget Sound area that may be impacted include 20 or so port districts extending from the San Juan Islands to Olympia. These range from small facilities to very large ports in Seattle and Tacoma, and a small port in Everett. These three ports represent more than 90 percent of the volume of commercial business by port districts within the Puget Sound area. The narrative regarding potential damage presented below also applies to most commercial and industrial facilities located along waterfront areas of Puget Sound.

- The Port of Seattle, shown in Figure 4-10, is the second largest port in the Northwest, generating revenue of more than $1.5 billion dollars annually. It is the 10th largest container port in the United States, and it ranks 45th in the world. Marine services include cargo and vessel terminals, moorage for commercial fishers, automobile handling facilities, marinas, and a cruise boat terminal. In 2002, the Port of Seattle handled about 1.5 million TEUs (ton equivalent units) of cargo through its 15 terminals; most is containerized.
- The Port of Tacoma is the largest port in the state and it has the largest container cargo facility. It is the seventh largest container port in the nation, and it ranks 43rd in the world. It has 11 cargo terminals. More than 70 percent of international cargo handled by the port goes to the central and eastern regions of the United States by train and road. The port also handles more than 70 percent of the marine cargo between Alaska and the lower 48 states.
- The Port of Everett is the smallest of the three ports, handling about 5,000 TEUs annually. However, it has a diverse business base that includes salt, oil, scrap metal, lumber, and wood products, agriculture, marinas, and a relatively new 1,000-acre business park. The port has three ship terminals, one of which contains two pile-supported piers. Primary use of one pier is to supply parts to Boeing's Everett plant.

Piers and wharves are pile-supported docks that extend into the water from the shore. Piers extend outward from the shore to allow berthing of ships perpendicular to the shore, while wharves allow berthing of ships parallel to shore. The age, condition, design and configuration of piers and wharves vary within each port, resulting in differences in probable performance during the scenario earthquake. Nearly all of the newer piers and wharves have pre-cast concrete piling. Timber piling support older piers, such as Piers 90 and 91 at the Port of Seattle.

The scenario earthquake will affect various types of port structures, such as piers, wharves, seawalls, container storage yards, marinas, upland buildings, cranes, and utilities. The common denominator of all structures is that they are located along, on, or near slopes at the edge of the water. Most of the ground in these areas is moderately or highly susceptible to

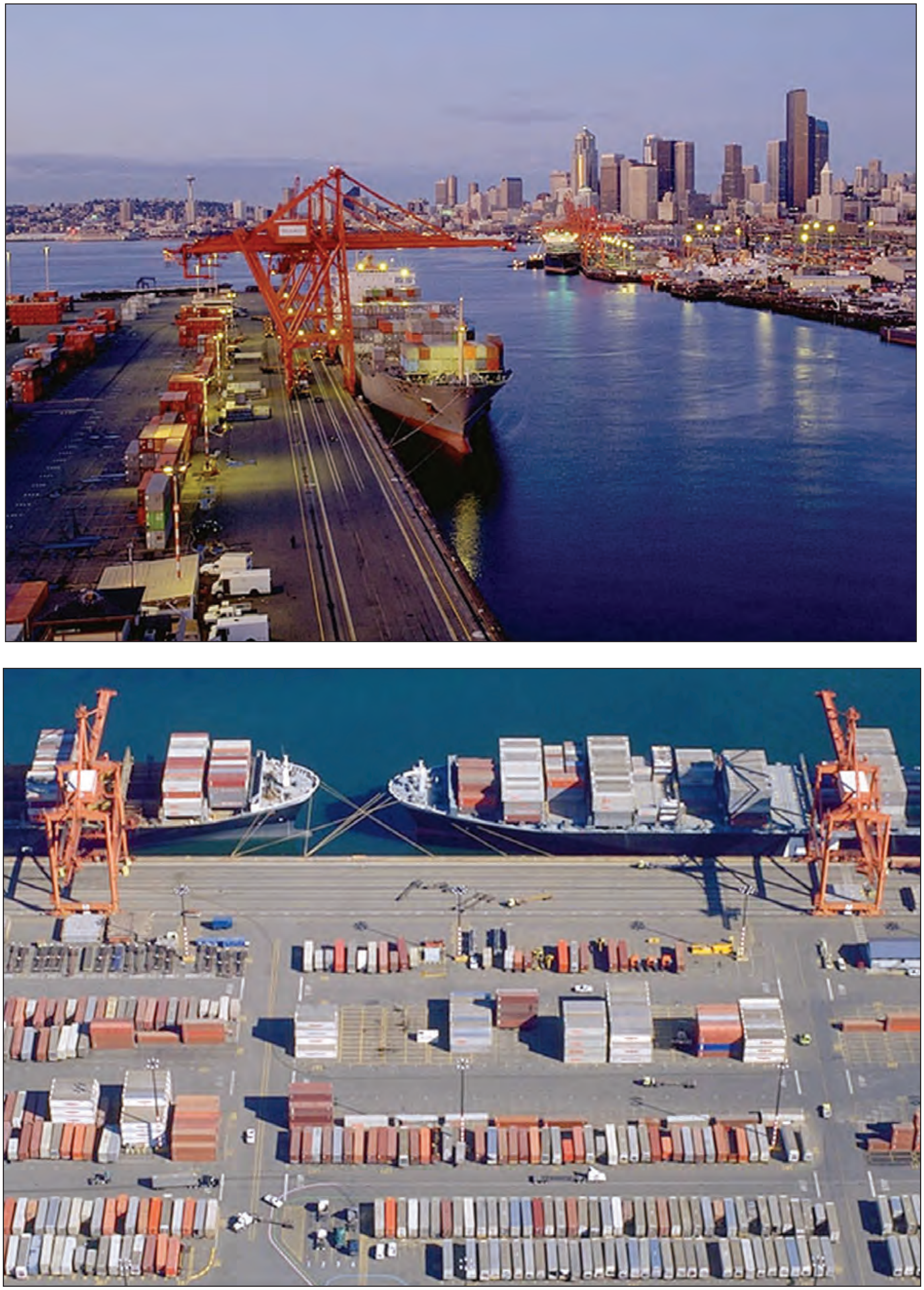

Figure 4-10. The Port of Seattle.

Photos / Don Wilson, Port of Seattle

Figure 4-11: Damaged quay walls and port facilities on Rokko Island from the 1995 Kobe earthquake. Quay walls were pushed outward by 6.5 to 10 feet, with 10- to 13-foot-deep depressed areas called grabens forming behind the walls.

Photo / Earthquake Engineering Research Institute © 1997

large lateral movements – either slope failures or lateral spreading from liquefaction – during strong shaking. Just as significant damage occurred during the Kobe earthquake in 1995, as shown in Figure 4-11, the scenario event will generate lateral ground movements of five feet or more in unimproved waterfront areas. Designs for piers and wharves do not account for this level of movement. Only a select few waterfront areas around Puget Sound have had ground improvement such as stone columns, pile-densification, or grouting to reduce potential for lateral spreading. The effects of lateral ground movement can extend 200 feet or more from the shore, as observed after the Kobe and Nisqually earthquakes. While lateral spreading will be the primary cause of damage to ports, strong ground shaking also will result in damage to many structures near and over the water.

There is the potential for a large submarine landslide in the Duwamish River delta, including Harbor Island. Many areas at the delta front are of marginal stability with respect to landsliding. Commencement Bay, in Tacoma, experienced a submarine landslide without an earthquake in 1894. The landslide of about 200 million cubic yards occurred suddenly and generated a 9-14 foot water wave that inundated the port. In 1943, a slower slide removed about 700 feet of the breakwater at the mouth of the Puyallup River.

If a submarine landslide occurs at Harbor Island, part of the island may disappear into Puget Sound, reducing the capacity of the port and causing environmental problems in Elliott

Bay from spilled petroleum fuels and contaminants such as lead and arsenic. All structures in this area will be devastated. A wave may be generated which will pound seafront facilities and vessels on the other side of the bay. The project team did not consider the impact of this potential landslide in the described loss estimates.

The primary damage to piers and wharves will be from lateral ground movement along the shoreline. This movement will cause the landward portion of the structure to move outward into the water, pushing piling along the entire dock outward as well. Most likely damaged will be the short piling and batter piling. Because of the flexibility of the structures and redundancy of many piling, total collapse is not expected. However, depending on the magnitude of ground movement, the damage could result in limited or no access from the land to the pier and could significantly reduce the performance of the pier or wharf. This type of damage is common, occurring on similar structures during earthquakes elsewhere. During a large earthquake in Chile, for example, one pier experienced significant displacement from the shoreline that put the pier out of commission for months. The 1989 Loma Prieta earthquake caused several piers at the Port of Oakland to experience structural damage from excessive lateral movements.

Container terminals that rely on the large cranes to load/unload containers from ships will experience structural damage, especially to the piling. Large soil movements, such as occurred in Kobe, may compromise access to the terminals. Damage to container cranes may be severe and utilities to the pier disrupted. In many cases, the structure will be of limited use – except perhaps as a temporary berthing for emergency supply ships – until damaged piling is replaced and access to the pier or wharf is restored.

The high ground accelerations from the scenario earthquake will generate significant pressure on seawalls, which are susceptible to movement caused by lateral spreading of the ground behind them. Damage to most seawalls will result in lowering of the fill behind them, and require replacement of many. Until seawalls are repaired, use of the land behind them will be limited to light loads.

The scenario earthquake also will affect container storage areas. Typically, these are large lots paved with asphalt or roller-compacted concrete. Such areas will experience differential settlement of several feet or more due to liquefaction, particularly close to the water where lateral spreading is a factor. There may be some flooding. Damaged lots will need to be regraded and resurfaced, both of which can be completed using conventional equipment in a relatively short time, depending on equipment and worker availability after the earthquake. Damage to containers and their contents will be limited to toppling and shaking.

Marinas typically have floating platforms secured in place with vertical piling driven into the marine soils. This type of structure is very resistant to strong ground shaking. The piling and the platforms they secure can move several feet without damage. Lateral movement along the shoreline that damages access ramps and utilities leading to the platforms will cause most of the damage. In addition, many of the buildings and other landside structures will experience structural damage. Ground settlement caused by liquefaction will affect roads and parking areas. Although difficult to estimate, some damage to boats in the marina will occur as they bang against the slips and other boats during severe ground shaking. Damage may occur from tsunami waves generated by landslides falling into the water nearby.

The Central Puget Sound region's ports face a difficult time following the scenario earthquake. It may be hard for ports to engage specialty contractors quickly to fix damaged piers and wharves, and to maintain operations so shipping lines do not leave for undamaged ports elsewhere. Past earthquakes provide important lessons about the time it can take for repairs and to restore lost shipping business. For example, about 80 percent of the wharves and terminals in the Port of Kobe, Japan were out of commission for more than two years following the 1995 earthquake. Liquefaction and lateral spreading caused extensive damage. Many shipping lines left for facilities at nearby undamaged ports. It has taken the Port of Kobe about 10 years to regain much of the business that moved following the earthquake.

Railroads

Within the region, the Burlington Northern and Santa Fe (BNSF) Railway owns lines from Portland to Vancouver, British Columbia, through Seattle and Everett; a line between Tukwila through Woodinville to Snohomish and various yards; and minor branches. The Union Pacific (UP) owns a line between Seattle and Tacoma, and yards and industry spurs in Seattle and Tacoma. South of Tacoma, the UP operates over the BNSF. Between Seattle and Tacoma, the tracks essentially are parallel, relatively close together and subject to the same hazards.

Passenger trains operated by Amtrak run on the BNSF lines to Portland, to Vancouver, British Columbia, and east from Everett. Commuter trains operate on the BNSF between Seattle and Tacoma, and between Seattle and Everett. Four northbound and four southbound passenger trains per day operate south of Seattle in addition to six commuter trains. Two passenger trains and four commuter trains operate in each direction along the Puget Sound shoreline north of Seattle. One passenger train in each direction operates between Seattle and Chicago through Everett.

Under normal conditions, railroads bring about 100,000 tons of freight per day into the area and carry a somewhat larger tonnage out. More than 95 percent of this tonnage has its origin or its destination in the area, with a major portion passing through the ports.

From Tacoma to downtown Seattle, railroad tracks are located in high liquefaction susceptibility zones. There are other segments, of more limited length, in zones of high and very high liquefaction susceptibility. Tracks in a number of areas are located in cuts or along hillsides or shorelines subject to landslides. Such a landslide occurred in the 1965 Puget Sound earthquake as shown in Figure 4-12. Lines also pass close to Seattle's seawall, which is vulnerable to the scenario earthquake. Both railroads operate through two tunnels near Tacoma. The BNSF operates through a tunnel under downtown Seattle and one in Everett.

There are more than 200 railroad bridges and trestles in the three counties of the study area with steel girder, truss spans, and concrete girder spans. Several of these are long and/or tall with lengths up to 2,650 feet and heights up to 160 feet. However, most of these long and/or high bridges are in the eastern part of the region where ground shaking will be less severe. In general, North American railroad bridges behave better than highway bridges in earthquakes. This probably relates to the continuity of the rails across the bridges and the high horizontal design loads required for forces imposed by trains.

Six bridges have moveable spans. Three of these are in Everett, two in Seattle and one is near Steilacoom. Many of the lines through the Green River Valley are on bridges that are about 100 years old in regions prone to liquefaction. Another of these older rail bridges carries all freight out of the Port of Tacoma. There also are more than 60 overpass structures owned by various agencies. Overpass spans have fallen on tracks in previous earthquakes.

Figure 4-12. Damage to the Union Pacific Railway occurred when hillside fill slid away from beneath a 400-foot section of the branch line just outside Olympia more than 37 miles from the epicenter during the 1965 Puget Sound earthquake.

Photo / University of California Berkeley

Facilities for servicing and repair of locomotives and repair of cars and facilities for loading and unloading containers and/or trailers are located in Seattle and Tacoma in regions of liquefiable soil.

The scenario magnitude 6.7 earthquake will cause various types of damage. The main tracks of both BNSF and UP railroads cross the fault rupture. The offset along the fault will damage track components and disturb its geometry. Although repairs to track geometry could allow operations to resume, maintaining acceptable track surface for operation at restricted speed could require surfacing the track after every train for an extended time. Over a month after the 1999 Kocaeli, Turkey earthquake, one location where the tracks crossed the fault rupture still required inspection of the track after every train and frequent surfacing to allow continued operation at 20 miles per hour.

Liquefaction-induced track damage will take up to a week to repair. Settlement caused by liquefaction could derail cars standing in rail yards. If there is extensive liquefaction in the area of yards, restoring full capacity and operations will take several weeks. Lines close to the Seattle seawall will distort severely. North of Seattle and southwest of Tacoma, where the tracks run along the shoreline, tracks could move toward Puget Sound. Among the most

Figure 4-13. Piers on BNSF Railway West Seattle bascule bridge moved together 6 inches in the Nisqually earthquake due to movement of the soil behind the abutment toward the water, then several inches more in the next few days.
Photos / William Byers

vulnerable to liquefaction and lateral spreading are older bridges in the Green River Valley that cross streams.

There is an increased probability of landslides if soils are saturated. Although the Nisqually earthquake occurred after a period of relatively dry weather, a landslide filled the track ditch near Tacoma, but did not bury the track. There are a number of natural and cut slopes in the area subject to landslides in wet weather without assistance of an earthquake. Clearing a major slide across a rail line easily requires one or more days after equipment reaches the site.

Derailments are possible if trains are in areas of severe ground shaking. Most of the railway tracks run perpendicular to the fault; past earthquakes indicate that overturning of cars during ground shaking is more likely if tracks are parallel to the fault. Derailments due to track conditions are unlikely after trains have reduced speed following the earthquake.

In addition, there will be widespread damage to signal systems, including grade crossing protection. Although this damage often is relatively quick and inexpensive to repair, the system may require testing after the repairs and train speeds will be severely restricted until repairs and testing are completed.

Movement of bridge abutments sufficient to interfere with operations of one or more of the region's moveable bridges is expected. Abutments on the BNSF Railway West Seattle bascule bridge in Figure 4-13 moved together about six inches in the Nisqually earthquake; the scenario earthquake will cause equal or greater problems.

Railway bridge movements due to liquefaction of less than one foot probably could be corrected by relocating span bearings on the substructure, which would require one or two days in addition to mobilization time. In the case of larger movements on girder spans, restoring service on temporary substructures will take a week or less. In the case of bridges with truss spans, construction of a temporary bridge on a parallel alignment may be necessary. Such a bridge could be constructed at a rate of about 50 feet every 24 hours.

The increased cost of rail operation with damaged facilities and lost revenue during the recovery period probably will exceed the cost of repairs. Damage to container and trailer handling facilities will reduce capacity for a significant period after the earthquake and prevent use of the facilities for several days. Damage to some passenger stations will require temporary arrangements to accommodate passengers during repair. Damage to locomotive and car repair facilities will require temporary transfer of work to alternate, less convenient locations. The same will be true of damage to locomotive servicing facilities.

Based on observation of railroad recovery from previous earthquakes, recovery will be a stepwise process. Some lines will return to service after initial inspection, which will require about six hours. Temporary repairs to allow operation with speed restrictions will require several days but, barring severe bridge damage, all of the important lines should be in service within five days. Normal speed operation will require two months if the fault rupture reaches the surface under tracks. Further time will be required if soil beneath the tracks near the Seattle seawall moves significantly. The effects of the earthquake will reduce the volume of freight on railroads during the recovery period. The demand for commuter service may increase with significant damage to highways, but availability of service depends upon condition of damaged rail lines. Since there are two lines in this area, it is probable that repairs to one will occur more quickly.

Ferries

Washington State Ferries (WSF) has 28 vessels that transport 26 million passengers between 20 terminals each year. This includes two operational foot ferries with a total capacity of 500. The terminals on the east side of Puget Sound most likely affected by the scenario earthquake are the Seattle Pier 50 walk-on terminal (with ships to Vashon Island) and Seattle Pier 52 (with ships to Bremerton and Bainbridge Island) as shown in Figure 4-14. Also affected will be the Fauntleroy terminal (with ships to Vashon Island and Southworth). More than 7.8 million people and 4.5 million vehicle trips originated at Piers 50 and 52 and in Fauntleroy in 2003. Other ferries, including the Victoria Clipper fleet at Pier 69 and sightseeing boats, also operate along the Seattle waterfront. The seawall behind these piers was completed in 1936 without any design considerations for earthquake.

While the state ferry system has no contingency plan specifically for an earthquake disaster, it regularly responds to unforeseen events such as storms, vessel casualties, and terminal casualties. In addition, generators are available to power the loading and offloading devices for passengers and vehicles in the case of an electricity interruption.

In an earthquake, WSF would reschedule service to nearby, undamaged terminals. Three-boat, as opposed to the normal two-boat, schedules could increase traffic flow. Ferries will help move people if land routes are blocked, as was done after the Kobe earthquake using temporary loading and unloading equipment.

The ferry facilities most susceptible to severe ground shaking are the terminal ports/piers to the seaward side of the seawall in Seattle. Damage from liquefaction and lateral

Figure 4-14: Seattle Pier 50 and 52 Washington State Ferry terminals.
Photo / Washington State Ferry System

spreading of the soil, and failure of the seawall, is expected. Significant damage to the ferry vessels is unlikely. The Seattle and Fauntleroy terminals may be down for several months. However, it is probable that foot passengers could embark and disembark at a temporary location in Seattle within a few days after the earthquake. Restoration of vehicular traffic could occur within a week, depending on the priority to fix ferry piers as opposed to other structures.

Chapter 5

Buildings

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■ *In Pioneer Square, Thea Rolfe and Mary Stevensdotter felt their building shake. They ducked under the desk to wait it out, emerging pale and scared at the sight of the beloved coffee/bookshop they had labored so hard to get off the ground. They carefully selected a retrofitted historic building, bolted all the bookshelves to the walls and strapped down computers. The inventory, however, was a mess on the floor. Beyond the rubble, they could see exposed rooms inside nearby buildings; their brick walls peeled away and landed onto parked vehicles below during the shaking. The women and their neighbors rushed to find survivors in the cars. The memories of this moment would be with them always.*

■ *Cynthia Liu just finished unloading a batch of her fresh gourmet chocolates at the Chocoholics Store in Issaquah. Her white knuckles gripped the steering wheel as the lurching parking lot rocked her car. She canvassed the parking lot and saw jittery shoppers exiting the shops; she also saw evidence of damage, especially in the office supply store, where boxes stacked to the ceiling were scattered in piles on the floor.*

■ *When the shaking stopped, Mark Fisher was among the crowd emptying out of downtown Seattle high-rises. The sidewalks filled with disoriented people like him. He looked back at his building relieved that the office tower appeared intact, although shattered glass from the building littered the sidewalk. Someone mentioned that water was gushing from a broken pipe on the 11th floor. Since Mark's company leased the 10th floor, he wondered if his office would survive the deluge. His eyes wandered down the street where a cloud of dust began to dissipate. The entire façade of a four-story building was on the ground and he could see office furniture inside. He fumbled for his cell phone to check on his wife Claire. There was no signal.*

This chapter provides an overview of building damage for the scenario earthquake and discusses expected performance for the most common types of structures. In the scenario event, many structures located near the Seattle Fault will experience very strong ground motions that generate forces far in excess of those experienced during the 2001 Nisqually earthquake. Unretrofitted, older structures will sustain heavy damage. Of particular concern are unreinforced masonry (old brick) and reinforced concrete tilt-up structures, which have performed poorly in past earthquakes and are common in the Central Puget Sound region. Modern structures built on firm soils should survive with varying degrees of damage.

Damage and economic losses to commercial and industrial buildings will be about $10.5 billion, with the most extensive damage anticipated in the regions along the fault rupture of the scenario earthquake and along low-lying river valleys. These areas have poor soils. Nearly 3,900 commercial and industrial buildings – about 27 percent of these buildings in the region – will experience moderate to extensive structural damage, resulting in closures and repairs. In addition, the scenario event will cause about $15.3 billion in damage to single- and multi-family residential structures, temporarily displacing more than 46,000 households.

