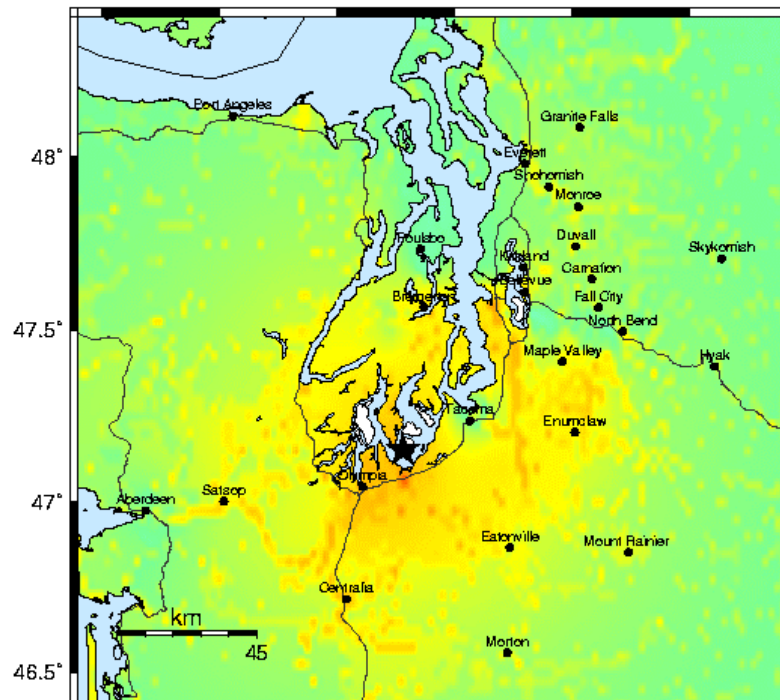


THE NISQUALLY EARTHQUAKE OF 28 FEBRUARY 2001

PRELIMINARY RECONNAISSANCE REPORT

PNSN Rapid Instrumental Intensity Map Epicenter: 17.6 km NE of Olympia, WA
Wed Feb 28, 2001 10:54:00 AM PST M 6.8 N47.15 W122.72 ID:0102261854



Nisqually Earthquake Clearinghouse Group

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The opinions expressed herein are those of the individual contributors and do not necessarily represent those of the supporting agencies.

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1 Introduction

The Nisqually earthquake occurred at 10:54 a.m. local time on Wednesday 28th February 2001. Its hypocenter lay 30 miles beneath the Nisqually delta area, approximately 11 miles northeast of Olympia WA. The moment magnitude was 6.8.

The tectonic setting of the Pacific Northwest includes three primary earthquake sources that affect seismic hazards in the Puget Sound region. The Cascadia Subduction Zone, where the Juan de Fuca Oceanic plate is subducted beneath the North American plate, has produced a number of great interplate earthquakes in the past. The subducting Juan de Fuca plate is also subject to deep intraplate earthquakes beneath Puget Sound, such as those that occurred in 1949 and 1965. Finally, there are numerous shallow crustal faults, like the Seattle Fault, a reverse fault that runs directly beneath Seattle and Bellevue. The Nisqually earthquake was of the second type – an extensional intraplate earthquake deep below the Puget Sound Region.

Loss of life due to the earthquake was limited to one person who suffered a heart attack that was attributed to earthquake trauma. Approximately 400 people were injured sufficiently to seek medical assistance. On the day of the earthquake, the state declared a state of emergency. The next day, the Governor requested federal assistance and estimated the economic consequences at \$2 billion.

Damage to buildings, bridges and lifelines varied across the region, and was correlated to local soil conditions. The damage to buildings was mainly nonstructural, with the majority of the structural damage occurring in unreinforced masonry buildings. The most prominent damage was to the Capitol Building in Olympia, in which the columns supporting the dome were damaged. Many bridges suffered light structural damage. However, most were never closed, or were re-opened shortly after the event. Only a few bridges, mainly built before the 1980s, were damaged sufficiently to require extended closure. Both the City of Seattle and the State Department of Transportation had embarked on bridge seismic retrofit programs during the previous decade.

Lifelines generally performed well, with the notable exception of airports. Sea-Tac International Airport suffered damage to the control tower and is now operating at partial capacity with a temporary tower. The runway at King County Airport (Boeing Field) suffered serious cracking and is open only to light traffic.

This report presents a preliminary description of the seismological background, the ground motions, the responses of natural and man-made structures to those ground motions and the societal consequences. The findings are preliminary and will inevitably be updated as more data become available and are analyzed. A more detailed report is planned for the future. Additional information is also available at <http://www.ce.washington.edu/~nisqually>.

2 Seismology

On Wednesday, 28 February 2001, a moment magnitude 6.8 earthquake occurred beneath the southern Puget Sound area of Washington State. The preliminary location by the University of Washington Seismological Laboratory places the earthquake at a depth of 52 km with an epicentral location of 47.149°N and 122.727°W. This location is near the Nisqually River delta about 18 km northeast of the city of Olympia, and the earthquake has therefore been named the Nisqually earthquake. The epicenter is 24 km southwest of the city of Tacoma and 58 km southwest of the city of Seattle. The origin time was 18:54:32 UTC, or 10:54:32 a.m. local time.

The Nisqually earthquake occurred within the eastward-dipping Wadati-Benioff zone of the subducted Juan de Fuca oceanic plate, which includes the hypocenters of many past earthquakes. The preliminary interpretation is that the event ruptured a nearly north-south striking fault in an extensional mode, consistent with down-dip extension within the subducted plate.

Other historical earthquakes that caused damage in western Washington State bear similarities to the Nisqually event (Figures 2.1 and 2.2). A magnitude 6.2 event in 1939