Highly Vulnerable Building Types

Unreinforced Masonry Buildings

Unreinforced masonry (URM) buildings have performed poorly in past earthquakes due to lack of adequate ties and connections, and lack of steel reinforcing within brick masonry load-bearing walls. There are about 2,200 URM buildings within

Building Codes

Major fires that killed thousands and destroyed millions of dollars in property drove development of the nation's earliest building codes. For example, Seattle's fire of 1889 prompted the city to adopt its first building code in 1894; like most codes of that era, it primarily dealt with fire protection. The first comprehensive building code on the West Coast was published in 1927; however, earthquake prevention measures were only recommendations.

Earthquake codes developed slowly, generally in reaction to damage observed in an earthquake. For example, in 1958, anchoring concrete or masonry walls to floors and roofs became a requirement, and after the Northridge earthquake in 1994, stronger steel frame connections were required.

Until the 1970s, there was no standardized building code in the State of Washington, as local governments were responsible for adopting their own codes. This led to a wide variation in minimum standards, with urban areas generally more progressive than outlying areas with less development activity. Today, the State Building Code Council mandates minimum standards for the entire state, with enforcement still left to local jurisdictions.

The table below provides a synopsis of the evolution of building codes in Western Washington, with emphasis on the City of Seattle. Development of building codes in other local jurisdictions generally follows a similar timeline.

Year	Building Code Development
1894	First building code published for Seattle.
1946	Earthquake requirements added to Seattle Building Code.
1953	Earthquake forces increased in the Seattle code in response to the 1949 Olympia earthquake, but requirements still less than those in the Uniform Building Code.
1955	State law mandates newly constructed hospitals, schools, places of assembly, and public buildings in Western Washington to withstand horizontal forces of an earthquake equal to 5 percent of the building's weight.
1974	1973 Uniform Building Code made the minimum standard throughout the state by the State Building Code Act.
2004	The 2003 edition of the International Building Code adopted by the State Building Code Council.

Safeguarding human life is the intent of earthquake design provisions of the building code. This means that a building's occupants should be able to exit following an earthquake. However, it is possible that a building will no longer be useable after a major earthquake or other disaster event.

Figure 5-1: A representative unreinforced masonry building in Seattle.
Photo / Mark Pierepiekarz

the three-county study region. The largest concentration of these buildings is south of downtown Seattle, particularly in the Pioneer Square and International District neighborhoods. Construction of most URM buildings (see Figure 5-1, for an example) occurred before 1940, during an era when wall anchorage to floors and roof generally was missing and use of low-strength lime mortar was common. These buildings usually range from one to six stories high and typically function as commercial, residential, and/or industrial buildings.

URM building damage was common during each of the last three significant earthquakes (1949, 1965, and 2001) in Western Washington. Following the 2001 Nisqually earthquake (Figure 5-2), 20 of the 31 red-tagged buildings (occupancy not permitted due to extensive damage) in Seattle were unreinforced masonry buildings. Another 50 URM buildings were yellow-tagged (limited occupancy permitted) due to either parapet failures or significant wall cracks.

Causes of failure in URM buildings include:

- **Inadequate Wall Anchorage** – Inadequate anchorage of walls to floors and roof commonly causes separation of masonry walls. Such failure of load-bearing walls can lead to building collapse.
- **Unstable Parapets and Appendages** – Tall, unbraced parapets, cornices, and other appendages typically fail due to inadequate support or inadequate attachment to the structure. Such failures present a life-safety hazard to both building occupants and pedestrians on sidewalks.
- **Large Horizontal Deflections** – Large deflections in floors and roofs, typically constructed of relatively flexible wood and decking, cause collapses of adjacent masonry walls.
- **Weak Masonry Walls** – The mortar used in URMs typically is made of lime and sand, with little or no cement. Such

Figure 5-2: Unreinforced masonry building damage, 2001 Nisqually earthquake.

mortar has limited strength and crumbles during prolonged strong ground shaking.

- **Open-Front Structures** – Large ground-level display windows and door openings create a weak story along a building's storefront. This results in a three-sided box structure that tends to twist during an earthquake. Additional loads and deflections from twisting can cause collapse.
- **Tall Slender Walls** – Slender URM walls in buildings with tall stories can buckle and collapse during strong ground shaking.
- **Fire Risk** – Fracture of unbraced gas and fire suppression piping cause fires. Unbraced pipes typically fail at elbows, Ts, wall penetrations, and connections to equipment lacking anchorage.

For the scenario earthquake, the most extensive damage to URM buildings occurs in the neighborhoods south of downtown Seattle where ground motions will be very strong and where building foundations rest on soils prone to liquefaction. Unless seismically retrofitted, many URM buildings in this area will sustain either extensive damage or collapse. Significant economic losses, injuries, and loss of life associated with damaged URM buildings will occur. Collapsed buildings will require search and rescue operations. Extensive damage to a majority of unretrofitted URM buildings will represent complete economic losses to their owners and require demolition. Moderately damaged URM buildings in historic districts will present additional challenges to historic preservation boards during the recovery period.

Lesser but still significant structural damage to URM buildings will occur in other areas where horizontal peak ground accelerations reach 0.3g (or 30 percent of gravity). A significant number of URM buildings in these areas will be uninhabitable because of tipping of parapets, local wall failures and visible wall cracks.

Seismic retrofitting of URM buildings can be effective in preventing major damage and

Figure 5-3: Undamaged retrofitted unreinforced masonry building in Seattle. Note bolts in side of building where anchors have been placed (see arrows).

Photo / Mark Pierepiekarz

loss of life; local building departments have encouraged seismic retrofits. Likewise, lenders and insurers recognized the high risks of URM construction. Consequently, seismic retrofitting – parapet bracing, wall anchors, steel bracing, and seismic shut-off gas valves – of some URM buildings has been completed. Figure 5-3 shows an example of a retrofitted URM building.

Tilt-Up Buildings

Pre-1973 reinforced concrete tilt-up buildings represent another class of highly vulnerable structures. Built in the greater Seattle area since the 1950s, the industrial area south of downtown Seattle is home to the majority of older tilt-up buildings (Figure 5-4). Expansion of

Figure 5-4: Example tilt-up building in Seattle.

Photo / Mark Pierepiekarz

tilt-up construction followed population growth into the suburbs. Today, tilt-ups are widespread throughout Snohomish, King, and Pierce Counties.

Tilt-up construction has evolved from the single-story warehouse and retail buildings to modern office buildings up to four stories high. Tilt-ups typically are box structures, with the concrete walls initially cast flat on the building floor slab, tilted into position around the perimeter, and then structurally interconnected with roof, floor, and other wall elements acting as shear walls. Additional interior shear walls or steel-braced frames may be present in narrow or irregularly-shaped buildings.

The connections between roof and walls are the critical link in tilt-up buildings resisting seismic forces. Inadequate or missing wall-to-roof connections have been a common source of failures in recent earthquakes. Modifications are made to the designs of these connections following each major earthquake.

Tilt-up buildings constructed prior to the adoption of the 1973 Uniform Building Code (UBC) will receive the most damage in an earthquake. Other such structures built prior to the 1990s and located in low-lying areas at high risk to liquefaction may receive significant damage. Retrofitting of wall-to-roof connections is an effective method of minimizing future earthquake damage in tilt-up structures.

Tilt-up damage in the 2001 Nisqually earthquake was minor, with relatively few buildings experiencing roof collapses (Figure 5-5). The scenario earthquake will generate much stronger ground shaking. Consequently, many tilt-up buildings, particularly those located in low-lying areas in near the Seattle Fault (I-90 corridor and along the Duwamish Waterway), will experience partial collapse. Some tilt-up buildings along river valleys in Bothell, Redmond, Kent, and Auburn will suffer similar damage. Older reinforced tilt-ups housing businesses, offices, restaurants, and retail in Kent, Auburn, and Puyallup may close for several weeks due to extensive damage.

Figure 5-5: Tilt-up building damage, 2001 Nisqually earthquake.

Photo / Mark Pierepiekarz

Figure 5-6: Downtown Seattle. Photo / Mark Pierepiekarz

Commercial Structures

General Damage to Low-Rise and Mid-Rise Structures

Downtown Seattle (Figure 5-6) – Half or more of businesses, offices, restaurants, and retail stores in the South of Downtown District, International District, Pioneer Square, and along the Elliot Bay waterfront will close indefinitely due to extensive damage to unreinforced masonry (URM) buildings, pre-cast reinforced concrete parking structures, and other pre-1970 structures. Modern buildings will close for a few days to a few weeks for damage inspections and repairs. Damage to roadway bridges and the Alaskan Way Viaduct will disrupt transportation access.

West and Southwest Seattle – Nearly one half of this class of buildings will close for four weeks, perhaps indefinitely due to extensive damage. Older buildings will receive significant damage due to loss of masonry and partial collapse. Newer retail and office structures will close for up to four weeks because of damage and a lack of power. Access by bridges will be limited.

North Seattle to Everett – Extensive damage will occur to about a third of the low- and mid-rise buildings in this area. However, many structures will survive intact because of lower levels of ground shaking. The grocers, businesses, offices, restaurants, and retail housed in older structures located in low lying areas with liquefaction prone soils will close for up to eight weeks due to damage and lack of water and power. Older construction along the Fremont waterfront will suffer significant damage with partial collapses. Businesses in more recent construction will close from a few days to a few weeks.

I-90 Corridor – Construction that is more modern will limit extensive damage to about a third of these buildings in this area. Businesses in the Mercer Island, Bellevue, and Issaquah Old Town districts will close for up to a month for inspections and repairs. Customers will look for alternative shopping areas if Interstate 90 is accessible, though many of its bridges may close for inspections and repair. Traffic will clog residential streets.

SR 167 Corridor (Renton/Kent/Auburn/Puyallup/Sumner) – Soil liquefaction will add to damage in river valley areas. More than half of the low- to mid-rise buildings in this area will experience extensive damage. Access is available, but some bridges will close. Many businesses will close due to lack of power and water rather than building damage. Other retail in more recent construction will close from a few days to a few weeks for inspections and repairs.

Damage to High-Rise Buildings

In general, high-rise buildings of eight or more stories perform fairly well when subjected to earthquake ground motions. However, two factors unique to the Puget Sound area will influence regional damage levels:

- The region has a larger percentage of older (pre-1975) buildings than other areas that have experienced major earthquakes of similar magnitude and proximity. There are relatively limited records of observed performance for pre-1941 high-rise buildings, constructed primarily of concrete or steel frames with masonry infill.
- The scenario earthquake will subject high-rise buildings in the southern portion of downtown Seattle to ground-shaking levels never experienced before by buildings of such height.

High-rise buildings are primarily in central business districts of Seattle, Tacoma, Everett and Bellevue. Construction vintages vary from the early 1900s to the present. Due to their proximity to the scenario earthquake fault rupture, Seattle and Bellevue central business districts will experience very strong ground motions, exceeding shaking levels recorded in downtown San Francisco and Los Angeles during the 1989 Loma Prieta and 1994 Northridge earthquakes, respectively. In Seattle and Bellevue central business districts, nearly all of high-rise buildings will show visible structural damage, and nearly half of the pre-1975 high-rise building stock will experience extensive damage. Collapse of a few older buildings will occur. Nonstructural damage will be widespread – including cracks in cladding systems, interior partitions, and ceilings, as well as fallen contents. In general, structural and nonstructural damage in Tacoma and Everett will be significantly lower due to lower levels of ground shaking.

Expected high-rise building performance is as follows:

Historic (pre-1941) high rise structures – These are primarily concrete-encased steel frames (“wind frames”) and cast-in-place concrete frames (see Figure 5-7). Most buildings are 15 or fewer stories and built with concrete or masonry-unfilled exterior walls. Extensive to complete structural damage of non-retrofitted high-rise buildings will occur in the Seattle central business district, including collapse of

Figure 5-7: A historic high-rise building.

Photo / Magnusson Klemencic Associates

some buildings with irregular features or an overall lack of lateral strength. There will be significant nonstructural and facade damage, especially to cornices, masonry veneer, and interior masonry or concrete partitions, particularly around stairs and elevator cores. Falling debris will cause injuries and fatalities. With about 80 percent of these unretrofitted older buildings experiencing severe damage, the economic impact will be substantial.

Intermediate vintage (1941-1975) buildings – Building heights generally range from 8 to 40 stories. These buildings often have structural systems that include steel frames with diagonal bracing members, moment-resisting steel or concrete beam-and-column frames, or concrete shear walls (Figure 5-8). Some of the moment-resisting frame buildings constructed early in the period include masonry infill walls. Few of the older buildings in this vintage have received seismic upgrades. In those that have, the addition of concrete shear walls or steel-braced frames is most common. Overall, moderate to complete structural damage, including a few partial or total collapses, of intermediate vintage buildings is expected. Damage includes shear failures in concrete piers and columns, and fractures of steel frame moment-resisting connections.

Modern (post-1975) buildings – This group of buildings has a wide range of structural systems, including steel-braced frames, steel or concrete moment-resisting frames, concrete shear walls (especially core walls), and hybrid systems. Building heights can exceed 75 stories, and some buildings include devices intended to dampen wind and seismic forces (Figure 5-9). These structures should survive, with most of those closest to the scenario earthquake's fault rupture experiencing moderate to extensive structural damage. Such damage includes buckling of steel braces, yielding of beams, and cracking of concrete shear walls. Fractures of welded beam-column connections will occur in pre-1994 steel moment-resisting frames, similar to that seen after the 1994 Northridge earthquake. Steel-braced frames will be vulnerable from buckling of slender bracing members. Extensive damage to cladding and nonstructural elements will occur. Few collapses are projected, but about a quarter of this vintage of buildings will experience substantial damage. Given that the scenario event is for a rare earthquake, this outcome is expected, based on the seismic performance intent of modern building codes – preventing collapse, but not necessarily preventing economic loss.

Figure 5-8: High-rise buildings of various vintages on First Hill, Seattle.
Photo / Mark Pierepiekarz

Figure 5-9: A modern high-rise building in Seattle.
Photo / Magnusson Klemencic Associates

Residential Structures

About 20 percent of single- and multi-family residential structures will experience moderate to extensive damage. This means, in most cases, a dwelling will be unsafe safe to occupy for some time (Figures 5-10 and 5-11). The scenario event will cause more than $15.3 billion in damage to residential structures, and temporarily displace more than 46,000 households. The loss-of-occupancy time will vary depending on the level of damage. Table 5-1 provides re-occupancy projections, based on observations of repair efforts from past earthquakes.

The most significant effects on residential structures from the scenario earthquake will be:

Figure 5-10: Example of residential damage expected in the scanario earthquake. Homes not bolted to their foundations can be shaken off them by strong ground shaking (see damage inside white circle). Photo / Applied Technology Council

Figure 5-11: Strong ground shaking can damage multi-story buildings in the same way it can damage single-family homes. This apartment building slid off its foundation because it was not bolted or had been poorly bolted to its foundation. Photo / Applied Technology Council

- Structural damage, such as collapse of unretrofitted unreinforced masonry buildings, collapse of buildings with large openings at ground level, unanchored structures sliding from foundations, and masonry chimney collapse resulting in collateral damage.
- Foundation damage due to permanent ground deformations from uneven ground settlement or landsliding.
- Nonstructural damage, such as broken gas pipes that create a fire hazard, and fractured water pipes that result in loss of potable and firefighting water supply.

Typical Residential Building Stock

Most housing south and north of downtown Seattle is wood-framed, single-family construction, though there is a significant number of two- to five-story multi-family structures (Figure 5-12). Homes in low-lying areas of Renton, Kent and areas further south generally are on soils susceptible to liquefaction. Consequently, significant structural damage will occur in these areas, even for structures built after 1980.

The worst-hit residential areas will be in communities that straddle the Seattle Fault, where ground shaking will be the strongest.

- In West Seattle, construction is wood-framed and consists primarily of single-family structures. Typical residences predate modern seismic design and thus have lower seismic resistance relative to modern construction. Soils tend to be generally stable, though some structures are located on or near steep slopes prone

Table 5-1: Household Loss of Occupancy Projections

% of Displaced Households	Time to Reoccupy
50% to 60%	2 weeks
25% to 35%	Less than 3 months
Up to 15%	More than 6 months

to landslides. Broken gas lines and unsecured gas-fired water heaters may produce fires that will spread throughout neighborhoods of closely-spaced buildings.

- Old and new multi-family structures are intermixed in Seattle's main core of Pioneer Square, the International District and Belltown. The pre-1950s buildings typically are multi-story unreinforced masonry, while modern structures typically are several stories of wood framing over a concrete podium structure. The low-lying Pioneer Square area and parts of the International District are on liquefaction prone soils. Capitol Hill and Beacon Hill residential stock varies widely in vintage and construction, but most structures are typically wood-framed, single-family units.
- In Issaquah and Bellevue, most of the residential stock is wood-framed and constructed after 1970. These structures tend to include structural elements and connections that provide basic seismic resistance. However, visible damage will be widespread since near-fault peak ground accelerations will reach 0.75g (or 75 percent gravity). Soils generally are stable except for areas near the fault rupture.

Industrial Facilities

The region is home to a wide range of industries. These include:

- Heavy industries such as brick manufacturing, aircraft manufacturing, and steel tank and equipment companies.
- Food, drug and chemical industries such as breweries, dry cleaners, fish fertilizer production, and paint manufacturing.

Figure 5-12: Modern multi-unit residential building example. Photo / D'Amato Conversano, Inc.

Figure 5-13: Duwamish Valley industrial zone.
Photo / Washington Department of Transportation, Aerial Photography

- Metal and mineral processing industries such those engaged in steel and metal manufacturing and galvanizing.
- High technology industries including those that produce computer parts and software, or provide telecommunication services.
- Construction industries such as those producing cement and roofing tar.

Some of these industries are in structures that predate modern seismic design. Industrial facilities in low-lying areas and in river valleys will be damaged by soil liquefaction. Potential seismic impacts to vulnerable facilities include structural damage, loss of manufacturing equipment, prolonged downtime, loss of production, and loss of market share.

For the scenario event, the facilities within about two miles of the fault rupture will have a high probability of at least moderate damage. Facilities within about 15 miles of the fault on poor soils will experience similar damage levels. This includes facilities along the Duwamish Valley (Figure 5-13), the Green River Valley, Redmond, Ballard, and Issaquah. More-distant facilities will experience less damage.

Figure 5-14: Industrial manufacturing facility in the Duwamish Valley.
Photo / Greg MacRae

Duwamish Valley Industrial Zone

The main area of interest is the Duwamish Valley south of downtown Seattle, where most industrial structures are located. Examples include a variety of facilities and buildings used for aircraft manufacturing and a mill belonging to the largest steel-maker in the country. Much of the area includes soils with moderate to high liquefaction potential.

Built before the 1970s, most Duwamish Valley industrial facilities predate modern earthquake engineering design and are not seismically retrofitted (Figure 5-14). Buildings in other industrial parks in places such as Kent and Redmond are newer, more modern construction.

The most common types of low-rise building construction in this area are unreinforced masonry, tilt-up, and light steel-frames with metal cladding. These structures feature open internal spaces to allow easy transport of goods and products by forklifts and cranes. As discussed previously, URM and pre-1973 tilt-up structures tend to be most vulnerable to earthquake damage.

Other structures are framed with reinforced concrete with partial story-height brick infill—an undesirable seismic feature. Some facilities have large concrete silos containing cement or other materials, tanks, conveyor belts, towers, and machinery. Some manufacturing facilities require significant electrical power to operate, but have only limited back-up power capability. Pile foundations support most of the heavy reinforced concrete buildings. Many of these include a floating slab to allow for settlement. Other, lighter industrial structures rest on shallow perimeter foundations with a reinforced concrete slab floor cast directly on grade.

General Facility Impacts

General seismic issues for industrial facilities include:

- **Site soil conditions** – Soil liquefaction causes uneven settlement, resulting in structural damage and impact on buried utilities. For example, large foundation settlements can fracture pipe-to-tank connections, as shown in Figure 5-15.

Figure 5-15: Fuel storage tank base settlement, 300mm sliding and broken pipes.
Photo / Mahotra

- **Earthquake resistance of buildings** – Unreinforced masonry and tilt-up buildings are particularly vulnerable to earthquake damage. Such buildings reconfigured over time may be missing vital structural walls and braces.
- **Production equipment and contents** – Industrial facilities will experience prolonged downtime and loss of production and market share from damage to storage racks, tanks, piping, transformers, production equipment, conveyors, and other equipment. Damage to storage towers and racks create safety concerns, inventory loss, and delivery interruptions. Unsecured equipment and dislodged conveyor systems disrupt manufacturing operations.
- **Hazardous or flammable chemicals** – Steel braces supporting elevated tanks will buckle and fracture. When collapses occur, hazardous and flammable materials may be released, resulting in environmental damage and risk to people.

In past major earthquakes, damage to industrial facilities also resulted in indirect losses. Functioning industry is required to help rebuild an impacted community. Earthquake damage in the industrial sector will slow the recovery process. Release of hazardous materials can have long-term effects on a community.

Central Puget Sound industry may not be able to assist in the immediate rebuilding of the region. Industrial areas typically are not the top priority for post-earthquake assistance and recovery. It may take many months for industrial production to become re-established, dampening the region's economy.

San Simeon, CA earthquake 2003. Photo / Federal Emergency Management Agency

Chapter 6

Essential Facilities

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■ *Workers were uncertain how the fires at the Ballard shipyard started – whether it was the arcing overhead power lines or the spilled solvents. That became irrelevant after the first fuel tank caught fire. The whole yard was aflame and the fire was spreading upland. This fire was larger than the others. Battalion Chief Clive Valencia knew that mutual aid was not coming, with Interstate 5 closed and at least one bridge over the Ship Canal lost. He could only hope that the rain would get worse. The chief kept trying to verify the status of his own stations and crew; more than half of his staff did not even live in Seattle – he knew that those who lived outside of the city would help in their own communities. He knew his crews were in for some very long hours. Clive hoped that the communities dependent on Seattle had implemented some of the plans that they had been considering. He suspected that Mercer Island had lost one water pipeline that crossed over Lake Washington on the Interstate 90 Bridge. Since this was the island's primary water source, he wondered whether the city had purchased the portable pumping system that it had been considering.*

■ *It was apparent to Lisa and Marjorie Bona that they were not going to get home to Bainbridge Island; at this point, all they wanted was to escape from the horrors of the Alaskan Way Viaduct, portions of which lay amid twisted cars and bodies. Luckily, they at least were at a place they needed to be. It took almost an hour to walk to the hospital for Marjorie's biopsy. The waiting room was packed; the longer they waited the more injured people they saw carried into the hospital. After an hour, they heard that the hospital was canceling all non-essential procedures until further notice. The sisters huddled in a corner on the floor feeling fortunate to be out of the rain. They did not know what to do.*

■ *Upstairs, Don Temkin, responsible for hospital logistics, was seriously concerned. The hospital operated on a just-in-time delivery schedule, with supplies delivered several times each day. Because of the I-5 closure, delivery trucks could not get through. Even if the generators held for surgeries taking place, he wondered how long the hospital would have sufficient food, medicine, and other supplies.*

Certain types of facilities are essential to the operation, response, and recovery of a community following a disaster. History has shown that damaging earthquakes can result in significant casualties, fires, and other situations that will directly affect the operation of these facilities.

The scenario M6.7 earthquake will overload the Puget Sound region's hospitals due to loss of capacity and the large number of casualties needing treatment. Many fires will erupt due to earthquake damage, seriously taxing the reduced capability of police and fire department, public service vehicles, and transportation routes. People will call 9-1-1 and police stations

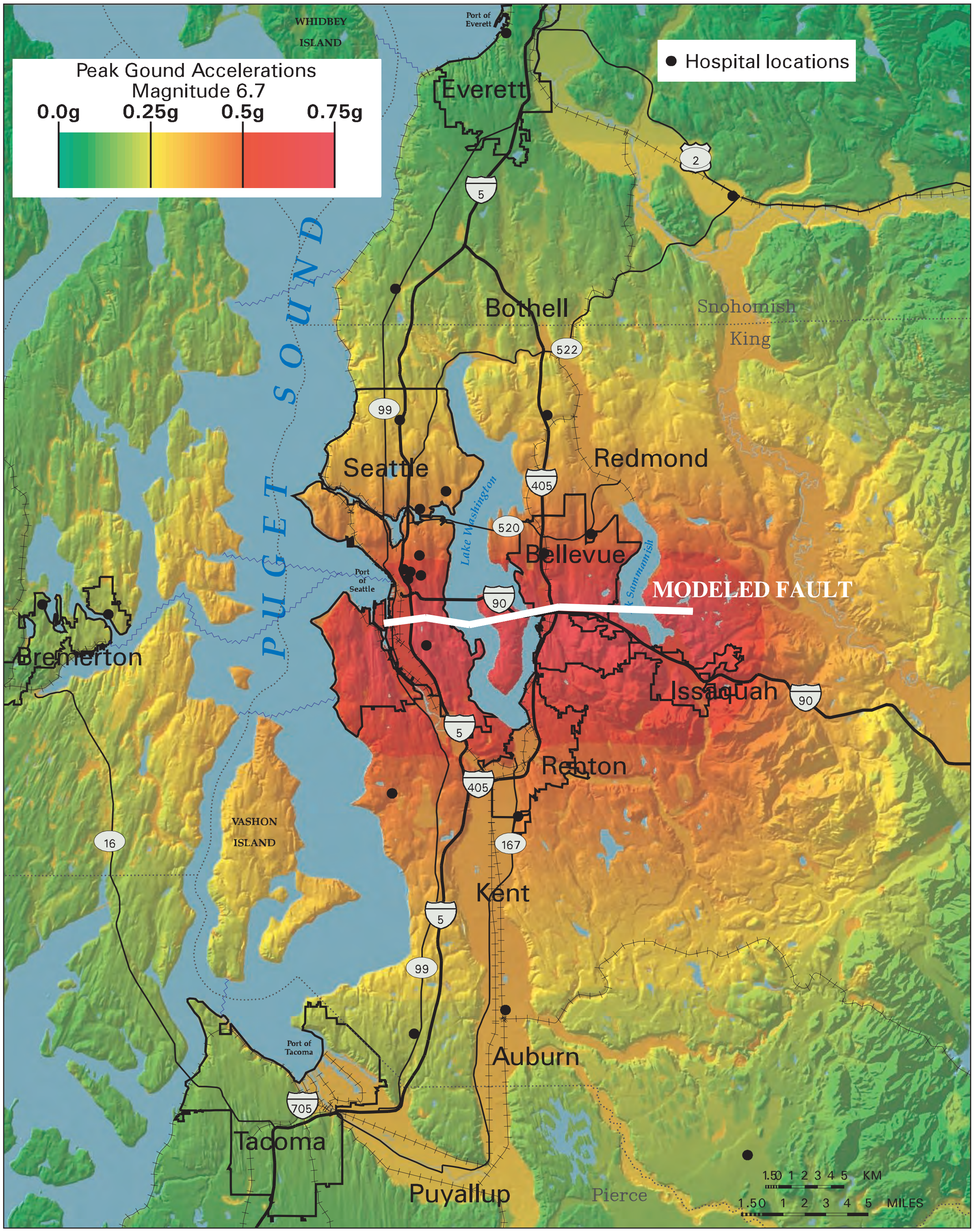

Figure 6-1: Geographic distribution of hospitals in the Puget Sound region overlaid on peak ground accelerations from the scenario earthquake. A significant portion of the region's hospital capability is in areas of very high ground motions caused by the scenario earthquake. Graphic / US Geological Survey

Figure 6-2: Olive View Hospital. Built before the 1971 Sylmar, CA earthquake, it was constructed with non-ductile concrete frames and shear walls vulnerable to ground shaking damage.
Photo / Earthquake Engineering Research Institute, © 1997

requesting help for a wide range of situations ranging from trapped people in earthquake damaged facilities to traffic control at damaged roads and bridges. Local communities will look to their schools as emergency shelters and locations for distribution of emergency supplies.

Hospitals

The study region has more than 25 hospitals as shown on Figure 6-1. Hospitals in the Central Puget Sound area are regional resources for patients from throughout Washington and Alaska; they also provide specialty care to patients from the rest of the United States. Harborview Medical Center in Seattle is Washington's only Level I adult trauma center, and serves as the health-care disaster control center for King County.

Hospitals in the region have more than 6,300 beds with about two-thirds in King County, which will experience the greatest ground motions and potential for damage. About 1,400 beds reside in northern Pierce County and 500 beds in southern Snohomish County. Hospitals in the region vary in age of construction from the 1920s to the present, with the majority of hospitals constructed since 1960. Most of the area's older hospitals have concrete floors and columns, and either concrete frames or concrete shear walls for lateral resistance. More-modern hospitals have steel floor framing and steel columns with metal deck and concrete fill for the floor system, and either steel moment frames or steel braced frames for lateral resistance.

Physical Damage Projection

Physical damage to hospitals will be widespread, with the greatest damage in the areas of highest ground motions. Structural damage will vary depending on the building type, age of construction and building location. Much of the hospital construction in the area of highest ground motions consist of non-ductile concrete frames and shear walls. This type of construction is susceptible to structural damage including significant concrete cracking and spalling, and, in some cases in previous earthquakes, resulting in partial collapse of buildings, shown in Figure 6-2.

Figure 6-3: Typical nonstructural damage.
Photo / Earthquake Engineering Research Institute, © 1997

Steel moment frames and steel brace frames of more current construction will experience damage similar to that observed during the 1994 Northridge earthquake – buckled and fractured braces and cracked moment-frame connections.

Compared to structural damage, nonstructural damage similar to that shown in Figure 6-3 can have an equal or greater impact on operations. Nonstructural damage from the Northridge earthquake closed some hospitals. Much of the damage experienced by hospitals in the scenario earthquake will be nonstructural, consisting of dislodged equipment, broken pipes and ducts, fallen ceilings, water damage from sprinkler systems, and spilled chemicals in laboratories. Nonstructural damage will be more prevalent in older unretrofitted buildings; even newer construction will experience some level of nonstructural damage.

Table 6-1: Estimate of Number of Available Hospital Beds at Various Time Periods Following Event

Time After Event	King County (4,400 Total Beds)		Pierce County (1,400 Total Beds)		Snohomish County (500 Total Beds)	
	# Beds Available	*% Beds Available*	*# Beds Available*	*% Beds Available*	*# Beds Available*	*% Beds Available*
1 Day	1,100	25%	1,110	79%	380	76%
3 Days	1,370	31%	1,160	83%	400	80%
7 Days	1,720	39%	1,230	88%	420	84%
30 Days	2,910	66%	1,340	96%	480	96%
90 Days	3,470	79%	1,390	99%	490	99%

Resulting Impacts

The region is likely to find itself with a shortage of hospital beds immediately after the earthquake because of increased demand and loss of capacity. Field triage facilities will care for the injured on a temporary basis. The earthquake will injure more than 6,000 people badly enough to require hospitalization. Table 6-1 provides an estimate of the number of hospital beds that will be available for service at periods of 1 day, 3 days, 7 days, 30 days, and 90

California Hospital Seismic Retrofit Program – SB 1953

Actions in California following the 1971 Sylmar earthquake provide an example for Washington to retrofit and strengthen hospitals vulnerable to severe ground shaking.

This earthquake destroyed two hospitals. As a result, California enacted the Alfred E. Alquist Hospital Facilities Seismic Safety Act, which established a seismic safety building standards program. Hospitals built in accordance with the standards of the Alquist Act experienced minimal structural damage during the 1994 Northridge Earthquake, while older structures experienced significant structural damage. However, facilities built in accordance with the provisions of the Alquist Act still experienced significant nonstructural damage.

A second seismic safety law for hospitals – Senate Bill 1953 – passed in California because of damage to hospitals in the Northridge earthquake. The goal of SB 1953 is to ensure that all existing acute-care hospitals remain operational after a design earthquake. The law affects 470 hospitals and 2,673 hospital buildings. The regulations established timelines for structural and nonstructural upgrades. For example, nonstructural work for most functional areas must be complete by 2008, while structural upgrades that ensure no risk to life safety must be complete by 2013. Complete compliance with the Alquist Act is required by 2030. Hospitals that do not meet specified timelines must be removed from acute-care service.

A report prepared by RAND Corporation for the California Healthcare Foundation estimates that by 2030, about 50 percent of California hospital buildings will be retrofitted, reconstructed, or closed, and 75 percent will undergo nonstructural renovations. Of the estimated $41.7 billion spent on hospital construction by 2030, only $3 billion will be for compliance with the provisions of SB 1953.

days following the scenario earthquake. These estimates are broken down by county, and as expected, the greatest impact will be in King County where ground motions will be the highest.

Short term response of hospitals to the scenario earthquake will consist of rapid reconfiguration of facilities and operations to provide continuity of care to patients, staff, and visitors. Emergency power systems will support the most critical areas of hospital operations such as fire and life safety systems, emergency rooms, surgeries, intensive care, laboratory and pharmacies; however, general environmental control systems typically do not connect to emergency power. Short-term provisions of potable water used for drinking and hand washing will be available, but will diminish quickly.

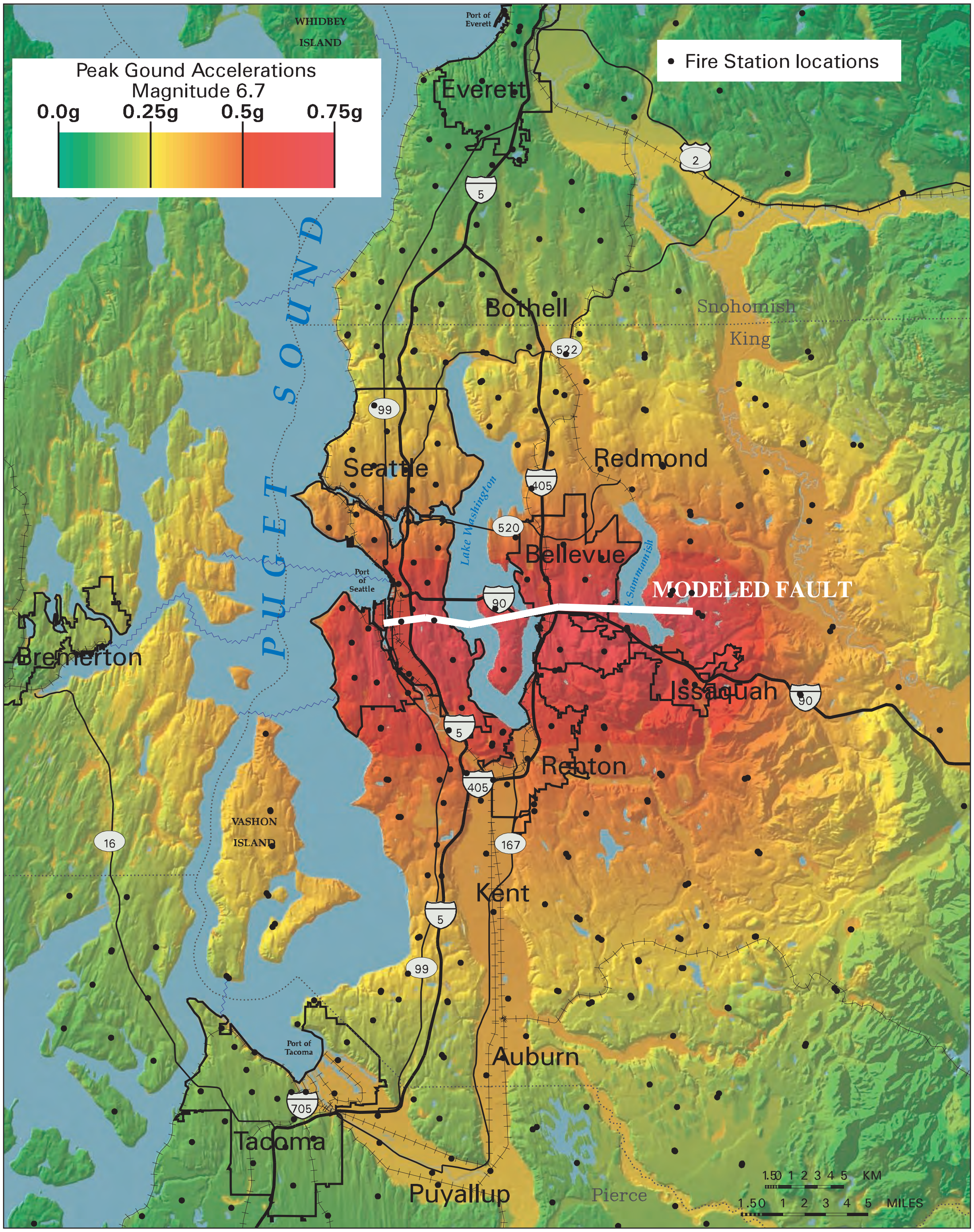

Figure 6-4: Geographic distribution of fire stations in the Puget Sound region overlaid on peak ground accelerations from the scenario earthquake. Graphic / US Geological Survey

Food services will shift from complex meal preparation to sustaining meals requiring fewer resources and ultimately extending the available food supply.

Health care staff will triage patients to focus on those with the highest medical needs and establish special care areas to provide services outside of the traditional patient room. Essential staff will extend their work shifts, and they will need in-house lodging until replacement staff arrives. Hospitals will delay non-essential or elective surgeries and procedures until their operations resume and staffing levels are restored. The loss of essential utilities such as electrical power, water, sewer, city-supplied steam, and just-in-time delivery of medical supplies, medical gases and pharmaceuticals will rapidly deteriorate the ability of the hospitals to sustain safe operations.

Regional plans allow hospitals in the three-county study region to shift patients to other less impacted counties; however, this will be largely dependent on availability of transportation routes and systems. In addition, the National Disaster Medical System may activate and help relocate patients to other areas of the country if the area hospitals are unavailable or cannot sustain operations.

Fire Stations

The study region contains more than 350 fire stations as shown in Figure 6-4. The size of the stations vary from single-story garage-like facilities to multi-story headquarters stations that house multiple pieces of apparatus, living and sleeping quarters, administrative offices, and public use space. Many of the smaller facilities are of wood frame construction. Other common building materials include reinforced masonry, pre-cast concrete, and cast-in-place concrete.

Age of fire stations varies throughout the region but fire stations generally are older than the average building stock in their neighborhoods. Older facilities typically performed poorly in past earthquakes, with less stringent design codes in place at the time of construction a primary contributor to such performance. Two common features that contribute to the seismic performance of fire stations include the apparatus bay doors and hose towers. Apparatus bay doors are necessary to allow vehicle passage in and out of the station; however, structurally they reduce the amount of wall available to resist earthquake forces. This can result in damage due to inadequate strength as well as significant lateral deflection of the building. Hose towers dry fire hoses. The towers are the equivalent of a three- or four-story building, but with a much smaller footprint. There is a small risk to life safety within a tower since they generally are unoccupied; however, they do represent a potential falling hazard onto the station below. A photograph of a typical fire station is in Figure 6-5.

Physical Damage Projection

Fire station performance during the scenario earthquake will be largely dependent on the level of ground shaking at the individual station location. The largest ground accelerations will occur along the fault rupture and in areas of poor soils away from the fault as indicated on Figure 6-4. Table 6-2 shows that fire stations in areas with

Table 6-2: Projected Damage to Fire Stations

Peak Ground Acceleration	% of Stations with Reduced Functionality	% of Stations Not Useable
Greater than 0.75g	More than 70%	20% to 30%
Between 0.45g and 0.75g	60% to 70%	10% to 20%
Between 0.30g and 0.45g	30% to 40%	Less than 10%
Between 0.15g and 0.30g	10% to 20%	Less than 5%
Less than 0.15g	Less than 10%	0%

Figure 6-5: A typical Seattle fire department station. Note the hose tower and wide apparatus doors. Photo / Mark Stewart

peak ground acceleration in excess of 45 percent of gravity will experience the greatest degree of damage, with 60 to 70 percent of the fire stations experiencing reduced functionality and 10 to 30 percent of the stations being unusable. This will pose a significant challenge to post-earthquake response and suppression of fires given that these areas also will experience the highest level of damage as well as the greatest demand for services. Areas near Everett and Tacoma will have significantly less damage with nearly all fire stations functional and generally useable.

Resulting Impacts

Some units will delay their response while personnel recover engines, tankers, and equipment trucks from damaged stations; some units may be unavailable because of damaged apparatus. Stations with heavy structural damage will be unusable. Some units will not be able to return to their stations and their equipment will be homeless at the end of initial shifts because of structural and nonstructural damage. Homeless apparatus and crews need temporary quarters that still allow for timely responses within a specific area. Temporary shoring and repairs will allow use of some stations. Some of the most heavily damaged stations will require significant repairs or replacement. While apparatus can be temporarily stored outside, temporary living and administrative quarters still will be necessary.

Police Stations

The study region contains more than 90 police stations as shown on Figure 6-6. Most police stations are of relatively modern construction or seismically retrofitted. Stations in smaller cities are located in City Halls typically not designed as essential facilities. Police response in an earthquake is heavily dependent on officers in the field. A centralized station is not essential to provide a reasonable level of service; however, communications centers are critical to deploying officers. Most communications centers are in buildings designed specifically as essential facilities. For example, the King County Sheriff's communications center is in a seismically hardened building with redundant systems designed for a large earthquake. In general, police stations performed very well in the Nisqually earthquake; however, ground accelerations for the scenario earthquake will be much larger than during the Nisqually event.

The performance of the transportation infrastructure is especially important to the overall performance of police response due to reliance on vehicles and mobility. Damage to major bridges and roadways in the area will hamper significantly the police response.

Physical Damage Projection

Damage at police stations should not be severe; in general, police stations will function at a somewhat reduced level following the scenario earthquake. For example, headquarters of the Seattle Police Department are in a building constructed in 2002, and department's Southwest Precinct is in a building specifically designed as an essential facility. The East Precinct is in a seismically retrofitted building. Some storage and parking facilities may experience higher levels of damage because they are more vulnerable to high ground motions.

Schools

The study area includes more than 1,200 school campuses as shown on Figure 6-7. Most campuses have several structures on a site. School types range from public and private K-12 to college or university and professional trade schools. Communities do not always consider schools as essential facilities; however, they have unique characteristics that set them apart from other building types. Society places a high value on protecting children as the primary occupants of schools, and classrooms (especially K-12) tend to have one of the highest occupant densities of any building type. Communities look to schools for temporary shelter and distribution points for emergency supplies following a disaster such as the scenario earthquake. Identifying a predominant building type for schools is not possible, as they typically cover all building materials including reinforced and unreinforced masonry, steel, concrete, and wood.

The earthquake impacts to schools in past earthquakes has been most predominate in unreinforced brick structures. The 1933 M6.3 Long Beach, CA earthquake, which resulted in a disproportionate amount of damage to school buildings, was a watershed event for enactment of building codes around the country. Fortunately, loss of life was minimal, as school was not in session at the time of the earthquake.