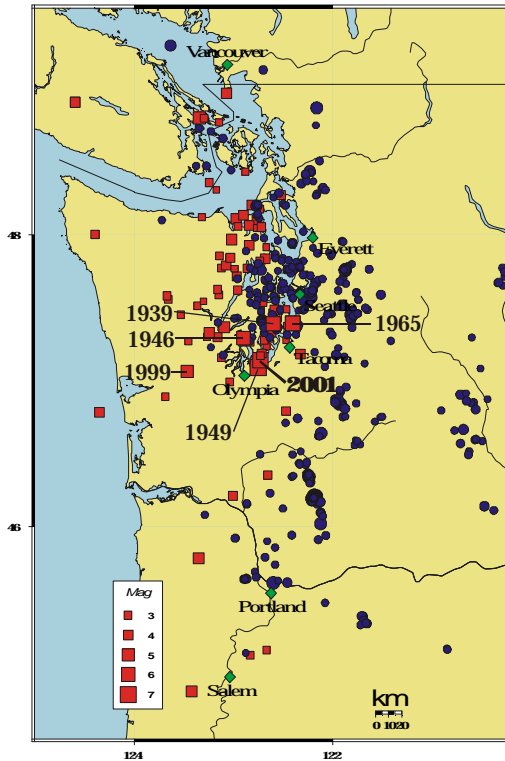


Figure 2.1: Map of the United States Pacific Northwest and southwest Canada showing the Nisqually earthquake in relation to historical seismicity. Earthquakes within the subducted Juan de Fuca plate are shown as red squares with the size of the square proportional to the magnitude. Earthquakes within the North American crust are shown as blue dots with the diameter of the dot proportional to the magnitude. Epicentral location accuracy for the 1965 and earlier events is less than for later earthquakes.

north of the mainshock. In addition to the aftershocks, two small earthquakes of magnitude 1.2 and 1.3 have occurred at depths of 25 and 28 km almost directly above the mainshock.

and a magnitude 6.4 event in 1946 had epicentral locations within approximately 60 km of the Nisqually earthquake's epicenter, and both are believed to have been deep events within the Juan de Fuca plate. The magnitude 7.1 Olympia earthquake of 1949 occurred within 20 km of the Nisqually earthquake and could have ruptured the same fault. The 1965 magnitude 6.5 Seattle earthquake occurred about 40 km northeast of the Nisqually earthquake and had a similar fault orientation as the 2001 event. In 1999, the moment magnitude 5.8 Satsop earthquake occurred within the subducting Juan de Fuca plate about 60 km to the west of the Nisqually earthquake.

The Nisqually mainshock was followed by two detected aftershocks that may be on the same fault. The first aftershock at 09:10:20 UTC (1:10 a.m. local time) on 1 March 2001 was a coda magnitude 3.4 event with a preliminary location of 47.197°N, 122.713°W, and a depth of 52 km. This event was about 6 km north of the mainshock. The second aftershock was a coda magnitude 2.7 event at 14:23:34 UTC (6:23 a.m. local time) on 1 March 2001. The hypocenter was 51 km deep at 47.180°N and 122.729°W, about 2.5 km

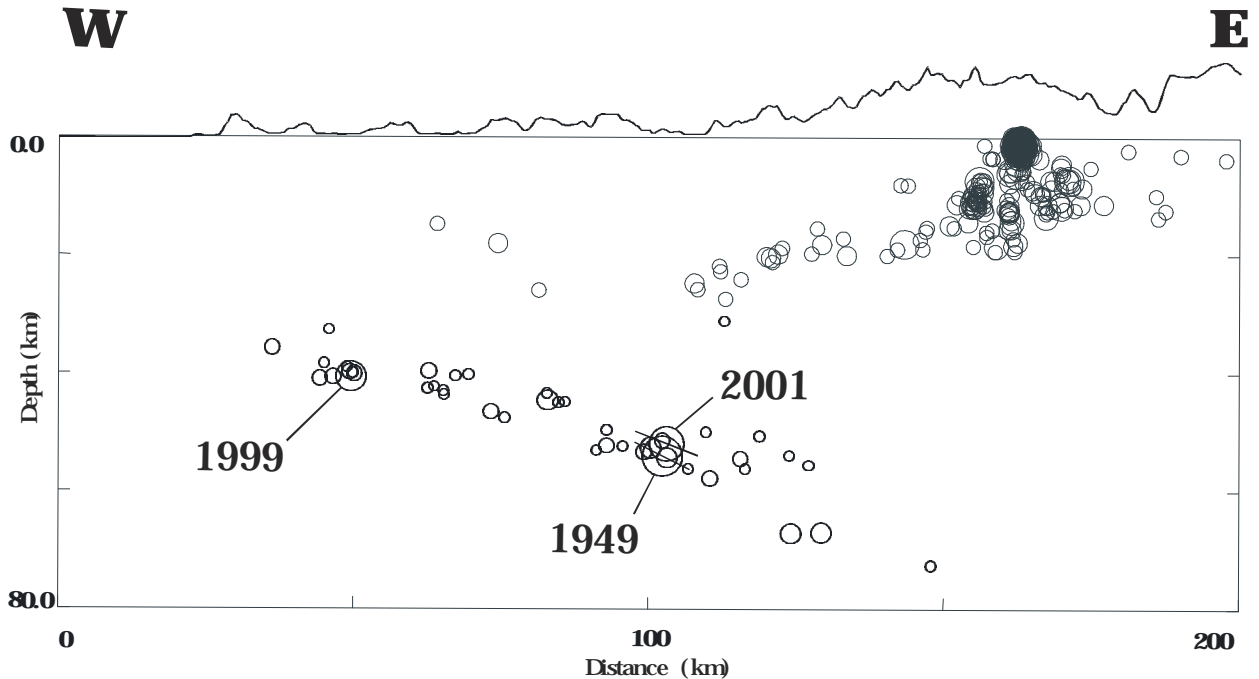


Figure 2.2: ENE-WSW cross section along the approximate dip of the Juan de Fuca plate showing the distribution of earthquakes near the Nisqually event. Earthquakes are denoted as circles with diameter proportional to magnitude. The lines through the 1949 and Nisqually hypocenters show the direction of the extensional stress. The eastward-dipping zone of deep earthquakes are within the subducted Juan de Fuca plate, whereas the earthquakes above 30 km depth lie within the North American crust. The large number of earthquakes near the surface on the east side of the figure are beneath the Cascade Range.

The Nisqually earthquake caused moderate ground motion throughout the Puget Sound region (Figure 2.3). Of the 31 stations for which preliminary data are available, only 13 show peak ground accelerations greater than 10% of gravity and only 2 stations recorded values greater than 25% of gravity. There are a number of stations from which the data have not yet been analyzed.

The ground motions vary widely from site to site due in part to the large differences in geologic conditions throughout the Puget Sound region (Figure 2.4). These variations do not appear to follow simple patterns based on distance or geologic unit. For example, station TBPA on valley fill in Tacoma had the same peak ground acceleration as station UPS on stiff glacial tills 9 km away. Both of these Tacoma stations are sited within 35 km of the epicenter but showed less ground acceleration than some of the stations in Seattle, 25 km farther from the epicenter, and less than station MBPA at an epicentral distance of about 115 km. Some of these variations may be due to radiation pattern, but nonetheless they highlight the need for a much denser network and the need for analysis of more than just the peak ground acceleration before general conclusions can be drawn. At this time, long-period ground motions have not been analyzed.

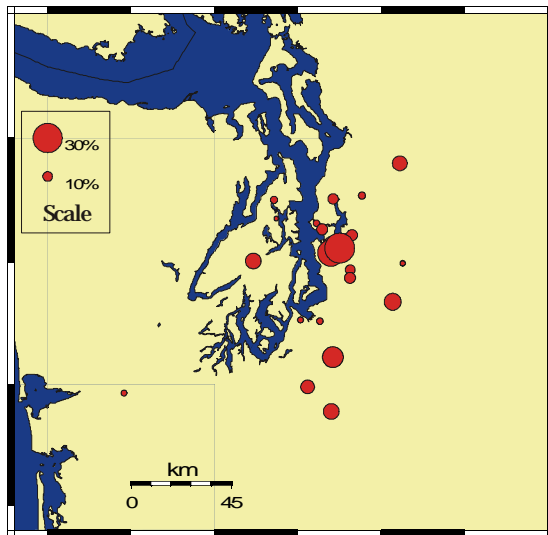


Figure 2.3: Locations of strong-motion recorders in the Puget Sound region, with the diameter of the circle proportional to the recorded peak ground acceleration.

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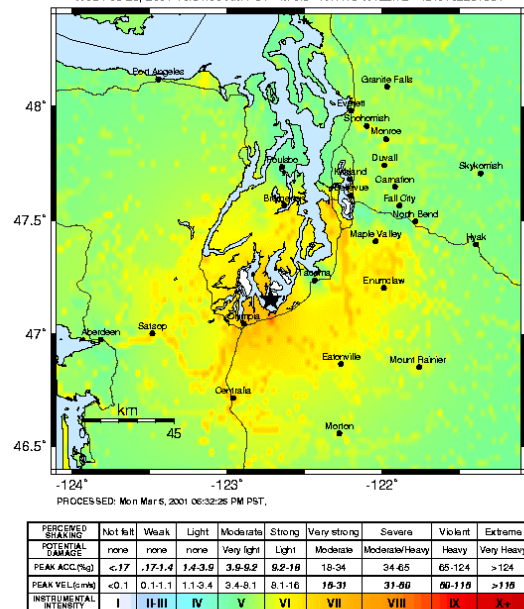


Figure 2.4: Instrumental intensity map produced by "Shakemap" for the Nisqually earthquake. The amplitudes are based on a model of the ground motion adjusted to reflect the surface geology and observed ground motions.

3 Geotechnical Considerations

The damage produced by the Nisqually earthquake was strongly influenced by geological and geotechnical factors. Early reconnaissance efforts have provided useful information on liquefaction and lateral spreading, landslides, and the performance of earth structures.

3.1 Geology

The geology of the Puget Lowland is dominated by a complex, alternating, and incomplete sequence of glacial and nonglacial deposits that rest upon an irregular bedrock surface. The depth to bedrock varies from zero to thousands of feet. Bedrock outcrops in an east-west band across the Lowland at the latitude of south Seattle and outcrops again along the perimeter of the Lowland. Numerous faults and folds have deformed the bedrock and overlying Quaternary sediments across the Lowland.

The current landscape is largely a result of repeated cycles of glacial scouring and deposition, and recent processes such as landsliding and river action. The north-south ridges and troughs of the Lowland (Figure 3.1) are the result of glacial scouring and subglacial stream erosion. The ridges are generally comprised of Pleistocene glacial and interglacial deposits, which are dense and stiff from preconsolidation by multiple advances of 3000-ft-thick ice sheets. Normally consolidated river and lake deposits of the last ice-sheet advance are locally present. These Pleistocene deposits are blanketed by normally consolidated Holocene deposits of colluvium; lake, river, and beach deposits; peat; and volcanic ashes and mudflows.

Alluvial sediment, predominantly uniform sand, lies hundreds of feet thick in the major river valleys. The steep bluffs and hillsides that border the river valleys, streams, Lake Washington, and the coastline of Puget Sound are mantled with colluvium, which tends to slide during or following periods of heavy precipitation.

Holocene deltas exist at the mouths of the Duwamish, Puyallup, and Nisqually Rivers, each of which originate on the slopes of Mt. Rainier. Sediments from Mt. Rainier, some of which were released in the form of large landslides (known as *lahars*), have occasionally choked river channels and blanketed the valley bottoms with sediment. These sediments have also contributed to the growth of the deltas, now heavily developed in Seattle and Tacoma. Use of these areas for industrial activities has required extensive modification, principally in the form of man-made fills and retaining structures. In



Figure. 3.1: Central Puget Sound region. Alluvial valleys are shown in light brown. Seattle fault zone shown as hatched

Seattle, extensive filling of former meanders and other depressions has occurred along the Duwamish River valley, and the tideflat north and east of the mouth of the river. Much of this filling was accomplished hydraulically (Fig. 3.2) from about 1890 to 1930 when the landscape of Seattle reached its current form. As a result, important industrial, port, and transportation facilities exist on loose, saturated soil deposits, both natural and man-made.



Figure. 3.2: Hydraulic filling of tideflats south of downtown Seattle during the 1890s.

3.2 Liquefaction

Soil liquefaction has been observed in a number of locations within the Puget Sound Basin. In a manner consistent with liquefaction observations from past earthquakes, principally those of 1949 and 1965, liquefaction was most commonly observed in low-lying alluvial valleys, river deltas, and poorly compacted man-made fills.

Extensive liquefaction was observed in localized areas. At the King County Airport (Boeing Field), which lies within the Duwamish River corridor south of downtown Seattle, extensive liquefaction was seen along the eastern runway where zones of ejecta covered areas some 300 ft long (Fig. 3.3). Ground surface settlements of up to 9 inches were observed in this area. A few



Figure 3.3: Sand boils at King County Airport

scattered sand boils were observed along the western runway of the airport, but a 4 ft wide, 6 ft deep sinkhole was reported at the north end of the western runway. Apparent ground oscillation caused the opening of cracks in pavement joints along both runways. Along the west edge of the western runway, a longitudinal crack, approximately 1000 ft. long and 1/2-inch to 1-inch wide was observed. The pattern of sand boils and areas of pavement cracking appear to correspond to an old meander of the Duwamish River. The southern half of the western runway (which was not in the area of the old river meander) appeared to be unaffected by ground shaking or liquefaction.