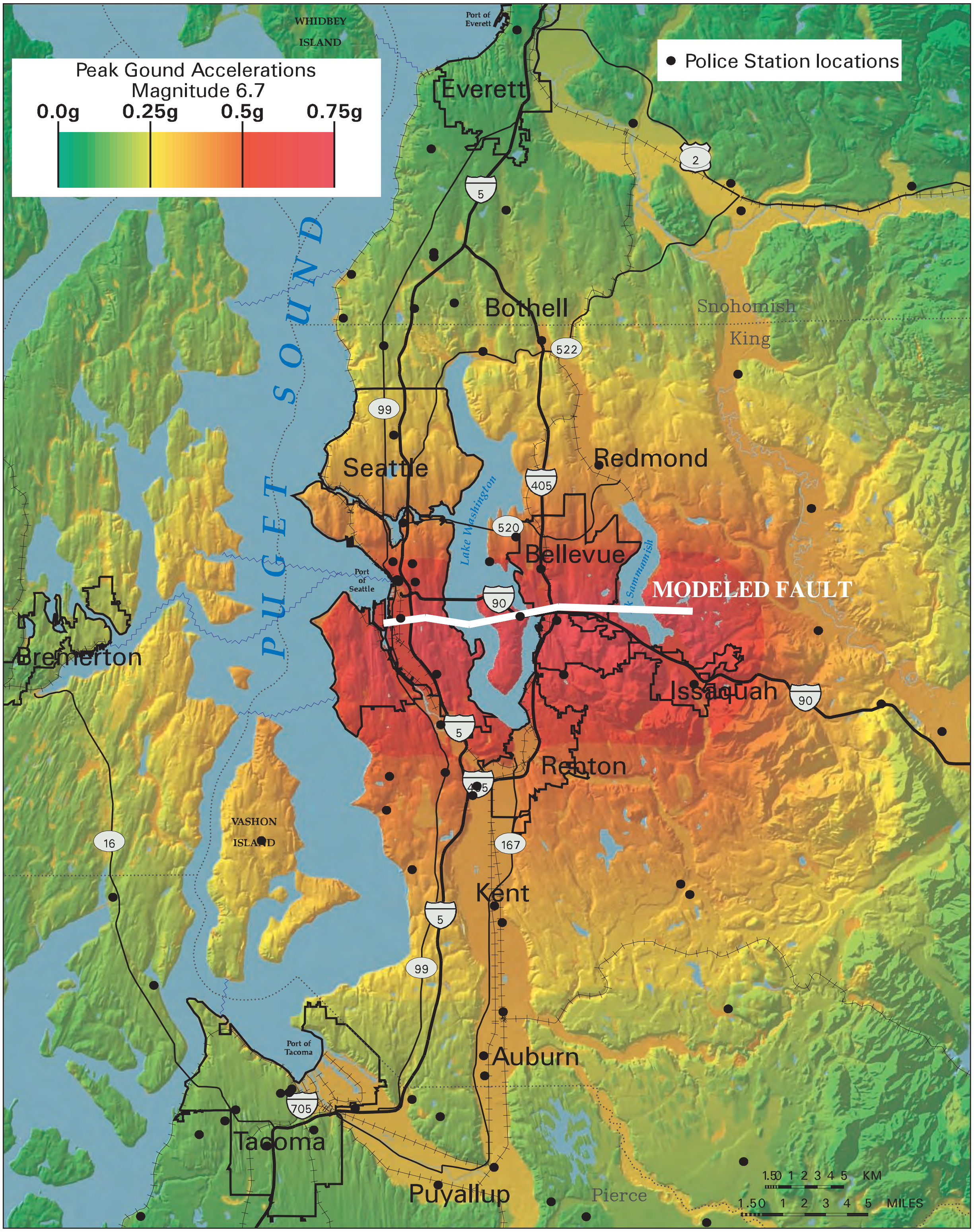

Figure 6-6: Geographic distribution of police stations in the Puget Sound region overlaid on peak ground accelerations from the scenario earthquake.

Graphic / US Geological Survey

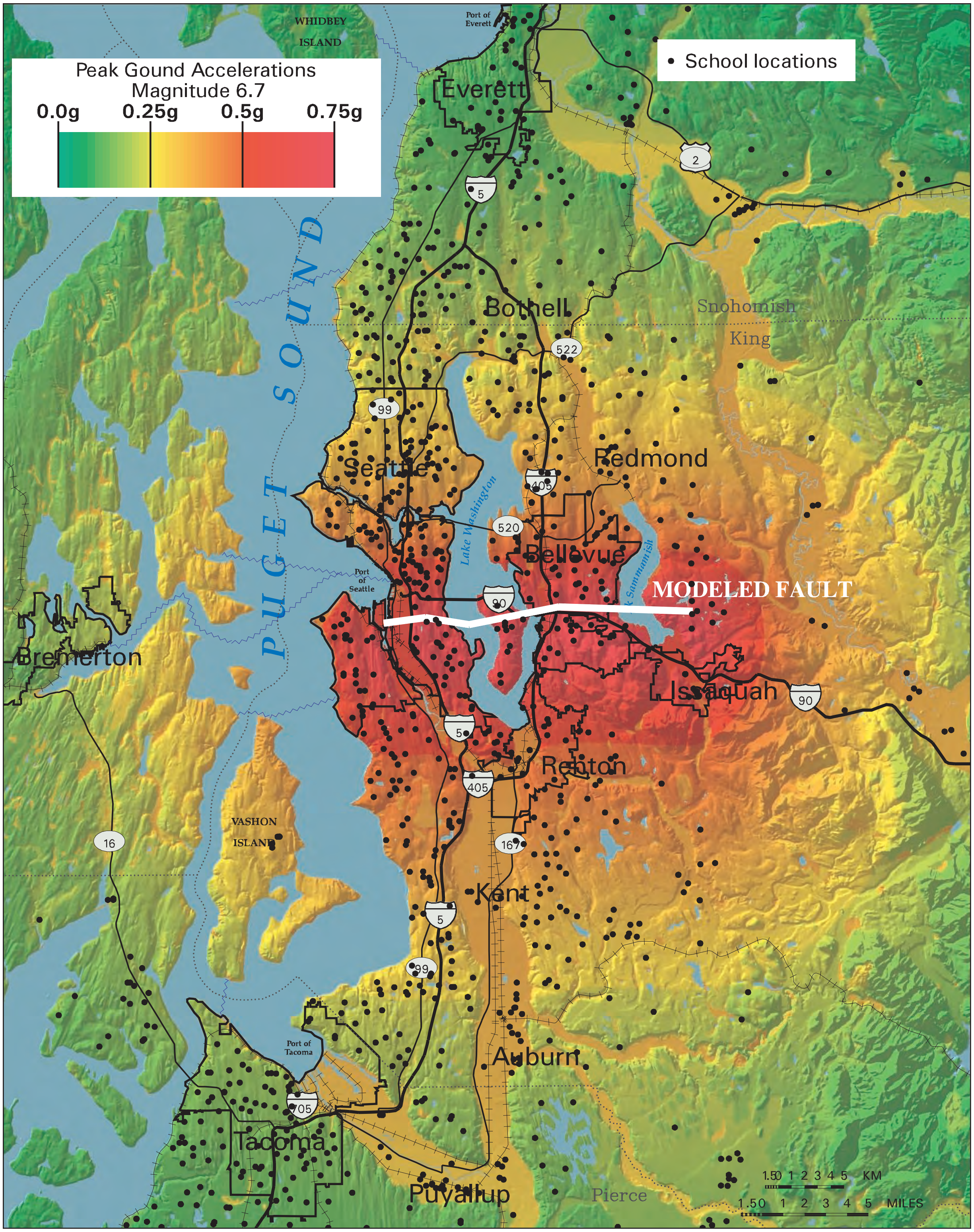

Figure 6-7: Geographic distribution of schools in the Puget Sound region overlaid on peak ground accelerations from the scenario earthquake.

Graphic / US Geological Survey

Table 6-3: Expected Damage to Schools

County	Damage (in percent)				
	No Damage	Slight	Moderate	Extensive	Complete
King County	23%	22%	29%	18%	8%
Pierce	64%	18%	12%	5%	1%
Snohomish	64%	14%	9%	3%	10%
Total Region	38%	20%	22%	13%	7%

The primary lesson learned from this earthquake was the need to create a building code that mandated safer construction for essential facilities such as schools. As a result, California passed the Field Act, which included strict building codes for schools. Subsequent building codes adopted in Washington included similar requirements, but have not required strengthening of buildings that predate more strict modern codes.

To the credit of many school districts within the three-county study area, voluntary strengthening of educational facilities has been ongoing for the past several years. However, the extent of this work and the number of children still attending school in vulnerable buildings is poorly documented.

Physical Damage Projection

As in the 1933 Long Beach event, the 1949 M6.8 Olympia and the 1965 M6.5 Seattle-Tacoma earthquakes disproportionately damaged schools. In these two earthquakes, Seattle schools built before 1950 suffered extensive structural and non-structural damage. The 1949 earthquake damaged 30 schools serving 10,000 students; 10 schools were condemned and permanently closed. Three schools in Seattle were torn down and one rebuilt. In the 1965 earthquake, eight Seattle schools serving 8,800 students closed at least temporarily, with two experiencing severe damage. Damage to school buildings in the study region caused by the 2001 M6.7 Nisqually earthquake was limited because of ongoing seismic strengthening, non-structural mitigation, and the number of schools built in recent years to modern building codes.

Following the scenario earthquake, however, many schools will not be immediately functional because of very high ground motions. Schools in King County will be particularly hard hit; more than half will experience at least moderate damage. Damage inspections and repairs will be necessary and some facilities may experience partial collapse. The campuses with the greatest level of damage will be those with unretrofitted, older buildings. Schools on poor soils also will experience higher levels of damage. Table 6-3 shows the expected level of damage to schools by county for the scenario earthquake. Buildings with slight and moderate damage will need inspection and repair but should be useable within a short time following the earthquake. Buildings with unrepairable damage will be demolished and rebuilt.

Looking at projected damage on a neighborhood level may paint a more alarming picture, depending on site-specific construction type and soil characteristics. For example, a recent study by the City of Seattle Emergency Management of six schools in Southwest Seattle using the M6.7 scenario earthquake predicts severe structural damage. Four of the six schools have a 60 percent or greater chance of experiencing extensive or complete damage.[1] All six have a low likelihood of being functional immediately after this earthquake.

Resulting Impacts

The most vulnerable schools – older buildings or those built on poor soils – will experience significant damage, rendering them

[1] City of Seattle Emergency Management, *HAZUS Pilot Project Report,* July, 2004. Note: HAZUS-MH modeling results factor in building type, but not whether or not the structure has been seismically retrofitted.

unavailable for an extended period. The loss of these facilities will cause a high level of distress in the community.

In the aftermath of the earthquake, schools will have difficulty meeting their immediate obligations of sheltering and feeding children, and connecting them with parents. Drawing from the Southwest Seattle School study results, nearby community centers, identified by Seattle Public Schools as the best option for indoor sheltering, are projected to be non-functional. Even if they are in operation, many of these same centers have been designated to shelter the general public, potentially leaving little space for students. In addition, many parents will be trying to pick up their children, but bridge damage will severely hinder their ability to reach schools. This leaves the school system with the immediate problem of how to take care of several thousand students in this area alone, not to mention long-term facility repair and restoration of educational programs.

It is likely that temporary solutions will include busing students to other open schools or available non-school buildings, double-shifting classes, and potentially using on-line teaching methods once telecommunication systems are restored. The priority assigned by local and state government agencies to repair schools will be higher than that for general building stock since school closures cause substantially more impacts to the community.

Also of concern is the Seattle campus of the University of Washington. Daily, the university is home to 39,000 students, 23,400 faculty and staff, hundreds of visitors and people in special needs populations including patients in hospitals and clinics, and thousands attending cultural or sporting events evenings and weekends. The university, one of the top research institutions in the nation, has significant holdings of irreplaceable research and research specimens in laboratories, as well as valuable artifacts in museums and art collections. While the campus is outside the area of greatest ground shaking, the impact of the scenario earthquake could cause serious damage to buildings and infrastructure and compromise the university's ability to function as an educational institution. The average age of buildings on the campus is 43 years. Among the areas of greatest concern to the university is damage to lifeline systems, structural and non-structural damage to vulnerable buildings, unsecured exterior building ornamentation, and buildings in landslide and liquefaction prone areas in the East Campus area.

It is important to note that many school districts in the three-county study area are renovating or replacing older buildings that represent high earthquake risks. The Seattle School District has been systematically upgrading its schools for the past 12 years. The Bellevue, Federal Way, Lake Washington, and Renton school districts also are upgrading campuses to current seismic safety standards. In addition, the University of Washington in a 1991 report identified 14 buildings likely to suffer major structural and non-structural damage in a major earthquake; four of these buildings have received retrofits. The completed work and work in progress, however, is only a part of an ongoing effort to reduce the vulnerability of the building stock and reduce the outage time for schools in the impacted area.

Nisqually earthquake 2001. Photo / Federal Emergency Management Agency

Chapter 7

Economic and Business Impact

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■ *Thea Rolfe and Mary Stevensdotter knew that after they cleaned up their coffee shop and bookstore, they needed customers. Their business relied on foot traffic. They wondered aloud how long it would be before businesses could reopen and tourists return to Pioneer Square. They doubted they could hang on that long. Since they were renters, they discussed the possibility of moving to another neighborhood. They did not want to stay in a place with bad memories.*

■ *George Volnitzski continued driving south. He knew that without refrigeration the inventory at his uncle's meat distribution business – and probably his job – would be lost. He asked himself why his uncle had not taken advantage of a co-op offer to buy emergency generators last month.*

This chapter presents three important kinds of information about the potential effects of the scenario Seattle Fault earthquake on businesses in the Central Puget Sound region. The opening section discusses the economic impacts of recent earthquakes on big cities, particularly Northridge and Kobe. Seattle and its seismic hazards are similar to both these cities, so their experience with recent earthquakes is pertinent.

The second section describes what it will be like for businesses in three sample neighborhoods to experience the earthquake – Issaquah, Renton, and Pioneer Square. The process of thinking through what an organization will have to cope with is an important part of disaster preparation. These vignettes should be helpful for those who are considering planning and preparation.

The third part of the chapter describes the issues that the region's contingency planners anticipate will be of greatest importance to businesses and non-profits coping in the aftermath of the scenario earthquake. Derived from the deliberation of the region's largest, most experienced contingency planning organization, the Cascadia Region Earthquake Workgroup, this section offers perspective for any organization assessing its plans and preparations for disasters.

Economic Impacts

Decision-makers and planners must give serious attention to the potential for major economic disruptions in future Puget Sound earthquake disasters. Two-thirds of Puget Sound business owners, based on their experience with the 2001 Nisqually earthquake, believe they are well prepared for earthquakes; only one third said the event alerted them to get better prepared. The lessons and experiences of the Nisqually event, as well as other major earthquakes, provide a wake-up call for the vulnerability of the regional economy, rather than a guide for what will occur in a future wcatastrophic disaster.

Major urban earthquakes can cause economic loss in the tens of billions of dollars. Extreme quakes can cause losses surpassing $100 billion. Economic impacts include direct property damage, lost business output and productivity, business failures and relocations, and reduced competitive advantage in the long term.

The impacts of three previous earthquakes –Northridge, Kobe, and Nisqually – are helpful in anticipating the likely effects of the scenario Seattle Fault earthquake. The Northridge earthquake that struck Los Angeles in 1994 was a moderate-sized event, but the costliest natural disaster in the nation's history to date. Northridge caused some $40 billion in damage and an additional $6.5 billion in estimated business interruption loss. The $12.5 billion in insured losses from Northridge alone amounts to more than $1,300 for every person living in Los Angeles County. Small businesses and those that rented rather than owned their space were the most vulnerable to long-term economic hardship or failure. The Northridge experience is an important analogue to the scenario quake because the Northridge fault was shallow and centered under a major, modern city, as is the Seattle fault.

The earthquake that struck Kobe, Japan, in 1995 was the world's first experience of a major earthquake striking a modern urban center. Official figures indicate a staggering $100 billion in damage; insurance covered only about $1 billion. Business disruption losses cost about another $100 billion. Economic sectors in decline before the disaster were especially vulnerable; the earthquake accelerated their decline. The experience of the Port of Kobe is an important example – its ranking among world container ports dropped from number 6 before the earthquake to number 17 after the disaster; in the 10 years since, its pre-earthquake ranking has not recovered.

The Kobe earthquake disaster is particularly instructive for this region for several reasons. First, it demonstrates the magnitude, range, and types of economic impacts that can occur in a truly catastrophic disaster. Second, both Kobe and Seattle are located away from the centers of national attention and concern regarding earthquake risk (that is, distant from Tokyo and California, respectively). Third, Kobe and Seattle are similar in many geographic respects: both are medium-sized port cities constrained between mountains and sea, with highly non-redundant transportation networks. None of Kobe's business sectors could really return to pre-quake levels of activity as long as the port and roads were under repair and reconstruction.

The Nisqually earthquake is significant because it is the most recent and costliest earthquake experienced to date by the Central Puget Sound region. While not a major disaster, and certainly not comparable in severity to the scenario Seattle Fault event, the Nisqually earthquake inflicted loss in the range of $2 to $4 billion, of which insurance covered just $305 million. On Harbor Island in Seattle, where poor soil led to the most severe shaking of the quake, half of all businesses had damage exceeding $10,000, and 40 percent of those received no insurance or aid. In the scenario Seattle Fault earthquake, much more of the region will experience shaking similar to that of Harbor Island.

Small businesses, those in the retail sector and those in neighborhoods with major transportation disruptions, were most vulnerable in the Nisqually earthquake. Damage to roads, bridges and buildings made it hard to conduct normal business in some locations for weeks. In locations such as downtown Olympia and Pioneer Square in Seattle, even businesses that experienced minimal physical damage suffered significant customer and revenue loss due to

Impact of Damage to Warehouses

More than $250 million worth of goods move to or from warehouses and distribution centers via truck every day in King, Pierce and Snohomish Counties. Commodities that move through these centers include food and kindred products, drugs and medical supplies, paper products, furniture, meats and fish, lumber and wood, steel and metals, petroleum products, machinery, and electrical supplies. Some of these products are shipped out of the region and out of state. The primary outbound destinations for trucked commodities are Oregon, Canada, and California.

Many warehouses and distribution centers in the Central Puget Sound region are in areas of poor soils prone to liquefaction and ground failures. Damage to these facilities from the scenario Seattle Fault earthquake will be considerable, significantly affecting the availability of goods throughout the region in the days and weeks after the event.

The efficient movement of goods from docks and trains to storage facilities, and then to final destinations such as retailers, restaurants, gas stations and automotive shops, hospitals, print shops, and manufacturers, also depends upon a highly reliable and available network of highways and secondary roads. The greater the damage to the road system, the more slowly available goods will move to grocery stores, gas stations, and other locations.

Significant damage to either storage facilities or to the road system likely will result in at least short-term shortages of basic consumables such as processed and fresh foods, gasoline and other fuels, pharmaceuticals and medical supplies, as well as products such as building materials needed for reconstruction. Such damage also will slow efforts to re-supply the region for some time. Goods will be slow to arrive and once they do, storage capacity will be limited.

Movement of outbound goods headed to nearby states or to Canada also will slow. Out-of-state businesses expecting shipments from Washington may look for other suppliers outside the state. This will hurt local companies who rely on outside markets for sale of their goods, such as fresh food producers and manufacturers of other commodities.

reduced foot traffic. Finally, the Nisqually earthquake caused runway damage at King County Airport (Boeing Field) and tower damage at Sea-Tac International Airport. Similar infrastructure vulnerabilities will yield disruptions that are more serious in the scenario earthquake.

While the vast majority of businesses can and do recover from severe natural events, certain categories of business are highly likely to fail, or to survive but never recover to earlier levels of market share and financial stability. Small businesses are more vulnerable than large ones, given that they have fewer resources and are less likely to have prepared or planned for such an event. Businesses that are only marginally successful at the time a disaster strikes often find the event is the last straw that breaks their already burdened financial backs. Even a strong business, though, can fail if a disaster hits at a moment when it is vulnerable, such as when it has taken on additional debt, for example. Finally, significant disruptions to a business' customer base leave it in danger of not recovering if customers cannot or prefer not to travel to them.

Some businesses choose to leave a region after a catastrophic event rather than rebuild and face the risk of another disaster. Firms that leave avoid the costs of repair and the risk of future loss of function, but they incur relocation expenses such as the costs of moving and rent at a new facility. Some businesses that move may have considered relocating before the disaster. Relocations are a normal part of business and economic activity, occurring all the time for various reasons; a disaster however, may precipitate a number of decisions to move.

Disasters sometimes lead to gain, as well as loss, for some regions and businesses. Construction businesses, for example, often experience short term gains, although some of this flows to construction firms outside the disaster region. If external resources finance reconstruction through inflows of insurance payments and federal government assistance, as opposed to regional savings, net regional losses will be less. Available excess capacity in the regional economy is also a factor in the extent of net loss or gain.

One of the most important lessons for the region from previous earthquake disasters is that damaged transportation and utility infrastructures often cause major economic disruption and loss. In Northridge, highway damage accounted for as much as 27 percent of the total business interruption loss, in addition to $33 million in losses from lengthier commuting times. Businesses reported that transportation problems caused as much disruption as did building and other infrastructure damage. These losses would have been much greater were it not for the substantial redundancy in the Los Angeles highway network – a redundancy not found in the Puget Sound. The economic impact of transportation loss in the scenario Seattle Fault earthquake is more likely to resemble the severe and protracted disruptions experienced in Kobe.

Electric power, water, and other utility infrastructure failures also contribute to economic disruption. While these outages will be of shorter duration than other sources of business interruption, they have the potential to affect very large areas, including those with little physical damage from the shaking itself. The best examples come from other disasters. In the 1999 M7.6 Chi-Chi earthquake that struck Taiwan, electric power outage lasted one to two weeks and may have caused more loss of gross domestic product than did actual damage to physical plant and equipment. For manufacturing, and in particular the critical semi-conductor industry, revenue losses far exceeded repair costs because of the power outages. In the 1993 Great Midwest Flood, transportation and utility disruptions caused more extensive business interruption losses in Des Moines, IA than did the flooding itself.

Indirect Losses

As mentioned previously, economic disruption also may occur to businesses and sectors that do not sustain a direct earthquake-caused loss. Physical damage and infrastructure disruptions can cause chain reactions transmitted up and down supply chains as losses impact customers of customers and suppliers of suppliers.