Numerous liquefaction features were also observed in the industrial area along the Duwamish River north of the King County Airport and south of downtown Seattle in an

area known as the Sodo District. Because of the flat topography of these areas, little evidence of consistent lateral deformation was observed. A number of structures in the Sodo area were extensively damaged by liquefaction-induced foundation failure; an example, in which some pile caps have separated from the columns and settled approximately 4 ft (out of sight), is shown in Fig. 3.4.



Figure 3.4: Settlement of pile cap in liquefied soil beneath industrial building south of downtown Seattle.

Lateral spreading was observed at a number of sites in the Olympia/Tumwater area. Several lateral spreads were observed along the banks of Capitol Lake south of downtown Olympia (Fig. 3.5). Capitol Lake was the site of similar lateral spreads in the 1949 and 1965 earthquakes. These spreads produced lateral displacements ranging from a few inches to several feet, and affected nearby roads, footpaths, railroads, and utilities. Lateral spreading at the



Figure 3.5: Lateral spreading at Capitol Lake



Figure 3.6: Lateral spreading at Sunset Lake trailer park in Tumwater.

Sunset Lake mobile home park removed a portion of roadway and damaged utilities and trailer foundation slabs.

Careful reconnaissance of other areas, such as the Ports of Olympia and Tacoma, the Puyallup River valley, and the Nisqually Delta, where liquefiable soils are known to exist, revealed surprisingly limited evidence of liquefaction and/or lateral spreading.

3.3 Landslides

A number of landslides were observed within the Puget Sound Basin. Many of these slides occurred in natural materials, such as the 400 ft long slide on the northeast side of Capitol Lake (Fig. 3.7). Other slides occurred in engineered fills, particularly at locations where they spanned low-lying areas of natural soils (Fig. 3.8). A flow slide removed part



Figure 3.7: Landslide at Capitol Lake in Olympia.



Figure 3.8: Landslide along Martin Way in Olympia.

of Highway 101 just west of Olympia, closing both northbound lanes of traffic.

A significant landslide temporarily dammed the Cedar River in Renton; nearby construction equipment was quickly mobilized to breach the dam and divert the river from nearby homes. Other landslides occurred in the colluvial soils that mantle the slopes of many hills in the Puget Sound Basin; the number of these slides was no doubt tempered by the unseasonably dry weather that preceded the earthquake.

3.4 Earth Structures

Some damage to earth structures was observed. A mechanically stabilized earth (MSE) wall supporting a hotel parking lot in Tumwater failed following the earthquake, however, the question of whether a broken water pipe at the top of the slope was a cause or a consequence of the wall failure has not yet been answered.



Figure 3.9: Failure of MSE wall in Tumwater.

Liquefaction did cause movements of retaining structures at the Port of Seattle, but the movements were small enough that their function was not compromised. Settlement of 2-6 inches was observed at the Washington State Ferry Terminal (Colman Dock) along the Seattle waterfront. A pier adjacent to the Navy Reserve Center on Lake Union also moved approximately 4 inches.

4 Buildings

4.1 General

Building damage was observed throughout the Puget Sound region, but heavy damage was highly localized. In particular, severe damage was observed in the city of Olympia, at Seatac Airport, and in southern Seattle from Pioneer Square south into the Sodo area (Table 4.1). Structures damaged included office buildings, residences, schools, hospitals, airport structures and churches. These structures and the surrounding areas around were closed for various lengths of time following the earthquake.

Structural damage was primarily concentrated in older unreinforced masonry buildings, with some damage reported to wood-frame structures and reinforced concrete structures. In general, new buildings and buildings that had recently been seismically upgraded typically displayed good structural performance, but many still sustained non-structural damage.

Structural and non-structural damage also resulted from geotechnical failures. In general, areas that sustained the most significant damage were built on fill or weak soils. Lateral spreading and settlement induced large deformations, which resulted in nonstructural and some structural damage. Landslides caused damage to houses.

Most buildings performed well from a life-safety standpoint, in that the limited structural damage that occurred caused no loss of life or collapse. However, the economic cost of the nonstructural damage is high. At the time of writing, the City of Seattle estimated the losses due to damage to buildings in the city to be \$39,237,000, based on a rapid assessment of over 342 structures.

Table 4.1. Summary of Red and Yellow-Tagged Buildings in Urban Areas

Area	Number of Red-Tagged Buildings	Number of Yellow-Tagged Buildings	Total Number of Buildings Inspected
City of Seattle	26	161	342
City of Olympia	2	43	300
Capitol Campus Facilities (Olympia)	3	2	31
Pierce County	1	12	25
City of Puyallup	0	2	60
City of Renton	8	3	100
Tukwila	1	1	Not Reported
Unincorporated Thurston County	2	6	120
Unincorporated King County	5	4	22

The following sections briefly summarize the damage observed immediately following the earthquake. Examples of damage states are provided.

4.2 Performance of Unreinforced Masonry Buildings

Unreinforced masonry (URM) buildings built before 1950 exhibited the poorest behavior. The most common damage included shedding of brick from parapets and chimneys. Other URM buildings exhibited diagonal “stair-step” cracking in walls and piers (Figure 4.1), damage to walls in the upper stories (Figure 4.2), vertical cracking in walls, damage to masonry arches, and damage to walls as a result of pounding (Figure 4.3). In many cases, fallen brick resulted in damage to objects, such as cars and canopies, outside the building (e.g. Figure 4.2).



Figure 4.1: Wall Cracking - Olympian Apartments



Figure 4.2: Brick Parapet and Wall Failure - Fenix Cafe



Figure 4.3: Pounding Damage

4.3 Performance of Reinforced Concrete Buildings

Damage to reinforced concrete buildings was not as widespread as the damage to URM buildings. The structural damage sustained by reinforced concrete frame structures, with and without brick infill, included cracking in beams and columns, column spalling (Figure 4.4), and cracking in beam-column joints. Structural walls exhibited diagonal cracking and damage at the construction joints (Figure 4.5). Little structural damage was reported to new reinforced concrete buildings, including tilt-up construction, immediately following the earthquake.



Figure 4.4: Concrete Spalling in RC Column



Figure 4.5: Damage at Construction Joint

4.4 Performance of Wood Frame Buildings

In general, the performance of wood frame residential structures was good. For the most part, damage to wood-frame houses was limited to chimney damage or separation of

concrete or block walls from the rest of the structure. However, some wood frame commercial structures sustained significant damage, in downtown Seattle (Figure 4.6) as well as other places in the Puget Sound area. Landslides caused severe damage to wood frame buildings in Burien, as well as to timber houses resting on long timber piles built on the shore at Salmon Beach in Tacoma. One house at Salmon Beach collapsed into the sea.