For example, an indirect loss occurs at a factory when production slows or stops because a damaged supplier fails to ship a critical component. The extent of indirect loss to the factory depends on availability of alternative source of the component, availability of the transportation system over which supplies of the component are moved, the length of the production disruption, and the ability of the factory to postpone production. The same sort of disruption occurs in the supply chains of retailers and service industries such as banking and health care.

Indirect impacts of disaster damage can be many. Shortages of crucial items can limit production, retail sales and, potentially, exports. Limited production means demand for raw materials or components from suppliers is reduced. Reduced availability of a specific good or service may, over time, diminish demand regionally, nationally, and globally. Firms facing loss of supply or production because of indirect impacts have four options: 1) import additional supplies from outside the affected region, 2) identify factories with excess capacity, 3) use existing inventories, or 4) seek unused stock elsewhere.

What to Expect

Described below are the kinds of experiences small businesses in three neighborhoods near the Seattle Fault can expect in the scenario earthquake. The neighborhoods are commercial sections of Issaquah, Renton, and Seattle. Each presents a different profile of building structures and lifeline challenges. They illustrate what will happen to common types of buildings and neighborhoods in zones that experience severe ground shaking in a Seattle Fault earthquake.

Issaquah

In spite of poor soil and proximity to the rupture of the Seattle Fault, a 1970s era neighborhood shopping center in Issaquah just off Interstate 90 should withstand the expected 0.5g (50 percent of gravity) ground shaking. The single-story, masonry-block structures with light, wood-frame roofing in this center are designed to avoid collapse; they have significant sheer walls, solid backs and sides, and supplemental exterior columns. Still, they will face important challenges in the scenario earthquake.

Shoppers and workers will have quite a frightening experience during the earthquake. In the supermarket that serves as the magnet store for the center, contents will fall, walls will crack loudly, glass will break and electricity will fail. There will be few items of furniture beneath which shoppers can ride out the quake. It will be a seriously frightening initial minutes. Some injuries from glass breakage and falling contents are expected.

Several of the businesses, including small restaurants, rely on gas for heating and cooking. Gas-fired grills and heaters without automatic shut off valves could catch fire. Fires present dire threats following earthquakes when water systems fail. Water systems along Interstate 90 will fail in several spots. It will be days before repairs are made and service is restored.

Shoppers will grab their cell phones to check in with home or office as soon as the earthquake occurs, only to find overloaded networks. People will spend frustrating, tense time traveling

Figure 7-1: In Issaquah. A neighborhood shopping center and nearby light industry. Photos / Mark Pierepiekarz

home to check on loved ones or back to work. Fortunately, nearby roads and overpasses are engineered to withstand the level of shaking anticipated at locations along I-90 near the fault rupture; damage should be limited to occasional sink holes and cracks. Still, travel will be very difficult. Electricity will be out, so traffic signals will not work. Traffic volume will be high, slow moving, congested and prone to accidents. Most importantly, emergency vehicles will have difficulty negotiating dense traffic in order to reach people who need assistance at the scenes of collapses, injuries, fires and accidents.

Most merchants will close pending safety inspection, which may take three to four days since inspectors will be in high demand and short supply. The wait for inspection may not itself delay clean up and recovery, however, because water and electricity are unlikely to be available during the initial few days. Clean up and business resumption will not be possible until utilities are restored.

While direct damage will not be devastating at our shopping mall, it will be expensive and take some time to repair. Almost all of the shopping center's buildings should be structurally sound, but they will not appear particularly safe and they certainly will not look attractive, with broken windows, lots of cracked walls and columns, separation of some walls, and other surface damage. Customers may prefer to shop at nearby centers to the north, which should experience less noticeable damage. Whether the shopping mall eventually recovers its customer base depends, in part, on how savvy their competitors are at exploiting the opportunity to win dislocated customers permanently.

The mall's small businesses will be the most threatened by reduced customer flow. A chain supermarket can ride out some hard weeks with help from headquarters but the restaurants and gift shops and dry cleaners that are secondary destinations for the grocery customers have few slack funds to draw upon. Perhaps most frightening for small business survival is the prospect that the chain retailer might close its store if it determines recovery in this location will be too slow. This would leave the small firms with no magnet for customers.

The best news at this shopping mall is that deaths are unlikely and injuries should not be too serious or numerous. However, not far from our shopping center, blocks of light industrial businesses face a more serious set of outcomes.

One-story, inexpensively built 1960s-era tilt-up buildings are common in the Issaquah region. These tend to collapse in earthquakes, presenting a threat to life. Other common small-business structures are one-story concrete block buildings that probably will be repairable after a quake, though at great expense. In these structures, we find light industries such as plate-glass firms and auto-body shops. Contents in these types of businesses present a serious risk to occupants. Large pieces of heavy equipment will move surprising distances and at surprising speeds during a severe quake. Large pieces of glass, solvents and tools not well secured when the scenario earthquake hits will present threats to life and limb. Employees will need strong objects under which they can drop, cover and hold to avoid serious injuries.

Repairs will take time and be expensive. Contractors and materials will be in huge demand in the months following the earthquake. Delays in work will be long and prices high. Business owners need to recognize that repairing small damage can be surprisingly expensive. A crack in a wall of an office, for example, necessitates repair then repainting a whole room. A single broken bottle of sauce or oil can so seriously stain a carpet or floor that replacement is required. For small businesses, repair costs can quickly add up to sums that dwarf or obliterate profits.

Renton

The oldest commercial section of Renton consists of 1920s and 1930s era two-story, unreinforced masonry storefronts in the low-lying flat part of town. Uphill of this early 20th century downtown are strips of more modern commercial construction typified by the buildings that flank Rainier Avenue, one of the of region's major north-south thoroughfares.

The soils in the flat lands around Renton's Boeing and Paccar/Kenworth manufacturing plants will liquefy in this scenario event. As explained in Chapter 3, Seattle's main water line, important underground electrical lines, and major gas and gasoline pipelines all run through this area. The performance of these lines will affect the entire Puget Sound region. Renton will bear the additional worry that major leaks of water or gas might occur there. It is possible a major water line break will cause flooding in addition to other earthquake damage, or, more frighteningly, a flammable gas leak or gasoline spill could occur.

Figure 7-2: Renton. An older suburb with a small downtown and nearby commercial strip. Photos / Mark Pierepiekarz

Old downtown Renton

The small historic blocks around Wells Avenue and Second and Third Streets have a number of small, low-margin businesses. While these businesses do not generate significant foot traffic, they populate and animate the pretty, old buildings, helping Renton to preserve the pleasant, historic aesthetic that draws restaurants, pubs and professional offices into newer, safer buildings nearby. The older buildings commonly have large expanses of glass on their lower floors, creating a weak condition prone to failure in an earthquake. There are no obvious signs of retrofit on most of the buildings.

Many of the old downtown buildings will fail in the scenario earthquake. Some collapses are certain. Lives will be in danger as second floors collapse down, contents slide and fall, floors give way and walls buckle. Safety will be an issue outside, as falling bricks and shattering glass shower streets and sidewalks. When the shaking stops, this neighborhood will be awash in debris and emergency workers will be searching for injured occupants.

Damage and debris will persist for quite a long time, disrupting both foot and auto traffic. With an extended disruption to customer access, profound direct damage and loss of inventory, most of the marginal businesses in Renton's downtown will never recover. In addition, it will be extremely expensive to restore or replace these buildings with structures designed to have a historic feel. The historic aesthetic of this section of Renton will, sadly, most certainly be lost.

Newer Renton

Just up the hill from old downtown Renton, a mix of small businesses in modified multi-story residential buildings, 1960s and 1970s era single- and multi-story commercial construction, and several one-story, national-franchise businesses line Rainier Avenue. The soil is better here than the liquefiable soil in the lowland. Also, these newer, lighter buildings are less vulnerable to collapse than the older, unreinforced masonry structures.

Though lower and lighter, a number of the newer buildings share one major earthquake vulnerability: large expanses of glass at street level and almost no shear wall. Ground floor glass makes for attractive commercial space but poor earthquake performance. As buildings move, the relatively weak, brittle glass fails. Life-threatening collapse is not a huge concern as most of the structures are single story with no heavy roofs to crush occupants. However, structural damage will be extensive; repair will be so expensive that it might not be worthwhile. Many of the small businesses here own their buildings. If they are not insured, have high deductibles or if their insurer is slow in making payments, they will be in danger of not rebuilding in time to recover.

Rainier Avenue in Renton is one of the region's major north-south transportation routes. With the Alaskan Way Viaduct closed from collapse, Rainier Avenue becomes an even more vital transportation route for many months or years. In addition, if parts of Interstate 5 close for repair, Rainier Avenue will become one of the few ways for people south of the city to get to jobs in and near Seattle. Months of serious daily congestion will occur.

One positive effect is that businesses along the Rainier ridge can expect increased volume. A modern fast-food restaurant on Rainier Avenue, with sound, single-story construction, should be relatively undamaged by the quake and will be ready to enjoy a windfall influx of hungry, albeit frustrated, travelers within days.

Figure 7-3: Pioneer Square. Late 19th and early 20th century construction (some of it retrofitted) on liquefiable soil.

Photo / Mark Pierepiekarz

Pioneer Square

Seattle's Pioneer Square neighborhood is historic, attractive and built on some of the worst soil in the region in terms of liquefaction risk. Given the extensive damage and disruption there during the Nisqually earthquake, few should be surprised when the scenario earthquake also hits it hard.

The level of ground shaking expected in Pioneer Square from the scenario event will be two to three times more intense than it was during the Nisqually earthquake. It will be similar to the worst levels of ground shaking in the 1994 Northridge earthquake and in downtown Kobe during the 1995 event. Ground accelerations will exceed the levels anticipated by even the most recent building codes. Unretrofitted brick buildings will collapse, and some retrofitted buildings will have so much damage they will become unsafe for occupancy. However, many retrofitted buildings should resist collapse in this earthquake; they will shed less material onto streets and sidewalks than unimproved structures. Since collapse is the most common cause of earthquake deaths, past retrofit investments will save lives in Pioneer Square.

However, damage still will be extensive. Most buildings will be closed immediately pending inspection. It will take several days before city inspectors determine whether buildings are safe for occupancy since trained inspectors will be in short supply. Inspectors will condemn many buildings.

Up to two-thirds of Pioneer Square buildings will close for months for extensive repair. Some will not be repairable or worth repair. With many buildings damaged or under visible, major reconstruction for some time, the neighborhood will become an undesirable destination. Foot traffic will be down for months; many small businesses will not survive.

One of the most serious immediate and long-term threats in this neighborhood is the elevated Alaskan Way Viaduct that travels above Alaskan Way at the western edge of Pioneer Square.

Some portions of the viaduct in this area will collapse in this quake, and lives will be lost. The disruption of highway repair and replacement will last for about six years.

With or without the viaduct's collapse, Pioneer Square will resemble a war zone in the weeks following a Seattle Fault quake. In the first few months, it will be a ghost town. Whether it returns as a historic asset and nationally recognized destination in the long run will be a matter of civic choice. It will be far more expensive to rebuild historic structures than raze them and start over.

Business Recovery and Resumption

The most immediate and widespread business disruptions will result from concerns for life and safety. Many, if not all, of the businesses near the fault rupture of the scenario earthquake will stop operations to assess the condition of their employees and building occupants. It is inevitable that some businesses will experience structural damage and collapses that injure and kill employees and customers. Surviving employees will be concerned about their loved ones and homes.

Transportation disruption will affect employees, first responders, those assessing damage, suppliers and customers. The ability to navigate amidst the debris is crucial. Even if buildings or alternative operation centers survive, such facilities will be worthless if personnel, suppliers and customers cannot reach them.

In this age of just-in-time inventory practices, few businesses hold large inventories. Perhaps surprisingly, most major corporations do not have contingency plans. Though a firm may be well prepared and have contingency plans, its suppliers may not. Many suppliers have their home offices or warehouses in the most vulnerable areas of the region such as the Duwamish Valley, where damage will be heavy. Limited on-site inventories and anticipated disruptions to suppliers and supplies will limit functionality even in businesses that suffer no structural or nonstructural damage. Many neighborhoods and markets will not have access to goods and services because of poor surface transportation. Given small inventories, residents around the region will have trouble securing basics such as groceries and medical services. It is important to note that even hospitals adhere to just-in-time inventory management, carrying only a few days' inventory of most materials and medication.

Few businesses have emergency power capabilities and those that do typically carry it only for critical processes and only over the short term. The scenario Seattle Fault event will interrupt power supplies, and small- and medium-sized businesses will not be able to function. With power disruptions come communication disruptions. Many businesses will be unable to communicate with their customers, suppliers and distributors. Small banks that will be a driving force behind the region's recovery following the earthquake will be unable to communicate with larger banks; one consequence is that the cash needed for recovery may not be readily available.

Major banks believe that their downtown facilities will survive well enough to be operational but that branch offices may not. Similarly, major hospitals may be occupiable, but satellite clinics may not. Hospital complexes concentrated within the greater downtown area will lose considerable functionality, suffer staffing shortages and be strapped for needed re-supply of medical supplies and pharmaceuticals due to just-in-time inventory management. Also important will be the fear of re-occupying buildings and a greatly reduced capability to assess damaged structures because of poor surface transportation. The lack of assessment capability will interrupt business operations throughout the region.

Ultimately, the scenario Seattle Fault earthquake will create a new future that will not include many local and regional businesses. Some businesses without large cash reserves will not survive. Corporate money and highly trained workers could leave.

Priority Concerns

Listed in order of priority, businesses should consider the implications of the following concerns as they plan for disaster contingencies such as the scenario earthquake:

1. **Personnel Concerns** – Immediately following the earthquake, staff will be concerned about their families. Employees who are out of the office may be difficult to contact. Injuries may prevent employees from coming to work. Extraordinary family needs, such as childcare, damage to schools or spouses' offices, will affect the ability of a company to recover rapidly. Contingency planners need to assess the vulnerabilities of employees and their families – where they live, whether or not they have personal family preparedness plans, and whether their homes are secure. Transportation disruptions will affect staff commutes. The same concerns will affect a firm's suppliers and distributors; some will cope with them better than others. Customers will not have easy access to a company's goods or services and over time may choose another business out of the region to meet their needs.

2. **Loss of Power** – Loss of power in certain key industries deserves special attention. The financial services industry, for example, will experience loss of access to central cash vaults and data processing centers. This will disrupt the availability of paper and electronic funds available to the public, businesses, and government. Electricity companies may be able to produce energy for the region but disabled main transmission lines could present distribution problems.

3. **Surface Transportation** – Manufacturing will cease until roads are available. Staff will not be able to commute to work or travel to customers. Replacement staff may not be able to travel. Retail businesses cannot operate offsite. Banks, the Federal Reserve, and the national money movement system are dependent on roads and the airports. The region's cash couriers and their vaults are located in the vulnerable Duwamish Valley area. Mail pickup and delivery will stop. Suppliers cannot replenish depleted inventories. Limited access to properties will slow damage assessment and the processing of insurance claims.

4. **Communication with Customers** – While most large businesses have contingency plans for internal communication, few have communication options with vendors and suppliers. Establishing offsite operations centers depends on the availability of uninterrupted communication. Few small and medium-sized businesses have developed ways to communicate among themselves in emergency conditions. Breakdowns in communication systems compromise the security of confidential information. Customers will have trouble knowing whether a business is open or not. Many businesses have not addressed communication alternatives with suppliers and customers.

5. **Physical Loss** – Collapsed buildings will kill and injure both employees and customers. Fallen debris will compromise surface transportation. Many regional warehouses are located in vulnerable areas. Damaged warehouses will make inventories unavailable. Media portrayals of neighborhood damage will discourage customers.
6. **Just-In-Time Inventories** – Businesses keep very small inventories. Delivered daily are groceries and medical products. Disruptions in deliveries cause disruption of business. Many suppliers base their operations in warehouses in the vulnerable Duwamish Valley area; they will not be able to meet customers' immediate needs. Isolated customers will be particularly vulnerable.
7. **Permanent Loss of Business** – Highly skilled personnel may leave the area; replacement workers will be reluctant to move into the region. Locally based businesses in severely affected neighborhoods may not have cash on hand to survive and recover. Many small businesses may not be able to take advantage of recovery funds. Suppliers may not be able to locate alternative warehousing facilities close to markets. Retailers in damaged areas that are dependent on commuting customers may not be able to survive.

Help Preparing Your Business

The Cascadia Region Earthquake Workgroup is a coalition of businesses, nonprofits and governmental bodies dedicated to helping our region prepare for and reduce damage from earthquakes. Its website includes helpful advice on preparation for homeowners, businesses and public officials: **http://www.crew.org**.

The City of Seattle's Emergency Management Office offers advice on preparing for emergencies and links to other useful resources: **http://www.seattle.gov/emergency_mgt/**

The nonprofit Institute for Business and Home Safety offers guidance to help businesses prepare for potential disasters, including advice to help employees better prepare their homes and families. Their free materials are available at: **http://www.ibhs.org**

Chapter 8

Individual and Community Impacts, Response and Recovery

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The scenario Seattle Fault earthquake finds most of the region's residents at work, school, shopping, heading for appointments, or involved in various activities outside of their home as described in earlier chapters. The earthquake badly damages homes, office buildings, warehouses, manufacturing plants, schools, port facilities, utilities and transportation routes from the south end of downtown Seattle east through Bellevue and throughout river valleys north and south of the cities. Collapsing structures and highway bridges kill or badly hurt thousands of people. Communication links are swamped or broken, making communication difficult if not impossible throughout the region. Police, fire, and medical aid units begin responding to hundreds of calls for help. Areas closest to the epicenter of the earthquake and to the fault rupture appear to be devastated. As the initial response gets underway, decision makers begin considering the implications of the disaster and hasten decisions on policy issues related to rebuilding and restoring the well-being of their communities.

Among the biggest concerns facing the region immediately after the earthquake are that:

- Police, fire, and medical aid units will be overwhelmed in the initial hours after the earthquake.
- Damage to transportation systems will make movement of people and freight around and through King County, and perhaps throughout the region, difficult for weeks or months.
- Demand for emergency shelter, food and water by displaced individuals and stranded commuters will place tremendous demand on available community resources.
- Disruptions to transportation, telecommunication and utility systems, and damage to key facilities will complicate the task of getting the local economy back on its feet. With the three-county study region providing about half of all jobs in the State of Washington and being the hub of state's international trade, restoring the economy quickly will be a daunting task for both local and state government agencies and the private sector.

Disaster response and a community's recovery from the consequences of a major earthquake similar to this event on the Seattle Fault typically begin simultaneously. Previous chapters described potential damage and losses to the region's built environment. This chapter discusses some of the implications of

Figure 8-1. A M6.7 earthquake on the Seattle Fault will have impacts region-wide, from business centers to neighborhoods such as this one, whose roads and utilities were extensively damaged by the 2001 Nisqually earthquake.
Photo / Steve Kramer, University of Washington

those losses and their impact on the people and economy of the region.

Impact on People

The scenario Seattle Fault earthquake will have a significant impact on people. The earthquake and its aftermath will disrupt individuals and families who live and work closest to the fault or on poor soils for weeks or months. Collapsed buildings or falling debris will kill or injure thousands of people, and trap hundreds of others. Hospitals closest to the fault may be unable to provide care to the injured because of damage to their facilities. Damage to the transportation system will impede emergency responders, including teams that search through collapsed structures, and prevent many commuters from returning home. Shelter space will be limited because of damage to schools and community centers. Water for drinking and firefighting will be scarce because of pipeline breaks. Untreated wastewater will pollute soils and waterways near sewer line breaks.

The time of day the M6.7 scenario earthquake occurs – 11:37 a.m. – is the worst for human casualties, because most people are involved in activities outside their home – working, at school, shopping, for example. At midday, people are more likely to be in structures that do not perform as well as residential structures built of wood. Table 8-1 indicates the scenario earthquake will fatally injure more than 1,660 people and injure more than 24,000. About 6,100 people will suffer injuries that are life threatening or require hospitalization.

Caring for the number of injured will be difficult immediately after the earthquake.

Table 8-1: Estimates of Injuries and Deaths Caused by Scenario M 6.7 Earthquake

Deaths	1,662
Life-Threatening Injuries	858
Injuries Require Hospitalization	5,223
Minor Injuries	18,165
Total Casualties	**25,908**

Source: HAZUS-MH, March 2004

The region will have a shortage of health care services, medical supplies, and drugs. Compounding damage to hospitals will be a lack of supplies and staff because significant damage to the region's transportation system will prevent them from getting to hospitals and clinics. The lack of health care services will be significant not only in Central Puget Sound, but also to people from adjacent states and around the nation because of the expertise of the region's health care system in specialty areas such as cancer care and organ transplantation, for example.

In the initial weeks, the region will rely on the resources of neighboring counties and the National Disaster Medical System for assistance.

Specialized search and rescue teams will pull many of the injured from badly damaged or partially collapsed structures. It may take rescuers many hours, perhaps days, after the earthquake to free trapped people. Although the Puget Sound region is home to one of the nation's Urban Search and Rescue Teams, local responders will need additional help. Most members of the local team will be unavailable, responding in their everyday jobs as firefighters, police officers, and emergency medical technicians. Depending upon the number and types of structures with trapped people, state authorities will request additional teams, but assistance will be at least 24 to 48 hours away.

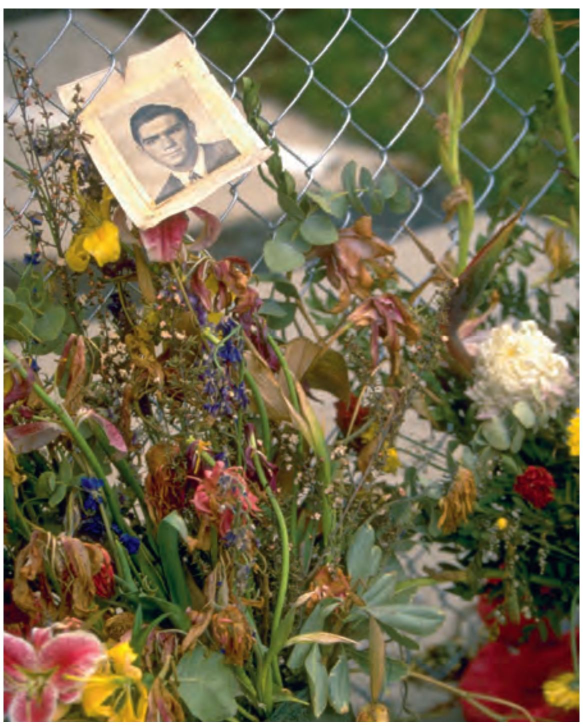


Figure 8-2. Sidewalk memorials like this one from the Northridge earthquake will spring up throughout the Central Puget Sound region as friends and relatives mourn the nearly 26,000 people killed or injured by the scenario earthquake. Photo / Federal Emergency Management Agency

Hundreds of thousands of commuters will have difficulty returning home after the scenario earthquake because of damage to key transportation corridors and a lack of alternative routes. More than a quarter-million people commute daily via car, mass transit or ferry across county lines in the three-county region. Another 800,000 people commute to work each day within King County. Detours will be available, but as was seen following the 1989 Loma Prieta earthquake in the San Francisco Bay area, the commute home is likely to be many hours long and very slow for those who are able to leave. For many, such as walk-on ferry commuters without cars, it could be impossible. Commuters unable to return home and unable to find other lodging will seek food, water, and bed space at emergency shelters, especially on a cold, rainy late fall day.

Among the significant problems that communities face is the ability to provide emergency shelter to persons displaced by the earthquake. Thousands of stranded commuters will need shelter, but also individuals and families with homes who cannot find temporary housing with friends, relatives or at a hotel, also need a place to stay. The earthquake will displace more than 46,000 households; nearly 11,000 people will be unable to find temporary housing elsewhere and will seek emergency

Figure 8-3: Damage to transportation routes will make it difficult for commuters in the Central Puget Sound region to return home following the scenario M6.7 earthquake. The Alaskan Way Viaduct, which carries one-quarter of all traffic through Seattle, is similar in age and construction to the Cypress Structure of the Nimitz Freeway in Oakland (above), which collapsed during the 1989 M6.7 Loma Prieta earthquake. Photo / Earthquake Engineering Research Institute, © 1997

shelter in public facilities. Some communities use schools as emergency shelters. However, about 40 percent of the region's schools will experience at least moderate damage in the earthquake, complicating community choices of potential shelter availability.

A number of groups will require special attention and pose challenges to responders immediately after the earthquake. These include schoolchildren, the disabled, retirees, and non-English speaking people.

There are a half-million children in more than 1,200 schools in the three-county area. Many schools received seismic safety upgrades in recent years, making them safer for students and staff. However, the earthquake will badly damage the most vulnerable schools, and injure hundreds of children and adults in them. Damaged schools will be unavailable for an extended period, and districts must find ways to accommodate a significant population of displaced students in the days immediately following the earthquake.

People who are disabled will require special attention from communities because of their special needs. Most do not work or do not earn enough to make adequate preparations for a disaster. The earthquake will displace many because they live in older housing damaged by the ground shaking. The number of disabled who do not live in a care center is considerable in the three-county area – about one in six working-age people, and more than four in 10 of them are senior citizens.

Like the disabled, senior citizens will require special attention from communities. They, too, have limited incomes, are less likely to have made adequate preparations for a disaster, more likely to live in older homes damaged by the earthquake, and more likely to have medical conditions requiring medications and ongoing care. They also face difficulty after a disaster; because of their age, some could become injured or disabled, and their limited income may not qualify them for disaster loans. The three-county area has about 300,000 people of retirement age, 65 or older.

Language and cultural barriers will pose difficulties throughout the region. The Central Puget Sound region is home to substantial populations of people who do not speak English as their primary language. One area badly damaged by the earthquake will be Seattle's International District, because the Seattle Fault runs through this cultural and commercial center for the region's Asian American and Pacific Islander communities. In previous events with significant community-wide impact, culture and language barriers lead to confusion about what was happening and how people should respond. For example, many from the Asian community did not understand why their children were at community and recreation centers rather than at school during a statewide teacher's strike in the mid 1990s. Following the 1994 Northridge earthquake in California, many individuals, primarily Latinos, were reluctant for apply for government disaster assistance because they were afraid they would be arrested or deported.

Figure 8-4. Temporary shelters and feeding stations like this one will be established throughout the region to care for the thousands of people who will be made homeless by the scenario earthquake.
Photo / Federal Emergency Management Agency

Figure 8-5. Local fire departments will have to make choices on how to do the most good with the resources and personnel available immediately after the earthquake. High priority situations such as a massive structure fire may pull resources from lesser priority events.
Photo / National Oceanic and Atmospheric Administration

Local and State Response

■ *Calls from dispatchers fill the air at Station #3. However, firefighters discovered they cannot deploy their engines and tankers because the doors to the equipment bays are jammed shut. The station shifted just enough during the earthquake to bind the doors closed. Through the station windows, firefighters see badly damaged buildings and smoke from nearby fires. It is obvious that people are trapped and hurt. The firefighters rush back to the equipment bay to see if somehow they can pry open the doors.*

■ *Police Officer Marsha Benner cannot reach dispatchers to provide information on the damage she sees and to request fire and medical aid units at the partially collapsed building as she approaches. She sees water gushing from a broken water main flooding the street and injured people walking around in a daze. A few individuals run from the hardware store across the street with shovels, picks, ropes, and ladders to help trapped people.*

■ *City Manager Scott Walter summons staff to the emergency operations center. They begin the process of finding out what happened in the city, determining how its residents are coping, and coordinating the response efforts of city departments. Public Works Director Brandon Marks is concerned that the unfinished project to retrofit the city's water tanks did not protect them from the ground shaking and they may be badly damaged or have collapsed. He tries to send a crew to check on the tanks, but cannot get through on the city's radio system.*

The scenario magnitude 6.7 earthquake on the Seattle Fault will overwhelm the fire, rescue, and emergency medical services responders of the Central Puget Sound region.

Calls to public safety agencies for help will increase dramatically. Damage to apparatus and facilities, injuries to personnel, and damage to roads and bridges will affect response times of firefighters, police officers, and emergency medical staff. King County's robust 800 MHZ public safety radio system will be overloaded, making communication between dispatchers and responders, and between responders, difficult.

Public safety personnel will make immediate decisions about how to do the most good for the most people with the resources immediately available in the area. Initially, responders may address higher priority problems to keep them from escalating, draining available resources from less severe incidents. A single-site, extraordinary event may require the activation of mutual aid agreements. For example, one high-rise fire in the region may require a response from as many as eight different fire departments to ensure operational success, safety of response personnel, and backfill coverage.

Emergency medical responders will adjust standards of care for the injured because of damage to the transportation system. For example, it may become necessary to deliver hospital-like care within a heavily impacted neighborhood from temporary facilities until air or ground transportation can take patients outside the area.

In the minutes after the earthquake, City and County Emergency Operations Centers (EOC) will open. Representatives of government services and other response partners including utility companies, social service networks, and schools will staff them. The EOCs will generate an assessment of the earthquake's impact and the needs of individual communities, and mobilize personnel and resources to address immediate needs, such as fire suppression, victim rescue, medical treatment, hazardous material control, public safety information, and hazard protection. Staff at the centers will prioritize and coordinate missions to begin restoring power, water, medical services, telecommunications, fuel, and other systems.

One of the key concerns of local government immediately after the earthquake will be availability of water. Restoring service as quickly as possible after the earthquake is important for a number of reasons – water is needed to sustain human life, as well as for sanitation, business, and industry uses. Lack of water for firefighting will be most critical in the hours after the earth-

Figure 8-6. Providing water for personal use such as cooking and drinking will be important immediately after the scenario M6.7 earthquake.
Photo / Federal Emergency Management Agency

STATE OF WASHINGTON
OFFICE OF THE GOVERNOR
P.O. Box 40002 • Olympia, Washington 98504-0002 • (360) 753-6780 • TTY/TDD (360) 753-6466

PROCLAMATION BY THE GOVERNOR

WHEREAS, an Earthquake occurred February 28, 2001 threatening citizens and property of Washington State;

WHEREAS, a 7.0 Richter scale Earthquake occurred 10.9 miles northeast of Olympia in Puget Sound, causing extensive damage to homes, businesses, public utilities, public facilities, and infrastructure in King, Thurston, Pierce, Kitsap, and possibly other counties.

WHEREAS, the Washington State Military Department has activated the state Emergency Operations Center, implemented response procedures, and is coordinating resources to support local officials in alleviating the immediate social and economic impacts to people, property, and infrastructure, and is assessing the magnitude of the event;

NOW, THEREFORE, I, Gary Locke, Governor of the state of Washington, as a result of the aforementioned situation and under RCW 38.08, 38.52, and 43.06, do hereby proclaim that a State of Emergency exists in Western Washington and direct the supporting plans and procedures to the *Washington State Comprehensive Emergency Management Plan* be implemented. State agencies and departments are directed to utilize state resources and to do everything possible to assist affected political subdivisions in an effort to respond to and recover from the event. I also hereby order into active state service the Washington National Guard, or such part thereof as may be necessary in the opinion of the Adjutant General, to perform such duties as directed by competent authority. Additionally, the Washington State Military Department, Emergency Management Division is instructed to coordinate all event-related assistance to the affected areas.

IN WITNESS WHEREOF, I have hereunto set my hand and caused the seal of the state of Washington to be affixed at Olympia, this 28 of February, A. D., Two Thousand and one.

Governor of Washington

BY THE GOVE[RNOR]

Secretary of State

Figure 8-7. A Proclamation of Emergency from the Governor, like this one from the Nisqually earthquake, facilitates use of state resources to respond to the scenario event, as well as helps the state access federal emergency and recovery programs and funds.

Graphic / Washington Military Department, Emergency Management Division

quake. The earthquake will trigger about 130 fires, burning more than a half-billion dollars in property. More than half the water systems in the region will experience at least moderate damage, with service cut to one-third of the region's 1.2 million households by the earthquake. A month later, more than 20 percent of the region's households will remain without water service.

Communities will have difficulty dealing with multiple environmental problems caused by the earthquake. Release of hazardous materials may generate fires and explosions, cause human health hazards, and pollute the air, water, and soil. The impacts of such incidents will vary, depending on the type and amount of materials released, and the timeliness and effectiveness of the response. Large numbers of factories and storage sites with hazardous materials and chemicals are located on liquefiable soil in areas such as the Duwamish industrial area of Seattle and the Green River valley. Both the Ports of Seattle and Tacoma serve as major transfer and storage sites for fuel and other hazardous materials. In addition, trucks and trains routinely transport hazardous materials along major highways and rail corridors damaged by the earthquake.

One source of environmental concern will be release of untreated wastewater in areas where major sewer lines in poor soils break from severe ground shaking. Discharges of sewage will occur into Lake Washington and Lake Sammamish as well as into the Green River/Duwamish River. Untreated wastewater will flow into Elliott Bay from treatment plants at West Point and Renton if those plants lose power. While emergency power could return undamaged pump stations and treatment plants to service quickly, repairs to large-diameter sewer lines could take weeks. Everett, Puyallup, and Tacoma also operate sewage treatment plans in poor soils along the Snohomish and Puyallup Rivers, respectively. These plants and the lines feeding them will sustain less damage, reducing the potential for pollution and health hazards in those areas.

Communities heavily impacted by the earthquake will ask for resources from neighboring communities outside the area of impact, the private sector, and the State of Washington. The state's primary role in responding to a damaging earthquake is to support the response and recovery efforts of affected communities.

The first actions of state government are to activate its Emergency Operations Center, establish communication with impacted communities and Indian Tribes to assess the situation and obtain preliminary damage reports, and begin deploying state personnel and resources. As communities proclaim local emergencies, they will ask the Governor to proclaim a State of Emergency and to request federal help. A proclamation of emergency from the Governor facilitates the use of state resources and begins the process of requesting a disaster declaration from the President. Such a declaration provides the state with access to disaster assistance programs and funds to help the communities respond to and then recover from the impacts of the earthquake.

The state responds in a number of ways and provides a variety of assistance, depending on local needs, including:

- Inspecting the state highway system for damage, making emergency repairs and establishing detours.
- Inspecting dams for safety.
- Cleaning up hazardous materials spills.
- Providing security at disaster sites and transportation for equipment, supplies, and people.
- Providing food, water, and bedding for emergency shelters.
- Obtaining help from other states through a nation-wide mutual-aid agreement called the Emergency Management Assistance Compact.
- Beginning activities to help restore the region's economic vitality.

Individual Response and Recovery

- *Bob Walton placed a call to his 74 year old mother at home in Mountlake. Amazingly, he gets through. She is fine, although very upset – dishes spilled on the middle of the kitchen floor, television and computer smashed on the floor in the family room, windows cracked, a corner of the house slid off the foundation, and chimney toppled. She said that she had not heard from Bob's sister. He wished he had talked his mother into taking advantage of the home retrofit program available in her neighborhood. He had no idea how (or even when) he would be able to get across the Lake Washington to help her.*

- *Jerry Liu's concern for his wife Cynthia grew by the minute. His calls to her cell phone were not getting through, and he worried she was trapped in the house, the store, or worse. He hoped they had not let their earthquake insurance lapse; he and Cynthia considered not renewing their policy because they thought all the talk at a recent neighborhood meeting about such a damaging earthquake was just that, talk.*

- *Amy King worked hard to calm her fourth graders as they stood in line in the breezeway of their school. A few started to cry. Amy wanted to cry, too. She did not know whether the school had a procedure —would the school bus the children home, or keep them until their parents arrived to pick them up? Sunrise Elementary was a special magnet school with children from all over the city. Who knew how long it would take all the children to get home safely. She remembered a snowstorm 20 years ago where some of the children did not get home until almost midnight. This looked much worse.*

Figure 8-8. Damage to single-family homes and other residential structures will temporarily displace about 46,000 households after the scenario Seattle Fault earthquake. Among the damage that will be seen is unreinforced, poorly bolted or unbolted homes being shaken off their foundations. Photo / Federal Emergency Management Agency

Figure 8-9. FEMA and the State of Washington will establish field offices following the scenario earthquake to inform people about available disaster assistance and to help them apply. Photo / Federal Emergency Management Agency

After the earthquake, residents will take care of minor injuries and assess their homes for damage. Residents will evacuate homes where there is major damage, fire, or the evidence of utility hazards. Those homeowners who participate in neighborhood preparedness or response programs (such as Seattle Disaster Aid and Response Teams or Community Emergency Response Teams) will help neighbors, shut off leaking gas, and perform first aid. Trained neighbors will have emergency kits, food and water, and will be able to help others who are unaware of what to do following the earthquake.

Deciding whether homes are safe to remain in will be the focus of individuals and families. The earthquake will displace about 46,000 households in the region; they will need to relocate, if not with other family or friends, then to temporary shelters. This will place a great demand on local government resources, especially schools and community centers, many of which will be damaged and initially unusable. Outdoor shelters or tents may not be a good option during the rainy, fall weather; following the Northridge, CA earthquake in January 1994, outside shelters were unsuitable because of heavy rain.

With telephone services generally unavailable immediately following the earthquake, family members in separate locations throughout the region will not be able to communicate or find one another. The psychological impact of the earthquake can be significant and will last even after all family members account for one another. Post-disaster stress can continue for months following this earthquake, heightened by injury or death of family members or friends, temporary relocation, repairing damage, replacing cherished items and household goods, and other factors. While some will sustain serious but not life-threatening injuries, a few people will die in their homes during the quake. Unsecured items flying about while the ground is shaking will cause many of the injuries that occur in homes. Those who secured their belongings will fare far better protecting their possessions, limiting damage costs and injuries.

Disasters can disrupt the social environment just as much as they affect the physical environment. Loss of life and housing pose the largest social burdens, as people struggle to rebuild their lives without loved ones or the familiarity of their homes. Temporary and long-term housing arrangements will disrupt people's lives and may force them to relocate permanently outside of their neighborhood or community. In addition, temporary or permanent closures of community centers, churches, schools, interest groups and social clubs will stress the community's social fabric.

While the earthquake will affect everyone in some way, there will be different impacts on different socio-economic and racial/ethnic groups. Typically, people with fewer social and economic resources will have more difficulty recovering from the disaster. Moreover, groups such as the elderly, the disabled and non-English speakers have special needs and will be more reliant on social networks and government social services during the recovery process.

Personal and financial stress and anxiety resulting from disruptions at home, work, school, and daycare may result in higher incidence of social and psychological problems, such as increased absenteeism, alcohol or drug abuse, and physical abuse.

Resources to help individuals and families recover from a major disaster such as the scenario Seattle Fault earthquake are limited. Few have earthquake insurance or the savings to cover their expenses for an extended period. While a Presidential disaster declaration will make federal aid available for affected individuals and families, such assistance is for uninsured losses only. Disaster grants generally are geared toward people with lower incomes, but some individuals in greatest need will not apply due to cultural issues or even mistrust of government assistance.

The first line of financial assistance is insurance. However, the percentage of homes and businesses with earthquake insurance in Washington is low, believed to be about 10 percent of homeowners and perhaps up to 20 percent of businesses. The reasons why are many – coverage must be purchased separately, often at considerable additional cost; it carries a large deductible of 10-20 percent; and earthquake insurance is not readily available because of large industry losses in major disasters such as California earthquakes in 1989 and 1994, Hurricane Andrew in 1992, and the terrorist attacks of September 11, 2001. Perhaps more importantly, some of the public does not believe or is unaware of the area's susceptibility to devastating earthquakes. Most believe that the federal government will repay them for their damage and losses.

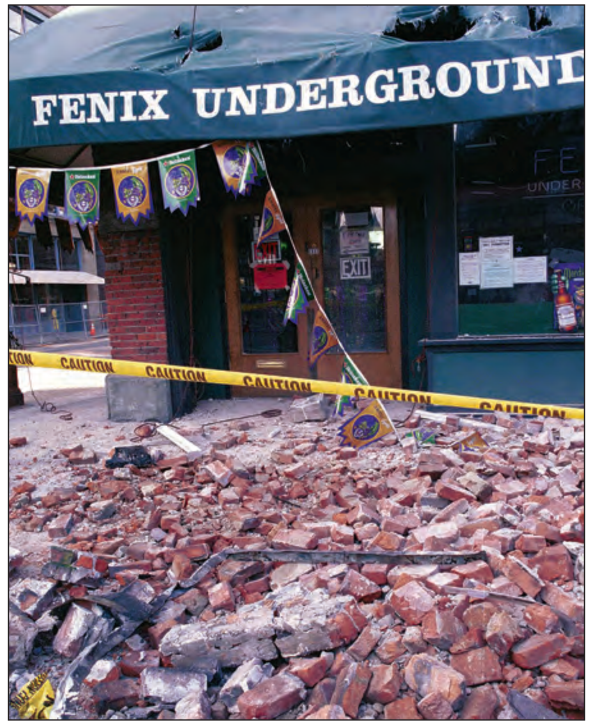
Government assistance is limited following a disaster. Individuals and families who are creditworthy initially will be steered into low-interest loan programs. Others who are not will receive grants to help repair damaged homes and take care of immediate needs. Homeowners often expect that government assistance will rebuild them to where they were before the earthquake, but in reality, this assistance will only help them get back on their feet.

The potential is great for individuals and families unable to carry the financial burden of their losses to relocate to another area, possibly with other family members.

Community Recovery

■ *In the days following the earthquake, City Manager Scott Walter begins thinking about how to rebuild his community and restore the economic vitality of downtown. Thank goodness, most of the neighborhoods can implement a fast-track permitting process for projects that complied with their long-range plans. Regional State Highway Manager Terry Crawford works with local transportation directors to prioritize and facilitate repairs to key links in the region's transportation*

Figure 8-10. A Seattle Fault earthquake poses a serious threat to the region's historic and cultural resources. Reconstruction of damaged historic structures can hinder the economic recovery of an area dependant on them.
Photo / Federal Emergency Management Agency



system. Port Director Carmen Rogers orders her management team to develop a plan to not only repair damaged facilities at the airport and sea port, but to also develop strategy to keep shipping companies from leaving the area. State Economic Development Director Lindsay Russell organizes a summit of regional, state and national economic development specialists to develop strategies to assist businesses and manufacturers affected by the earthquake so they can rebuild quickly and remain in the region.

For community and state leaders, the impacts of the Seattle Fault scenario earthquake extend beyond the cost of repairing shattered buildings and broken freeway bridges to lost business output and productivity, resulting in business failures and loss of competitiveness in the national and global marketplace.

The earthquake will cost the region at least $33 billion in lost business income and repairs to buildings (residential, business, industrial, and public) and transportation and utilities infrastructure (Table 8-2). Nearly 85 percent of the building related losses will be to residential structures. The total compares to the $40 billion in reconstruction costs from the 1994 Northridge, CA earthquake, the $200 billion cost of the 1995 Kobe, Japan earthquake, and the $2 – $4 billion cost of the 2001 Nisqually earthquake.

Among the key recovery issues facing local and state officials are removing debris, rebuilding the region's transportation infrastructure, reprioritizing capital investments, revitalizing the region's economy, restoring historic and cultural assets, and determining how to apply new knowledge of the earthquake hazard to land-use policies.

The recovery and reconstruction process begins immediately after a disaster event and continues long after the response has ended. Earthquake recovery, in particular, can be drawn-out, due in part to extensive structural

Table 8-2. Projected Economic Losses Caused by Scenario M6.7 Earthquake

Total Economic Loss to Region	$33 billion
Income Loss *Losses associated with inability to operate a business*	**$3.8 billion**
Building Loss *Estimated costs to repair or replace damage to buildings, contents, inventories*	**$22.3 billion**
Transportation System Loss *Estimated repair cost for highways and bridges, mass transit, air and water ports*	**$5.5 billion**
Utility System Loss *Estimated repair cost for communication, power, gas, oil, potable and waste water systems*	**$1.4 billion**

Source: HAZUS-MH, March 2004; figures adjusted to 2004 dollars.

damage requiring engineered repairs and the propensity for some damage to remain undiscovered until long after the event. The fact that the Federal-State Disaster Field Office for the Northridge earthquake remained open for more than 10 years is a telling sign how long it will take a severely impacted community to recover.