Figure 4.6: Wood Frame Structure – Seattle Chocolates Building

4.5 Performance of Retrofitted Buildings

Seismic retrofit programs have been developed and implemented in different locations in the Puget Sound area. The city of Seattle received a one-year Project Impact Grant from FEMA. One of the primary objectives was to encourage and assist homeowners in the seismic retrofitting of residences. Additionally, several key government buildings and city hospitals, including the State Capitol, the King County Courthouse, and the Harborview Medical Center (the region's only Level 1 trauma center) were slated for

seismic upgrading. However, at the time of the earthquake, few of the planned retrofitting measures had been implemented.

Some URM and older wood frame buildings showed evidence of having been seismically retrofitted. For these structures, the most common retrofitting schemes consisted of tying the walls to the floor diaphragms. In some cases, stiff elements, such as reinforced concrete walls and braced steel frames, were used to retrofit URM buildings. Retrofitted structures generally performed well. However, many unretrofitted URM structures also showed no sign of brick damage. Examples of the performance of retrofitted buildings are provided below.

A six-story URM structure in Seattle was retrofitted by epoxy grouting the walls back to the slabs of the bottom two stories. The other floors were unoccupied. Brick was shed from the wall in only the top story, as shown in Figure 4.7.



Figure 4.7: Brick Wall Damage to Retrofitted Building

A nine-story URM, flat-slab-column building was retrofitted with steel frames, using a “life-safety” criterion, in order to protect the structure against collapse. Eccentrically braced chevron frames (EBFs) had been installed on the 3rd and 6th floors, with concentrically braced frames on the other floors. The EBFs showed paint flaking at the links that indicated yielding (Figure 4.8) in the east-west direction, but not in the north-south direction. No yielding was observed in the concentrically braced frames on the 1st and 5th floors.



Figure 4.8: Paint Flaking at Link of EBF in Retrofitted Building

The control tower at SeaTac Airport sustained damage. In 1973, the tower had been raised and the lower 4 stories were seismically retrofitted with structural steel braces. No damage was seen in those stories. However, the welds failed in the eight 5-in. steel tube mullions supporting the heavy glass and the roof of the control tower (Figure 4.9). Nonstructural damage, described in Section 4.6, also occurred. The cost of repairing the tower is expected to exceed \$2 million.



Figure 4.9: SeaTac Control Tower Mullion Fracture

4.6 Damage to Non-Structural Elements

Nonstructural damage interrupted service at large companies such as Boeing, Starbucks and Amazon.com, as well as at many small businesses. Service provided by city and state governments was interrupted.



Figure 4.10: Damage to Ceilings and Light Fixtures

Both interior and exterior non-structural elements were damaged. On the interior, damage to ceiling finishes, wall finishes, windows, partitions, electrical and mechanical fixtures, piping, and building contents was common (Figure 4.10). Exterior masonry walls also suffered. Non-structural damage was observed in new and retrofitted buildings as well as in older, unretrofitted buildings.

Damage to ceiling finishes included cracking in drywall, spalling of plaster, and damage to acoustical tile. Buildings at the Boeing campus sustained ceiling damage, damage to windows, and water damage, which resulted in an interruption of service. Fallen ceilings at a number of schools prompted temporary closure. 75 out of 96 Seattle schools reported some damage.

Pedestrian walkways were damaged, affecting building access. On the Boeing campus in Renton and in State Capitol buildings in Olympia, damage was observed at connections between the pedestrian bridges and buildings.

Damage to electrical and mechanical fixtures was observed in new and old buildings. In some buildings, damage to sprinkler systems and piping resulted in building closure. In a 9-story URM building that had been seismically upgraded, building closure was primarily due to damage to electrical fixtures and water damage.

Nonstructural damage at critical facilities impacted service. Damage at SeaTac Airport was extensive and reduced service to approximately 50% of normal capacity. The North Satellite Terminal was closed for a day as a result of water damage. Damage to Terminal C included damage to ceiling tiles and light fixtures. Pounding between the wings and the main terminal building also caused internal damage.

Damage to building contents was also widespread and problematic. Libraries as far north as the University of Washington (UW) were closed as a result of damage to bookracks (Figure 4.11). Large in-plane displacements of the racks were common. When implemented, bracing of the racks out-of-plane prevented displacements in that direction.

A complete assessment of the damage sustained by hospitals is not yet available. However several sustained significant interior damage and damage at connections between buildings. Nonetheless, Hospital function was not interrupted significantly.



Figure 4.11: Bookshelf Damage and Loss of Shelf Contents, UW Engineering Library

5 Bridges

The Nisqually earthquake affected bridges over a large area. For example, thirty miles south of the epicenter, a bridge in Chehalis (I-5) was closed temporarily because of damage to its bearings. Fifty miles northeast of the epicenter, the Tolt Hill Bridge remains closed one week after the earthquake. Based on initial inspections, the Washington State Department of Transportation (WSDOT) identified approximately 40 bridges that had suffered some damage. The City of Seattle Engineering Department reported that 22 of its bridges had been damaged. A number of other city and county agencies identified additional damaged bridges, including one owned by King County that remains closed.

In most cases, the damage to the affected bridges was light, and the bridge function was interrupted only temporarily or not at all. Damage to superstructures included cracking and spalling at expansion joints; spalling or collapse of railings; and at least one failure of a restrainer system. No spans collapsed. Damage to substructures included bearing damage, as well as cracking and spalling of columns and abutments. In a few columns, shear cracking was observed.

Four bridges that suffered substantial damage are described in the sections that follow. Two of these bridges were in poor condition before the earthquake. Three of the four were constructed before the early 1980s, when WSDOT increased their requirements for seismic design

5.1 Pre-1980 Bridges with Severe Damage

Holgate Street Overpass (Seattle)

The Holgate Street overpass over I-5, constructed in 1965, is located approximately one mile south of downtown Seattle. Its vertical alignment requires the bridge to have a steep grade, dropping approximately 50 ft from the freeway to its termination at the west abutment. The section west of I-5 is supported on columns of various lengths to accommodate the grade.

The shortest column, closest to the west abutment, failed in shear (Figure 5.1). During the earthquake, the cover spalled over the central half of the column height on the north and south sides. No signs of plastic hinging were observed at the



Figure 5.1: Shear Failure of Short Column of Holgate Ave. Overpass over I-5

top or bottom of the column. The column was permeated by diagonal cracks, indicating shear deformation in the east-west direction.

The failed circular column has a diameter of 4 feet and a clear height of 13 ft. It is reinforced longitudinally with #14 bars at 5-in. centers around the perimeter and #4 hoops at 12-in centers over the column height. The hoops have 24-in. laps.

The hypothesis of an east-west shear failure is supported by the abutment configuration and the damage observed to the bearings. At the abutment, 6-in. diameter steel roller bearings equipped with alignment pins allow nearly free motion in the longitudinal direction (east-west) so, in this direction, the short column was the stiffest support. The southernmost bearing experienced excessive longitudinal movement, causing the pins to come out of their sockets. In the transverse (north-south) direction, the relatively stiff west abutment appeared to have protected the column from large deformation demands.

The ramp was closed initially, but WSDOT re-opened the bridge a few days after the earthquake.

4th Avenue Bridge (Olympia)

The 4th Avenue Bridge (Fig. 5.2) in Olympia consists of three spans of arches and approximately fifteen spans of reinforced concrete frames. It was constructed in 1920 and retrofitted after the 1949 Earthquake. Even before the 2001 earthquake, this bridge had significant cracking and spalling, and had been scheduled for replacement.



Figure 5.2: Collapsed Railing on 4th Avenue Bridge

Other than partial collapse of the concrete bridge railings on both sides of the bridge during the earthquake, the arch spans suffered little new damage. The reinforced concrete frames sustained much heavier damage. The tallest columns (nearest the arches) spalled near the bottom of the top flare, and cracks appear to have widened in beams near the ground level. The most potentially catastrophic damage was the formation of shear cracks near the corbels at the top of some of the shorter columns (Fig. 5.3).

Magnolia Viaduct (Seattle)

The Magnolia Viaduct carries traffic from the residential district of Magnolia, over Piers 90 and 91 of the Port of Seattle, to Elliott Avenue West. Before the earthquake, the structure carried an average daily traffic of 18,000 vehicles per day. The bridge was severely damaged during the earthquake and was closed immediately.

The viaduct runs approximately E-W for about half a mile long and, at the west end, it is supported on piers that range up to approximately 80 ft in height. Over much of its length, it is founded on fill. Although the original reinforced concrete structure was built in 1929, two major retrofits, which added steel bracing, have taken place since then. The substructure consists of reinforced concrete bents that contain horizontal and diagonal bracing. The octagonal columns contain spiral confinement reinforcement, but the horizontal and diagonal braces (reinforced concrete T-sections) contain little confining steel. The braces have corroded over the years and have been patched extensively. Sets of three bents form longitudinal frames, which are separated by expansion joints. Each frame is braced longitudinally by a reinforced concrete system.



Figure 5.3: Shear Crack at Top of Column of 4th Ave. Bridge

The majority of the damage occurred in the transverse reinforced concrete braces. All the diagonal members slope upwards towards the south. Since they likely have different properties in tension and compression, the structural system should be expected to have an asymmetrical response. The bars in many of the braces yielded in tension, and when the load was reverse, they buckled in compression. The widely spaced transverse reinforcement facilitated buckling. Many bars exhibit significant corrosion, some are smooth round bars (even in the primary reinforcement) and all have scant transverse tie steel. The corrosion has led to loss of cover over extensive regions of the members, resulting in main bars that are now exposed and unsupported.

The columns appear to have suffered little damage due to either seismic forces or corrosion.



Figure 5.4: Magnolia Viaduct



Figure 5.5: Damaged Brace in Viaduct

5.2 Post-1980 Bridge with Significant Damage

The most recently constructed bridge (early 1990s) to sustain significant damage was the Fourth Avenue on-ramp to I-90 in Seattle. At Sixth Avenue, the on-ramp has an in-span expansion joint and sliding bearings. The bearings were apparently designed to carry vertical loads and allow longitudinal expansion. Guide bars were provided to restrain transverse displacements.

As shown in Figure 5.6, damage to this joint consisted of spalling of concrete on the north and south top corners of the bearing seat, which exposed some reinforcement. Bearing seat damage resulted from transverse shear forces, which failed the studs that connected the masonry plate to the concrete seat. The failure of this detail, which had been previously identified as vulnerable, led to closure of the bridge.



Figure 5.6: Joint Damage to Fourth Ave. Onramp

6 Lifelines

Lifeline systems, with the exception of airports, performed remarkably well during the event and the impact of lifeline damage was in most cases minimal. Lifelines include water, wastewater, electrical power, communications, natural gas and liquid fuels, and transportation systems. The systems are made up of many links and nodes, distributed over a large area. The buried pipelines that make up much of water, wastewater, gas, and liquid fuel systems are often heavily damaged due to liquefaction and lateral spreading. However, in this earthquake, the lateral spreading in urban areas was limited, so pipeline damage was minimal.

6.1 Water Supply

Damage to water supplies was minimal. The cities of Seattle and Tacoma, the two largest suppliers in the area, reported minimal damage to their systems. Both systems were operational immediately after the earthquake and maintained service in the days following it. The two systems combined are believed to have suffered no more than 20 pipeline failures. This number may be compared with more than 1,000 pipeline failures in each of the Northridge and Kobe earthquakes if the different magnitudes of the events are taken into account. Some of the pipeline failures were in the liquefiable soils in Seattle near the Duwamish River. By contrast, the City of Kent, which has an extensive pipeline distribution system in the highly liquefiable soils of the Kent/Green River Valley, reported no damage. This lack of damage was surprising to lifeline researchers. Neither system reported damage to either in-town terminal reservoirs or steel tanks.

Damage to water supply systems included damage to the Dexter Horton Building, which houses many of the Seattle Public Utilities staff. This building is yellow-tagged, and remains closed.

Seattle reported a 500-foot long crack in the Cascades Dam at Lake Youngs.

Steel standpipe anchorages fractured (Figure 6.1), and braces to elevated tanks were damaged in water systems in the Tacoma area and on the Kitsap Peninsula. In one case, a standpipe, designed to modern AWWA standards, suffered anchor bolt damage.

Many systems reported power failures. However, power was generally restored within 4 to 6 hours, and did not seriously impact service.

A boil water order was instituted in



Figure 6.1. Broken anchor strap on 450,000-gallon water standpipe.

Snoqualmie due to turbid water. The McAllister Springs supply serving Olympia was also turbid for a period following the event, but the system otherwise maintained operation, undamaged.