As soon as possible after the President declares the earthquake-stricken area as a disaster, the State of Washington and Federal Emergency Management Agency will establish a Joint Field Office to administer federal assistance programs. In addition to programs for individuals and families mentioned previously, other programs provide funds to help public agencies and eligible non-profit organizations reconstruct damaged facilities and offer grants for projects and plans to mitigate future hazard-caused damage. Further, the state will convene a Recovery and Restoration Task Force, with representatives from key state and local agencies, to coordinate recovery and mitigation efforts and to advise state government on appropriate policy issues.

The most critical economic restoration initiative facing the region is repair of damaged transportation systems. A study conducted in the late 1990s on the major highways between the Ports of Tacoma and Seattle shows that large segments of one or more of these routes would be closed for at least 90 days, perhaps for as long as a year, from a magnitude 6.5 or 7 earthquake on the Seattle Fault. While the study did not examine major routes north or east of Harbor Island in Seattle, these routes also would expe-

Figure 8-11. Among the activities that will take place immediately after the scenario M6.7 earthquake is inspection of damaged buildings. Those determined to be unsafe will receive a red tag from inspectors.

Photo / Federal Emergency Management Agency

Figure 8-12. The speed with which damage to the transportation infrastructure is repaired will have a direct impact on how quickly the economies of the Central Puget Sound region and the state recover following the scenario earthquake.

Photo / Federal Emergency Management Agency

rience significant damage. The impact will be staggering – commerce will have a difficult time moving to and from docks, warehouses, and end users such as grocery stores, retailers, hospitals and manufacturers, many of whom rely on just in time shipping for goods, supplies, and equipment.

A key lesson from the Northridge and Kobe earthquakes for decision makers is that damaged transportation and utilities infrastructure often cause major economic disruption. Following the Northridge earthquake, businesses indicated that damage to transportation systems appeared to be as great a source of disruption to their operations as building and infrastructure damage. Losses in the Los Angeles area would have been greater if not for the region's redundant freeway network. Kobe's experience may provide a better example of what to expect in Seattle. Both share geographic attributes – they are medium-size port cities located between mountains and the sea – and each has transportation networks with little redundancy.

Research conducted by Dr. Stephanie Chang of the University of British Columbia following the Kobe earthquake showed damage to transportation systems slowed the recovery of the Kobe region's economy. While utilities repairs took three to four months, it took up to 21 months to repair rail lines and highways, and more than two years to complete repairs at the Port of Kobe. The extended period needed to restore transportation systems cut cargo traffic in half at the port, the sixth largest container port in the world before the earthquake. During the reconstruction period, some shippers moved permanently away from Kobe to other ports outside the disaster area. The same

Figure 8-13. Rebuilding damage quickly will be important in revitalizing communities and limiting vandalism and crime in neighborhoods. Photo / Federal Emergency Management Agency

thing happened to the Port of Seward following the 1964 Great Alaska earthquake; much of Seward's business went to the Port of Anchorage.

The long-term economic impact of damage to the region's transportation systems depends upon the scale of damage as well as the ports' vulnerability to competition. Washington is one of the most trade-dependent states in the country. It is the fifth-largest exporter in the nation, and the Ports of Seattle and Tacoma handled more than $57 billion in waterborne international trade in 2000. Both ports are important engines in the economy of the region and the state. Beyond water ports, the Nisqually earthquake showed the physical and economic vulnerability of the region's air transport system, with significant damage to runways at Boeing Field (King County International Airport) and to the air traffic control system at Sea-Tac International Airport.

Both local and state governments may have to revise capital project priorities to facilitate repair of damaged public transportation and utilities infrastructure so they can restore essential services. Reordering priorities can be financially difficult when contracts are in place or considerable monies already spent for projects. Decisions are necessary on whether to rebuild infrastructure to codes that existed when they were originally constructed or to current codes that take into account the known earthquake hazard. Restoration of privately owned telecommunication, electricity, and natural gas systems will need to be coordinated with repair to damaged transportation networks.

An issue that public agencies will tackle early in the recovery is removal and disposal of debris. The scenario earthquake will generate an estimated 9 million tons of debris, or about 360,000 truckloads of reinforced concrete and steel, wood and brick that have to be disposed of in an environmentally safe manner. Hazardous materials such as asbestos, lead-based paint or chemicals will contaminate some of the debris, requiring special handling and disposal. Officials will have to identify one or more disposal sites for the debris.

Economic revitalization planning will be critical to the future of affected communities. Decision makers must address private building owners anxious to rebuild and redevelop as quickly as possible, especially those with the resources to fund immediate reconstruction work. Decision makers also may face significant numbers of unattended damaged buildings that give the appearance a neighborhood is abandoned. Neglected structures can have significant impact on the long-term economic viability of area businesses, as well as on safety and crime.

The recovery period represents an opportunity to implement plans and policies that an affected community already has adopted. Such plans might include implementation of neighborhood redevelopment or capital improvement plans, as well as policies and incentives related to historic preservation. Addressing the retrofit of unreinforced masonry structures will be important, as these buildings become more vulnerable with age and each earthquake.

Highly impacted jurisdictions may reassess their land-use policies to minimize development in hazardous areas, and revise critical area regulations required by the state's Growth Management Act. This law requires all cities, towns, and counties in the state to identify critical areas and to protect them by preventing or limiting development. (Critical areas include those that are seismically active and subject to landslide or other types of ground failure.) In areas where development is planned or cannot be avoided, mitigation measures are required. Additionally, communities must consider the requirements of the State Shorelines Management Act, State Environmental Policy Act (and possibly the National Environmental Policy Act, if federal funds are used) to ensure rebuilding takes place in an environmentally sound manner.

Earthquakes pose a serious threat to historic and cultural resources. Although settled significantly later than the East Coast, Washington has a wealth of historic resources that reflect its early growth as a Western lumber, shipping, and agricultural center. The region has many listings on the National Register of Historic Places; King County alone has 223 buildings, bridges, vessels and other sites on the register. Pierce County has 165 sites listed, and Snohomish County, 44.

The reconstruction process for damaged historic structures and districts can be complicated and time-consuming. Lack of agreement between property owners and the community on appropriate repairs or demolition can result in lengthy negotiations. Federal regulations often come into play. According to the National Historic Preservation Act, the Federal Emergency Management Agency must review the effects of demolition, repair, or reconstruction on disaster-damaged historic structures before awarding funds for their restoration. This occurs regardless of whether buildings are on the National Register of Historic Places. Protracted repairs can hinder the economic recovery of an area dependent upon the draw of its historic character.

The immediate post-disaster period typically is the only time when state and local policy makers consider and pass proactive disaster legislation. The window of opportunity can be small, so the public voice can move elected officials forward on specific issues. Committees and commissions will be a tremendous tool to keep these matters on the civic agenda, especially as local and state administrations change.

Chapter 9

A Call To Action

Contributors

The Seattle Fault Earthquake Scenario Project Team

The Seattle Fault Earthquake Scenario created a unique opportunity to draw on the knowledge and advice of many of our region's experts in the fields of earth and life sciences, earthquake engineering, planning and emergency management. The multi-disciplinary project team developed a broad, unbiased look at the Puget Sound region's and the State of Washington's vulnerability to one of their top earthquake threats – the Seattle Fault. The recommendations that follow represent only the beginning of a conversation to continue to improve our state's resilience to earthquakes and other hazards that could lead to disasters. We have an opportunity to act. The time to act is now.

The Seattle Fault Earthquake Scenario provides a forward-looking assessment of a real and credible earthquake threat in the Central Puget Sound region. A multi-disciplinary team of engineers, planners, geologists, seismologists, economists, and emergency managers spent thousands of hours examining for the first time the implications of a major earthquake on the Seattle Fault. The team used state-of-the-art earthquake hazard assessment tools and information on development and development trends in analyzing and evaluating the hazard posed by the scenario earthquake, and estimating the life-safety and socio-economic risks to our region. The 3 Ds of disaster – Deaths (more than 1,600), Dollars ($33 billion in direct and indirect costs), and Downtime (months to years for recovery of the impacted region) – are significant for this event.

This earthquake project provides a focal point to help raise the level of awareness of the region's earthquake threat and on discussions on how to reduce its vulnerability. It applies a combination of best available science with an infusion of best available multi-disciplinary knowledge to the complex problem of reducing our region's earthquake vulnerability while improving our region's preparedness. It is written in straightforward terms so the region and state's elected officials, business owners, lifeline managers, first responders and emergency managers, and the design, construction and building safety community have the best information available on the region's top earthquake threat.

Now is the time to act. We cannot wait for the next big devastating earthquake, which could be in the Western United States or perhaps Western Washington, to remind us to act. We already have had three reminders during the last 55 years in Puget Sound – in 1949, 1965, and again in 2001. Three times, we have experienced damaged schools, bridges, and airports. Three times, we have seen the fate of unreinforced masonry buildings from Olympia to Seattle. Three times, we have seen businesses experience significant downtime and disruption. But these local reminders pale in comparison to the dangers of the Seattle Fault.

During the past 25 years, significant advancements have improved the awareness and understanding of the region's earthquake vulnerability. Seismic mitigation programs in our state have improved the earthquake performance of certain infrastructure and reduced risks to the public. However, regional and state leaders must use this opportunity to not only continue existing efforts but also to reinvigorate past efforts that have stalled. New seismic risk reduction programs and directives – derived from the hard lessons learned from the significant earthquake losses experienced by neighboring states and Seattle's sister city Kobe, Japan – are needed. There is much to accomplish. The time to act is now.

The Seattle Fault Earthquake Scenario Project Team respectfully presents the following recommendations as a call for action by regional and state elected officials. Four recommendations are Priority Recommendations, meaning they are the steps that should be given first consideration by policy makers.

Priority Recommendation No. 1

Establish an Independent State Seismic Safety Board or Commission

Establish a funded state-level seismic safety board or commission, reporting directly to the Governor to recommend policies and programs to reduce the earthquake risk in Washington. Specifically, the board or commission would have the following roles:

- **Planning** – Develop an Earthquake Loss Reduction Plan for the state based on the best available science of the earthquake threat.
- **Coordination** – In concert with the State Emergency Management Division, facilitate coordination of earthquake-related programs for agencies at all levels of government and with non-governmental organizations. This includes, where practical, coordinating earthquake loss-reduction activities with other loss-reduction programs such as homeland security.
- **Legislative Advisory** – Propose legislative initiatives related to seismic safety, review all seismic related bills presented to Congress, the state Legislature and local government, and develop recommendations to the Governor.
- **Implementation** – Monitor implementation of the State's Earthquake Loss Reduction Plan, and support implementation of the State's Enhanced Hazard Mitigation Plan.
- **Public Education** – Facilitate coordination of public education programs to improve understanding of seismic safety issues by governmental bodies, private companies, organizations, and citizens.

Rationale:

Washington has the second highest earthquake risk in the nation, behind only California. The Federal Emergency Management Agency projects the long-term average economic loss to Washington from damage and lost income due to earthquakes is more than $228 million annually. The probability of strong ground motion and the economic consequences of that ground motion underpin this annual loss estimate.

Currently, a number of state and local agencies have earthquake loss-reduction efforts underway. These inadequately funded efforts focus on public education and are poorly coordinated with other similar loss-reduction activities. For example, the State's Earthquake Program has $112,050 available for state fiscal year 2005, primarily for public education. The State of Washington and local governments have developed natural hazard mitigation plans, but many of the mitigation strategies identified in the plans are for hazards other than earthquake and most of the strategies are unfunded. Federal mitigation programs provide the state with grant funding following disasters – the state had $26 million following the 2001 Nisqually earthquake – but requests ($72 million) far outstripped availability of funds.

Washington has had a number of committees working on seismic safety issues since 1990, all of which developed recommendations to reduce earthquake losses. However, none of the committees – including a committee of the Governor's Emergency Management Council, which provided seismic safety recommendations to the council in early 2004 – has had the authority to implement loss reduction actions.

Without an independent state seismic safety board or commission to develop a comprehensive statewide loss reduction strategy, there is less likely to be:

- Identification of the most vulnerable elements of transportation and lifeline networks, which have many owners, both public and private.
- A timely fix of major identified seismic vulnerabilities.
- Coordination of efforts between local and state agencies doing similar work.
- Increased awareness of the earthquake risk.
- New laws necessary to protect the lives and property of state residents from earthquakes.

California and Oregon created seismic safety commissions. California's Seismic Safety Commission, formed in 1975, is the oldest and most well-organized commission. Since its inception, this commission helped establish uniform seismic risk reduction strategies and furthered a wide variety of earthquake initiatives in California, ranging from legislation requiring retrofit of unreinforced masonry buildings to urban search and rescue. Some of these initiatives have served as seismic risk reduction models for communities around the world. Oregon's Seismic Safety Policy Advisory Commission, formed in 1991 to promote earthquake awareness and preparedness through education, research and legislation, has influenced that state's seismic program and codes. The advocacy of Oregon's commission spurred development of a package of bond issues to support seismic upgrading of critical structures such as hospitals, fire and police stations, public schools, community colleges, and the higher education system, approved by Oregon voters.

Not forming a seismic safety board or commission in Washington will result in the continuation of poorly funded, low-level, low-effort, earthquake loss-reduction activities of existing organizations.

Priority Recommendation No. 2

Implement Risk Reduction Plans for Critical Public Facilities

Identify critical public facilities statewide that have a high seismic risk and establish long-range plans to improve their safety in an earthquake. Such facilities include hospitals, schools, and police, fire and other critical infrastructure important for emergency response and long-term recovery. These facilities represent vulnerability to high loss of life or collateral loss such as reduced response capacity.

Implementing this recommendation requires coordination with ongoing homeland security risk-assessment efforts, to include:

- Adoption of a consistent methodology for conducting facility assessments.
- Assessment of public agency buildings and identification of seismically vulnerable facilities.
- Development of mitigation strategies to reduce earthquake losses to at-risk critical facilities.
- Identification of funding sources and possibly legislation to implement the strategies.

Rationale:

Without mitigation strategies to reduce the earthquake risk of critical public facilities, there will be more casualties in at-risk buildings, a reduced capacity to handle casualties and people made homeless, and an increase in response and recovery times. Damaged hospitals, for example, may have to turn away earthquake victims and possibly relocate existing patients.

To date, there has not been a comprehensive assessment of the seismic safety of critical facilities statewide. Some but not all state and local agencies have identified facilities potentially at risk for their hazard mitigation plans or capital improvement plans. An effort also is ongoing to identify potential facilities at risk to potential terrorist attack by local and state homeland security initiatives. These efforts have not been coordinated, and assessments completed to date have not used a consistent methodology to determine seismic risk. Without such assessments, it will be difficult to develop strategies to reduce earthquake loss, and those that are will be inadequate. Implementing loss-reduction strategies requires funding and possibly legislation.

An example of such legislation documenting and improving the seismic safety of critical facilities is California's Alquist Act. Enacted following the 1971 Sylmar earthquake, which resulted in the destruction of two major hospitals and the loss of 65 lives, the act established a statewide seismic safety building standards program. Amendments to the Alquist Act made after the 1994 Northridge earthquake requires all acute-care hospitals to remain operational following a design earthquake, and to make seismic upgrades meeting certain performance criteria. Hospitals that do not meet performance criteria by specific deadlines outlined in the law must be removed from service. Implementation of this program has resulted in acute-care hospitals in California being operational immediately after recent earthquakes.

Priority Recommendation No. 3

Retrofit of High Risk Buildings

Develop local and state funding and legislation requiring mandatory seismic retrofits of high-risk buildings, such as unreinforced masonry and tilt-up structures.

Rationale:

During the 1949 and 1965 earthquakes in Puget Sound, buildings with unreinforced brick walls and sand-lime mortar experienced more damage than any other type of construction. For example, two schools closed and a church condemned in Centralia, bricks and masonry from a gable over the main entrance of the Castle Rock high school collapsed and killed one student, and 1,900 brick walls in Seattle that collapsed, fractured or bulged were condemned and removed. Schools experienced a disproportionate level of damage in these earthquakes because of their brick construction. Extensive damage to unreinforced masonry buildings also occurred in the 2001 Nisqually earthquake, with 20 of the 31 buildings in Seattle red tagged due to extensive damage being URM buildings; another 50 of this building type were yellow-tagged for moderate damage. Luckily, because of time of day or school being out of session, casualties from URM building collapse in these earthquakes were limited.

Unreinforced masonry building damage and collapse can be deadly. URM buildings that collapsed killed people in the 1989 Loma Prieta earthquake. For example, two people died in Santa Cruz when the façade of an adjacent URM building collapsed onto the coffee shop they were in. In the South of Market District in San Francisco, a man waiting in his car died when part of the URM building in which his wife worked collapsed on top of him. More recently, collapse of an unreinforced masonry clock tower caused the only two deaths in the December 2003 Paso Robles earthquakes in California.

In 1986, California enacted a law requiring local governments in high seismic zones to inventory unreinforced masonry buildings, establish a URM loss reduction program, and report progress to the state by 1990. Local governments tailored their programs to meet their individual needs. The level of compliance with this law is quite high, with about 98 percent of the 25,500 URM buildings in California now in some sort of loss-reduction program; only about two thirds of the owners have reduced losses by voluntary retrofitting their buildings. Further work by the California Seismic Safety Commission suggests that mandatory strengthening by local governments is the most effective URM loss reduction program; it also found that voluntary strengthening has not been as effective because current economic incentives typically are insufficient to create a market-driven willingness to retrofit.

After the 2001 Nisqually earthquake, the City of Seattle and other communities investigated similar programs, but the effort died for lack of funding. The State of Washington must provide guidance and leadership for cities and counties to take action to improve the life-safety in high-risk buildings with known seismic hazards.

Many of the 2,200 URM buildings in the three-county study area of this project are located in poor soils and in the zone of strongest shaking expected from the Seattle Fault. The same is true of older buildings of tilt-up construction, which are similarly vulnerable to strong ground shaking because of inadequate connections between the walls and roof. Many of these structures have little or no seismic improvements. Not requiring full retrofit of these high-risk structures may result in unnecessary casualties and injuries of hundreds of people.

Priority Recommendation No. 4

Protect the Transportation Infrastructure

Establish and implement a strategy to quicken the pace of protecting seismically vulnerable critical transportation infrastructure.

Rationale:

Transportation infrastructure, particularly freeways, highways and local bridges, is essential to the health of Washington's economy. Trucks move about a quarter-billion dollars worth of goods through the three-county study area of this report every day; final distribution of most goods such as groceries, pharmaceuticals and other medical supplies, fuel, office supplies, and more is by truck. Millions of tons of food products from Eastern Washington and beyond move through the region via rail and seaports. Three-quarters of domestic waterborne cargo tonnage entering Alaska originates from Washington. More than a quarter-million commuters cross county lines to go to work in the region.

A transportation system – particularly the road network and bridges – badly damaged by an earthquake will delay emergency response in the hours after the event, restrict the movement of people and goods for months, and hamper the recovery of the Puget Sound region and Washington for months or years.

The lessons of past disasters are instructive for the Puget Sound region. Damage to transportation systems from the 1995 Kobe, Japan earthquake slowed the recovery of the region's economy. The extended period needed to restore transportation systems cut cargo traffic in half at the Port of Kobe, the sixth largest container port in the world before the earthquake. During reconstruction, some shippers moved permanently to other undamaged ports. The same thing happened to the Port of Seward following the 1964 Great Alaska earthquake; much of Seward's business went to the Port of Anchorage. More than one-quarter of the business interruption loss in the 1994 Northridge earthquake was from highway damage and longer commutes; losses would have been far greater were it not for the substantial redundancy in the Los Angeles highway network. During the 1993 Great Midwest Flood, business interruption losses in Des Moines, IA, caused by transportation disruptions were greater than damage caused by the flooding itself.

City, county and state agencies have been proactive in retrofitting their transportation assets, particularly bridges. However, financial resources limit their activities. For example, with current levels of funding it will take the Washington State Department of Transportation until 2070 to retrofit all state bridges in the current retrofit program (with the exception of the Alaskan Way Viaduct and those bridges with hollow core piles). This is a very long time. Furthermore, many bridges are located on steep hills or beside water where soil movements due to slides or liquefaction may cause severe structural distress. Unfortunately, foundation and soil remediation work is not part of the current retrofit plan, so failure of even the retrofitted structures during strong ground motions is possible.

Since the road-based transportation system is vital to both the immediate and long-term economic health of the state – regardless of whether there is a disaster – not increasing the pace of retrofitting soon will contribute to increased costs later, as well as large additional losses in terms of deaths, dollars and downtime from an earthquake disaster.

Other Recommendations of the Seattle Fault Earthquake Scenario Project Team

Recommendation No. 5

Accelerate Earthquake Hazard Assessments, Geological Mapping and the Use of these Studies

Continue to expand and improve information and maps on earthquakes and related geologic hazards, and require their use as best available science for state building codes, local land-use planning and development decisions, and local and state emergency response, recovery and continuity plans. Such work includes completing LIDAR mapping of all lowland fault systems in Western Washington and selected fault systems in Eastern Washington, and accelerating geologic mapping in urban areas and along critical transportation corridors.

Rationale:

In the 12 years since the U.S. Geologic Survey and others discovered that the Seattle Fault is active, there has been much progress understanding earthquake hazards and incorporating new scientific knowledge into products that help reduce the region's earthquake risk. In the past year, the Washington State Department of Natural Resources updated state soil and liquefaction zone maps, the University of Washington published new geologic maps of Seattle and the Tacoma area, and the U.S. Geologic Survey documented active faulting in Snohomish County along the Southern Whidbey Island Fault. Despite this progress, there is continuing uncertainty about the hazards posed by crustal faults and the strength of expected ground shaking.

Completing LIDAR mapping in Western Washington and in selected areas of Eastern Washington is the single most important step in reducing uncertainty surrounding earthquake hazard assessments of crustal faults. LIDAR is a high-resolution laser-based technology that allows geologists to document active crustal faults. Some LIDAR mapping has been completed in Puget Sound, but not yet over some of the main faults including the Doty Fault in Lewis County, the western portion of the Devils Mountain-Darrington Fault in Skagit and San Juan Counties, and an area in Spokane hit in recent years by a swarm of very shallow earthquakes. LIDAR also allows development of detailed landslide inventory maps, the first step in making landslide hazard maps; outside of Seattle, landslide hazard maps generally are poor or non-existent

It is necessary to accelerate the pace of producing digital geological maps — complete with online, digital geotechnical databases — of the state's urban areas. Digital maps form the starting point of virtually all major capital construction projects in Washington; while some areas such as Seattle have both modern geologic maps and digital databases, most areas do not. The databases are important not only for improved seismic engineering and estimates of strong ground shaking, but they also contribute to better design for other hazard reduction initiatives, such as anti-terrorism measures.

Better information about geological features will improve implementation in Washington of the 2003 International Building Code and enable better informed emergency response and recovery planning, critical areas designations, land-use planning decisions, and engineering solutions for new construction and building retrofits. Mandating use of this best available science will reduce the number of poor decisions for land-use planning and building design and construction.

Recommendation No. 6

Develop Incentives for Increased Seismic Safety

Develop financial and other incentives to increase the level of seismic safety in public and private buildings through structural and non-structural mitigation measures.

Rationale:

Incentives are designed to stimulate action while providing some reward or benefit to the individual or entity taking the action. It must be clear that the benefit will exceed the cost of the action taken. Incentives generally are required for owners of private and public buildings as they typically do not perform structural and or non-structural retrofits on their own initiative. Incentives can include tax reductions and credits, special purpose loan programs, and waiving of building permit and development fees, for example.

Development and implementation of appropriate incentives for various types of buildings and building owners is a complex undertaking, and will require much work by the various stakeholders involved – building owners and managers, earthquake professionals, taxing agencies, mortgage lenders, and insurance companies, among others. Encouraging owners through incentives to protect their own buildings will reduce deaths, dollars and downtime associated with a major earthquake and other disasters.

Recommendation No. 7

Expand Public Education Programs with Emphasis on Self-Sufficiency

Develop innovative programs to educate the public, public agencies, and the business community that both appropriately communicates the risk posed by earthquakes and generates action by individuals and organizations so they are self-sufficient for at least 72 hours following an earthquake.

Rationale:

A variety of public, private and non-profit organizations have spent hundreds of thousands of dollars in recent years to educate the public about Washington's earthquake hazard, actions to take in advance to prepare for earthquake as well as actions to take after the event has occurred. Public educators have not followed up to determine the effectiveness of their message nor whether individuals, families, or public and private organizations were any better prepared. The 2001 Nisqually earthquake provided researchers an opportunity to find out more about the level of knowledge of the earthquake threat and the level of preparedness.

Two studies of the impact of the Nisqually earthquake found the 2001 event did not stimulate the majority of households and small businesses to change their level of earthquake preparedness. One study showed that before the Nisqually event, less than half of the Puget Sound region's households had taken steps to prepare for an earthquake, and that afterward, four of five households did not increase their level of preparedness. The second study showed that 60 percent of small businesses lost productivity because of the Nisqually event, but only one third of small businesses increased their level of preparedness afterward. The firms increasing their preparedness were not the ones that necessarily experienced the most damage, but the ones that had taken precautions before. In other words, the careful grew more careful.

It is clear that many people, organizations, and businesses do not fully understand the region's earthquake threat nor have they fully considered what could happen when a major earthquake strikes. They believe that having survived the Nisqually event they are well prepared for the next earthquake. As a result, preparations to deal with a major earthquake such as an event on the Seattle Fault are inadequate. The public education status quo is not working effectively.

Improving the level of awareness and of preparedness in our communities must be a goal of both potentially impacted communities and the state. Public education programs must be revised and retooled to better address the Puget Sound region's and the state's earthquake threat so people and organizations are compelled to take action to prepare for the next major earthquake.

Without strong public education programs that spur action, too many individuals, households, and businesses will not be ready for the next major earthquake. This will lead to more deaths, injuries, damage, lost productivity, a reduced level of response, and a reduced capability to recover.

Recommendation No. 8

Enhance the Pacific Northwest Seismographic Network

Provide adequate funding to upgrade the region's seismograph network to make it more robust and to enhance its capabilities. This includes support from the State of Washington for federal funding initiatives such as the U.S. Geological Survey's Advanced National Seismic System, the National Earthquake Hazard Reduction Program and an enhanced National Tsunami Hazard Mitigation Program.

Rationale:

The Pacific Northwest Seismograph Network is one of the country's premier regional seismic networks, monitoring earthquake and volcanic activity across Washington and providing earthquake location and magnitude estimates in real time to emergency response organizations and the public. Data collected by the network, including that from 80 new urban strong motion stations, is key to understanding the effects of shaking on buildings and structures. The PNSN website (www.pnsn.org) has millions of visitors each year, and public agencies and the media depend on its staff to interpret seismic activity and current hazards research.

Despite its capabilities and reputation, the network's current finances do not allow for replacement of old equipment or installation of additional, modern instruments that will allow state and local communities to take full advantage of the network's existing products and real-time products under development. (Currently, the U.S. Geological Survey largely funds the network through both the National Earthquake Hazard Reduction Program and the Advanced National Seismic System Program; the U.S. Department of Energy in recent years, however, reduced funding for monitoring in the Hanford area.)

Ensuring rapid dissemination of earthquake-related information from locations anywhere in the state requires modernizing and expanding the seismic network, particularly in Eastern Washington. One area needing additional monitoring stations runs from Spokane south through Pullman and Clarkston. In addition, much of the network's existing equipment is old, installed in the 1960s and 1970s. This equipment lacks the capability of recording information needed for a rapid assessment of an earthquake. The ANSS management plan calls for federal funds to replace old seismic instruments and to improve monitoring statewide by adding 600 more strong motion stations, key for addressing engineering design issues.

The state and local communities should encourage Congress to fully fund the Advanced National Seismic System and ensure that newly installed seismic stations along the coast deployed specifically to monitor the Cascadia subduction zone include strong ground motion recording. Also, the state should develop a plan to bring real-time earthquake information to all county and city emergency managers using multiple communication channels. The ANSS has new real-time display systems, but currently there is no national strategy to ensure deployment of these systems.

Recommendation No. 9

Establish an Earthquake Information Clearinghouse

Establish an earthquake information clearinghouse to improve access to best available science and best practices for earthquakes and related geologic hazards in Washington for the public, government agencies, businesses and other organizations.

Rationale:

An earthquake information clearinghouse would provide the public, local planners, emergency managers, business contingency planners, engineers, researchers and others with information relevant to the state's earthquake threat and related to increasing earthquake safety. Providing a portal for this information would make it easier for homeowners, organization managers, and building owners to develop forward looking response and recovery plans as well as mitigation initiatives to reduce earthquake loss.

Appendix A

Earthquake Preparedness in Washington State

The February 28, 2001 magnitude 6.8 Nisqually earthquake provided a reminder that Washington is at risk to damaging earthquakes. Organizations have accomplished much in the past decade to improve the safety of people and property from a damaging earthquake.

Many people believe they are ready for whatever the region's next earthquake might throw at them based on how well they came through the Nisqually earthquake. However, much more needs to be done to educate decision makers and the public about the state's earthquake hazard, and to continue initiatives that will further improve the resiliency of the region's communities in advance of the next earthquake, which could be on the Seattle Fault Zone.

The Nisqually Earthquake

The state's most recent major earthquake, magnitude 6.8, struck the Puget Sound area at 10:54 a.m. on February 28, 2001. The epicenter was below Anderson Island near the Nisqually River delta in Puget Sound about 35 miles southwest of Seattle and 11 miles northeast of Olympia. Ground shaking lasted about 35 seconds. Two minor aftershocks occurred near the epicenter of the main shock.

The area of most intense ground shaking primarily occurred along the heavily populated north-south Interstate 5 corridor, from Olympia north through Seattle. This was due to the amplification of the earthquake waves on softer river valley sediments. The earthquake was felt over a large area – from Vancouver, British Columbia, to the north; Portland, Oregon, to the south; and Salt Lake City, Utah, to the southeast.

Various estimates have placed damage to public, business and household property caused by the Nisqually earthquake at from $2 billion to $4 billion. Damage to buildings, bridges and lifelines varied across the region, depending on local soil conditions. Damage primarily was nonstructural, with the majority of structural damage occurring in unreinforced masonry buildings constructed before 1950. In general, new buildings and those with recent seismic upgrades displayed good structural performance, although many still sustained non-structural damage.

Significant damage occurred in Olympia, at SeaTac Airport, and in south Seattle in the Pioneer Square and South of Downtown districts. Damaged were several state government buildings in Olympia, including the Legislative Building (the state's Capitol Building). The dome of the 74-year-old building sustained a deep crack in its limestone exterior and damage to supporting columns. There was non-structural damage throughout the building.

Figure A-1. Comparing the Nisqually Earthquake with Other Earthquakes and the Seattle Fault Scenario Earthquake

Earthquake	Estimated Loss (2004 $)
Nisqually, WA, M 6.8, 2001	$2 – 4 Billion
Olympia, WA, M 6.8, 1949	$200 Million
Seattle-Tacoma, WA, M 6.5, 1965	$75 Million
Seattle Fault, WA, scenario M 6.7 event	**$33 Billion**
Kobe, Japan M 6.9, 1995	Up to $200 Billion
Northridge, CA, M 6.7, 1994	$40 Billion
Loma Prieta, CA, M 6.9, 1989	$9 – 15 Billion

Most other state agency buildings closed in Olympia for one or more days for inspection and repair.

Lifeline systems generally performed well. Water utilities reported minor structural damage; a number of wells in Eastern Washington reportedly went dry. A gas-line leak caused a fire and explosion when two maintenance workers were resetting an earthquake valve at a correctional facility near Olympia. Nearly 220,000 customers lost power, but most had their service restored within a day. The volume of calls placed immediately after the earthquake overloaded landline and wireless phone systems.

Transportation systems suffered more damage. Seattle-Tacoma International Airport closed immediately because its control tower was disabled. A temporary backup control tower allowed reopening of the airport to limited traffic several hours after the quake. King County International Airport (Boeing Field) suffered serious cracking and gaps on the main runway due to soil liquefaction and lateral spreading; the runway reopened a week later.

While the area's overall transportation network remained functional, many highways, roads, and bridges were damaged. Several state routes and local roads closed temporarily due to slumping and pavement fractures. The quake badly damaged the Alaskan Way Viaduct (State Route 99), a major elevated freeway on the Seattle waterfront. Temporary repairs made the structure usable; the current preferred proposal to replace the freeway with a tunnel costs about $4 billion. Two busy local bridges closed due to significant damage – the Magnolia Bridge in Seattle and the Fourth Avenue Bridge in Olympia; they reopened weeks later after temporary repairs.

There was minor damage to docks in both the ports of Tacoma and Seattle, but not extensive enough to interrupt services.

The state's dams fared well. Of the 290 dams inspected by state engineers, only five had earthquake-related damage; these dams were susceptible because of their poor construction and weak foundations. Dams controlled or regulated by the Federal Energy Regulatory Commission, the Bureau of Reclamation, or the U.S. Army Corps of Engineers, were not damaged.

Damage to residential structures came in a variety of forms, from severe mudslide destruction of entire homes to breakage of replaceable personal property. A University of Washington study on residential loss estimated about one of every four Puget Sound households had damage. The study indicates that structural damage to roofs, walls, and foundations accounted for nearly two-thirds of losses, followed by chimney damage, and damages to nonstructural elements and household contents.

The State of Earthquake Safety in Washington

Earthquake safety has been a growing concern in Washington since the 1989 Loma Prieta earthquake in the San Francisco Bay Area. Scientists have been making steady progress in understanding the earthquake threat facing the state, learning more about the Cascadia Subduction Zone off the coast of Washington as well as identifying and studying major surface faults throughout the Puget Sound region. Public and private organizations have undertaken a number of initiatives to improve earthquake safety. Below are brief descriptions of some of those efforts.

Public Education

Every April is designated "Disaster Preparedness Month" in Washington. The State Emergency Management Division distributes preparedness materials that include the earthquake hazard to local jurisdictions, state agencies, schools, businesses, and the public. About 1.5 million residents participate in an annual statewide earthquake "Drop, Cover and Hold" drill. This program and its materials have received national recognition from the Western States Seismic Policy Council in 2003 and the International Association of Emergency Managers in 2003 and 2004.

The State Emergency Management Division published a booklet for elementary students entitled *How the Smart Family Survived a Tsunami* to address findings of an assessment of public understanding of the earthquake and tsunami hazards and levels of preparedness on the Washington coast. New Zealand's Institute of Geological and Nuclear Sciences assisted in the study. The booklet addresses the tsunami warning process and actions people should take following receipt of a tsunami warning. Other states and other countries susceptible to tsunamis are using the booklet, which won the 2004 National Earthquake Conference Award of Excellence.

A partnership involving the State Emergency Management Division, the Olympic Peninsula Intertribal Cultural Advisory Committee and others developed an instructional video for the K-6 state tsunami curriculum. A native storyteller from the Hoh Tribe and a two-dimensional animation describe a large earthquake and tsunami off the Washington coast from the perspective of a young Indian boy. This video is available in Alaska, California, and Oregon; eight South Pacific Nations plan to use the video in their public education programs.

Tribal Outreach

A first-ever workshop conducted in 2004 educated Indian Tribes about the earthquake and tsunami threats and provided public education materials and training opportunities geared specifically for them. The workshop featured a field trip to areas of subsidence along the coast that linked scientific evidence to coastal Native American oral history of large earthquakes. The workshop increased understanding of tribal needs and enhanced cooperation between tribal, state and federal government officials.

Safer Buildings

The Nisqually earthquake disaster provided $26 million for hazard mitigation projects and planning throughout Washington. Among the projects funded through the Hazard Mitigation Grant Program after the earthquake are these: 1) connecting overhead beams and installing equipment in the City of Aberdeen's main fire station to open apparatus doors when ground shaking is sensed; 2) seismically retrofitting of stand pipes, elevating water tanks, and protecting ground level tanks in the Highline Water District; 3) structurally improving and seismically retrofitting seven buildings on the campus of Clark College in Vancouver; and 4) retrofitting vulnerable homes in Seattle (see page 149).

One of the most important projects to come from the Nisqually earthquake is the seismic retrofit of the State Legislative Building (the state's Capitol Building). The structure, with the fourth largest masonry dome in the world, opened in 1928 and received seismic retrofits after the 1949 and 1965 earthquakes, as well as in 1976. At the time of the Nisqually earthquake, plans were underway to refurbish the building and complete additional seismic upgrades to protect against future earthquakes. The Nisqually earthquake shook the building but it did not cause significant damage. A $100 million project completed in November 2004 repaired earthquake damage, stabilized the dome, strengthened the building, and rehabilitated its systems.

The Legislature in 2003 approved the latest International Building Codes (IBC), implemented statewide by the State Building Code Council on July 1, 2004. Adoption of buildings codes that address the state's current earthquake hazard was one of the top policy recommendations of the state's Seismic Safety Committee in the fall of 2002.

In partnership with the National Tsunami Hazard Mitigation Program, the State Emergency Management Division continues to work with the engineering community to investigate whether there are adequate building designs available for both high seismic loading (zone 4 or equivalent in the International Building Code) and a tsunami inundation area. Many areas along the coast would be subject to strong ground shaking from a Cascadia subduction zone earthquake and inundation from an earthquake-generated tsunami within 30 minutes, providing little time for evacuation. Goal of this work is to develop guidance for retrofitting buildings to withstand forces of both the earthquake and tsunami, as well as remain available for vertical evacuation. Within three years, FEMA will develop a document to guide design and construction of buildings within the high seismic hazard-tsunami inundation zone.

Innovative Alert and Warning

The State Emergency Management Division in partnership with Federal Signal developed the All-Hazard Alert Broadcasting Radio System. The system uses NOAA Weather Radio and provides both tone and voice alert notification to communities for any hazardous situation, including earthquake and tsunami. Ocean Shores installed a pilot system on the beach in June 2003 for tsunami warning, and five more systems installed in other communities in 2004 for port security, and volcano and tsunami warning; plans call for additional tsunami warning systems in 2005. Deploying systems are Alaska, California, American Samoa and Guam, with the South Pacific countries of Fiji, Tonga and Samoa exploring their use. Four systems installed on the Seattle waterfront in 2005 will include chemical detectors, a weather station, cameras, and seismometers to allow real-time reporting for a variety of hazards. AHAB Radio received the 2004 National Earthquake Conference Award of Excellence.

Hazard Mitigation Planning

Washington was the first state in the nation to receive Federal Emergency Management Agency approval of its enhanced hazard mitigation plan. The plan identifies earthquake as one of the state's priority hazards, and used the concept of best available science in hazard profiles and risk assessment. Thirty-three counties in the state received FEMA approval for their hazard mitigation plans or are developing them. By mid 2005, approved local hazard mitigation plans will cover 84 percent of the state's population. The State Emergency Management Division provided more than $2 million in local planning grants from the Nisqually earthquake disaster and other sources to facilitate local planning. Improved hazard mitigation planning and federal approval of state and local hazard mitigation plans is a requirement of the Disaster Mitigation Act of 2000.

Reducing Business, Residential Losses

Seattle Project Impact developed a Disaster Resistant Business Toolkit using best practices and low-cost strategies to help businesses of all sizes and types prepare themselves against all hazards. The toolkit includes an interactive web-based resource with a clearinghouse for business disaster solutions and examples. Additionally, the Cascadia Region Earthquake Workgroup developed and distributed a video designed to encourage businesses large and small to prepare for catastrophic events. The video highlights how major businesses survived the 2001 Nisqually earthquake, and the lessons a small business learned following a devastating fire. Seattle Project Impact's Regional Home Retrofit Program has seismically retrofitted more than 600 homes. Based on the year of their construction, more than 250,000 houses in the 19 participating local jurisdictions are vulnerable to earthquakes. Seattle Project Impact is a public-private mitigation partnership lead by City of Seattle Emergency Management.

Earthquake Mapping

The Department of Natural Resources Division of Geology and Earth Resources produced National Earthquake Hazard Reduction Program soils maps and liquefaction susceptibility maps for every county in the state, with detailed maps prepared for select cities. The project, funded by a hazard mitigation grant following the Nisqually earthquake disaster, supports state implementation of the International Building Code and the International Residential Code as well as local and state preparedness and mitigation planning initiatives. The department also produced tsunami hazard maps for communities on the Pacific Coast and the Strait of Juan de Fuca, as well as for Seattle, Whidbey Island, Bellingham and Anacortes to help with emergency response and mitigation planning. Additional maps are planned for Tacoma and Olympia. The National Tsunami Hazard Mitigation Program and the NOAA Center for Tsunami Inundation Modeling Efforts assisted with map development.

Expanding Use of HAZUS

The State Emergency Management Division continues its collaborative efforts with FEMA Region X to provide instruction to the public and private sectors on the use of the HAZUS (short for Hazards US) loss estimation computer model. A users group works with various organizations to expand the use and knowledge of HAZUS and improve data sharing among users. Seattle completed a pilot project using HAZUS to support emergency response plans for schools in the Seattle Public School District. The project used several earthquake scenarios to analyze the seismic vulnerabilities of school facilities, nearby bridges and other resources upon which the schools would depend in an emergency. Damage estimates generated by HAZUS support mitigation and preparedness planning. Goal of the pilot project is to develop a template that other school districts can use to assess their schools and neighboring support facilities in order to develop appropriate mitigation and preparedness plans.

Improving Knowledge of the Earthquake Threat

The Cascadia Region Earthquake Workgroup completed a scenario document for a major earthquake in the Cascadia subduction zone off the coast of the Pacific Northwest. The document, Open File Report 05-05 published by the Oregon Department of Geology and Mineral Industries, provides a general assessment of how the region that runs from Vancouver, British Columbia in the north to Cape Mendocino, California in the south might fare in a magnitude 9 earthquake in the subduction zone.

What's Next?

Despite the initiatives described above – and others not included in the narrative – much more needs to be done to make the Puget Sound region, and the rest of Washington, safer from earthquakes such as the Seattle Fault scenario earthquake described in this publication.

Two studies completed after the 2001 earthquake provide some evidence. One study found that despite the fact the Nisqually earthquake caused about $1.5 billion in damage to 300,000 residences – one of every four in the Puget Sound region – the vast majority of people have made little effort to change their level of preparedness. A second study found that two-thirds of business owners said they are well prepared for an earthquake based on their experience with the Nisqually event, despite the fact that about 20 percent of small businesses in the region affected by the quake had a direct physical loss and 60 percent experienced productivity disruptions. Small businesses experienced about $2 billion in damage, lost productivity and lost sales.

What is more chilling is that the California's Seismic Safety Commission notes that state – despite efforts more significant and rigorous than Washington's to upgrade vulnerable structures such as hospitals and schools, enhance building codes, and other safety improvement – is still not prepared for a great earthquake. Many believe that the 1989 Loma Prieta and 1994 Northridge earthquakes – which expended much of their energy in mountains away from major cities and did not cause as much damage as they otherwise might have – gave people there a false sense of safety.

The project team hopes this scenario of a possible and scientifically probable earthquake on the Seattle Fault is a useful tool to improve the earthquake safety of the Puget Sound region and the State of Washington. Ultimately, it is up to the public through its elected officials to decide how much it is willing to invest and how much risk it is willing to take to prepare – or not prepare – for the next earthquake, which could devastate the region and disrupt its economy and lifestyle for months, perhaps many years after the event.

Appendix B

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Appendix C

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