6.2 Wastewater

Wastewater treatment facilities were essentially undamaged; however, disruption of power supply impacted these systems. King County Wastewater facility provides treatment for much of the Seattle region. It experienced a small discharge of untreated sewage, caused by an automatic shutdown of pumps, at the West Point Plant, but the plant returned to full operation after the event. The Tacoma Central Wastewater Treatment Plant, located adjacent to the Puyallup River in the Tacoma tide flats, was undamaged with the exception of one crack at a construction joint in a building. Emergency generators were brought on line when power to the site failed. The Pierce County wastewater system, which serves the area south and east of Tacoma, reported no significant damage.

6.3 Electrical Power

The impact of the Nisqually Earthquake on power supplies was minimal. The Bonneville Power Administration service, which provides much of the power to the region, was not interrupted. Their high voltage system (500 and 230 kV), including the 500 kV substation in the Tacoma tide-flats, suffered only minor damage. The peak acceleration in the area was on the order of 6% of gravity. By comparison, in the Northridge Earthquake, damage to high voltage equipment caused extensive regional power outages in the hours following the earthquake.

Seattle City Light reported 17,000 customers without power, and Puget Sound Energy reported 200,000 customers without power due to tripped circuit breakers, immediately after the earthquake. By 5:30 pm on the day of the earthquake, fewer than 8,000 customers were without power. Most power outages were in South King, Pierce and Thurston counties.

6.4 Communications

At least two users of the King County 800 MHz radio system reported that it was only partially functional on the day of the earthquake. That system is intended to provide reliable communications in disaster situations.

Wire and wireless communications were overloaded for the 24 hours following the earthquake. In the first few hours, the Internet provided a reliable means of communication. AT&T had rejected 7 million calls from outside the area as of mid-day on March 1. Voice mail service was interrupted in some locations through March 2.

6.5 Fuels

Puget Sound Energy distributes gas with regional transmission from the Williams Pipeline Company. Only one gas line leak was reported. A natural gas line explosion at Cedar Creek Correctional Center near Olympia injured two workers who had been resetting the line's earthquake valve.

Olympic Pipeline feeds liquid fuels to the region from the north. The pipeline was not damaged and was returned to operation after inspection.

Equilon Corporation on Harbor Island in King County reported a 1,300-gallon spill of diesel and gasoline.

6.6 Transportation

Earthquake damage significantly restricted air transportation in the Puget Sound region. All windows but one in the SeaTac Airport control tower broke (Figure 6.2). Currently, controllers are using a portable control tower with the result that capacity is limited to 24 flights per hour, down from the normal 40 per hour. Airport control towers are particularly vulnerable to seismic forces, because the need to have a nearly unobstructed 360-degree view limits the extent of the structural support that can be provided.



Figure 6.2. SeaTac Airport Control Tower Showing Broken Glass and Light Fixture Hanging from the Ceiling

Paine Field in Everett.

The North Satellite Terminal (home to United Airlines) was closed on February 28 as a result of water damage, but it was reopened on March 1.

At Boeing Field (King County International Airport), liquefaction resulted in a one-foot settlement on the runway that closed the facility to heavy traffic indefinitely. Many of the freight carriers serving Seattle are based at Boeing field, so this could have an impact on business. At least one carrier has relocated operations to

Sound Transit commuter trains remained operational, but Amtrak service was interrupted for a day. The BNSF suffered only minor track alignment problems, and resumed operation on the afternoon of the earthquake. 88 trains were delayed. There are unconfirmed reports of damage to a significant length of UPRR track in the Nisqually delta region.

The Washington State Ferry Terminal at Colman Dock in Seattle was closed on February 28, but reopened on March 1. Structural damage included some minor cracking in reinforced concrete columns and a 6-in. settlement in one area of the dock where cars queue for loading. Nonstructural damage to the system was incurred when the computer that ran the GPS for monitoring the position of ferries fell to the floor.

The Port of Tacoma reported buckled pavement and structural damage to three buildings, but neither Seattle nor Tacoma reported interruption of port service.

Bridge and road damage has closed highway segments in Seattle and Olympia, as well as in more rural areas. Two notable closures are the Magnolia Bridge in Seattle and the Deschutes Parkway and 4th Avenue Bridge in Olympia. The Magnolia bridge closure is impeding access to the Magnolia neighborhood. The Olympia closures severely restrict access to downtown Olympia from the south and west.

7 Governmental Response and Socio-Economic Aspects

7.1 Overview

Four considerations that stand that are related to the governmental response and socio-economic aspects of the Nisqually Earthquake: (1) the relatively small number of injuries and the limited demands placed on the emergency and post-event shelter and recovery systems; (2) the successful workings, at multiple levels, of the governmental response; (3) the dominating impact of business disruption, including the business of government; and (4) the uncertain implications of the event for societal concern about future earthquakes. While efforts to retrofit structures mobilize partnerships for seismic safety, and while raised awareness of earthquake risks in the region undoubtedly had a role in reducing harmful impacts, the report card for the effectiveness of these efforts should be considered incomplete.

7.2 Impacts: Injuries and Damages

As with any earthquake, the statistics about impacts of the event will likely change over time. What follows is based on statistics reported by official sources during the days immediately following the event. Reported injuries consist of one death (due to a stress-related heart attack at the time of the earthquake) and some 400 injuries, of which four are reported to be serious. From the six affected counties, statistics for damage to single family homes and apartments include 4 destroyed, 46 with major damage, and 120 with minor damage. Comparable statistics from the American Red Cross list 110 destroyed and 126 with major damage.

The most noteworthy affected sector has been the governmental sector with some 20 state buildings closed for several days for inspection, clean up, and repair. Similar disruptions occurred in governmental functions for several cities and counties. The State Capitol, housing legislative chambers and offices of the governor and other state officials, is likely to remain closed more than a week for inspection and immediate repair, followed by indefinite limited access. Damage to one of the state's key facilities for mental patients resulted in the relocation of 239 patients to another location. One prisoner escaped at the time of a county court appearance.

Some 125 persons have been reported as being displaced from their homes or apartments, mostly in Olympia. That number includes the state Governor and his family, who relocated to their house in Seattle after the governor's mansion was damaged. Five shelters were opened and initially housed 28 persons. One remained open after a few days, and all were closed within four days after the event.

Perhaps the most striking aspect of the damage from this event is the lack of the secondary effects that have been notable in recent urban earthquakes in the United States. Only one fire in an older building in downtown Seattle was reported by news media. There were no reports of notable hazardous materials incidents. Power was out to some 200,000 customers in the region, but was restored in a matter of hours for all but some 1,200 customers. Only water damage, largely related to nonstructural failures within buildings, can be cited as a noticeable secondary effect.

7.3 Governmental and Societal Response

Although the emergency and healthcare response systems were not highly stressed by this event, they seemed to work quite well. State and affected cities and counties were able to quickly mobilize their emergency operations centers, the relevant healthcare facilities quickly moved into crisis response mode, and relevant mayors and county executives rapidly declared emergencies. The only reported disruption to emergency services was a temporary outage of the 9-1-1 system in King County while calls were being switched over at the time of evacuation of the main center (due to damage to the center). The governor declared a state of emergency shortly after the event and requested federal assistance a day later. It was granted within hours and a federal disaster declaration was issued for six affected counties.

One of the unique aspects of the governmental response and recovery was the extent to which several jurisdictions made use of the Internet to post key information about the event, press releases, and information for employees. This served as a valuable resource to those affected by the closures of schools and employment.

The societal response was typical of that found after earthquakes. Phone lines were jammed with the local provider reported a 600 percent increase in both wire and wireless calls. Highway systems in the Puget Sound area were jammed as many people left work and went home. Many turned to the Internet when calls could not go through; the press cited MSN Hotmail as having 5 million more emails than normal on the afternoon of the earthquake. Internet chat areas were quickly dominated with individuals reporting their experiences during the earthquake.

7.4 Value of Damages and Economic Impacts

As is common after major earthquakes, the value of damages and their economic consequences are at best tenuous guesses for a number of weeks if not months. Within two hours of the event, FEMA, using HAZUS, produced estimates of potential economic losses of \$3.9 billion (with 26 potential deaths and 2,600 injuries). Other analyses, using HAZUS and different event assumptions, placed potential economic losses at \$2 billion. Within a few hours of the event, press accounts cited figures of \$1 billion worth of losses; the next day that figure that was revised upward to \$2 billion. The source of these estimates and the assumptions behind them are unclear. Preliminary damage estimates produced after initial inspections placed repair costs to SeaTac airport at \$30 million and

to highways and other transportation facilities at \$86 million. As of three days after the event, the estimates for repairs total over \$1 billion.

Many major employers suspended operations for a day or two but escaped with relatively minor losses. Business interruption arose largely from nonstructural and contents losses, from damage inspections, cleanup and initial repair. Some of the large businesses were able to contain losses by various work adjustments. Amazon.com sustained nonstructural building damage and temporarily closed its warehouse and customer service center in Seattle; however, it rerouted calls to out-of-state facilities and encouraged employees to telecommute. Because its website was unaffected, the company anticipates minimal financial impact. Microsoft closed one office building for several days and temporarily relocated 400 employees to other buildings. The Port of Seattle suspended cargo handling at two terminals for inspection and diverted ships to its other terminals. The Bon Marche closed one department store for two days due to water damage. Starbucks had to close its headquarters building, but was able to shift employees to a nearby facility. Headquarters functions were interrupted because water damage necessitated shutting down electric power and access to telephone and computer systems, but within a day makeshift measures to continue operations were put in place.

Boeing suffered greater business disruption due to damage at both its production facilities and Boeing Field. Most of its 90,000 workers in the Puget Sound region were sent home on the day of the earthquake. Some 80 percent returned to work within two days. The remainder, including employees at some of the Renton 737/757 plant, buildings, and corporate headquarters, were expected to be back five days after the event. Damage to the runway and control tower at Boeing Field will likely result in some of the Renton area work being diverted to Boeing's Everett and possibly Long Beach, California, facilities. One older building in Renton may need to be demolished. The company expects only slight delays in airplane deliveries and minimal financial impacts.

In contrast to other recent earthquakes, airport disruption is likely to be one of the main sources of business interruption loss in this event. Boeing Field handles not only Boeing aircraft in production but also small planes and much of the air cargo for the region. Carriers such as UPS and Airborne Express were forced to divert operations to SeaTac and Portland. Estimates for restoring full service at Boeing Field range from 3 to 6 weeks. SeaTac, the main passenger airport in the region, was closed for several hours. Aside from water and nonstructural damage in the terminals, the control tower suffered major nonstructural and possibly structural damage that may require 6 to 8 weeks to repair. Service was reduced by half in the first couple of days, but with an elevated temporary control tower in place, it is expected to return to 90 percent capacity within a week of the event. Flights suffered major delays in the initial few days after the earthquake.

This event underscores the role of nonstructural damages and business interruption in contributing to economic losses. While structural damage to businesses was very limited, the majority of business interruption appears to have been caused by widespread nonstructural damage, and by disruption due to inspection, and cleanup. In addition to

examples cited above, closure for inspection of the Alaskan Way Viaduct and other bridges caused major traffic delays. Such losses are typically overlooked in traditional earthquake loss models. They are also missing in tallies of losses from building inspection, insurance, and other sources of loss information.

The distribution of payments for losses among insurance, federal, and state sources will depend on the nature of the claims that are made and their eligibility for funding. Press accounts cite reinsurance firm estimates of likely insurable damages at several hundred million dollars. The degree of insurance coverage by affected businesses is at present unknown. Insurance companies estimate that some 12 percent of homeowners in the affected area have earthquake insurance coverage.

Noted above are the impacts to the governmental sector. While limited to a few days disruption of the business of government for most state agencies, there are still significant disruptions of legislative functions. Citizens and state vendors have also been affected by delays in processing of social and health payments. One key research question is how to place an economic value on the disruption of the business of government.

7.5 Societal Implications

The Nisqually earthquake might be considered an acute trauma from a societal perspective. It has been taken seriously by elected officials and has dominated the news for several days after the event. The tailing off of press coverage has occurred more slowly than after other recent, smaller earthquakes in the region. Elected officials and the media have done a generally good job in trying to understand the basis for the event and why this particular occurrence is very different than earthquakes in California.

There is a variety of anecdotal evidence that the investment in retrofitting of structures, in mobilizing partnerships for seismic safety, and in raising awareness of earthquake hazards in parts of this region did play a significant role in reducing potential harmful impacts. However, some have been perhaps too quick to claim success for these efforts on the basis of this event. The report card is more appropriately labeled as incomplete due to insufficient testing. Or, at least, more investigation needs to be undertaken as to the extent to which the Nisqually earthquake served as a test of the seismic integrity of buildings, lifeline, and other systems.

This earthquake has the potential for reawakening citizens and officials to the prospects for more damaging events. Yet, some of the media and official commentary have overly simplified the comparisons between this event and similar magnitude events like the Northridge earthquake, which, because of source and site characteristics, had very different shaking intensity. In this regard, the much lesser damage from this event has the potential for lulling citizens and officials into a false sense of security concerning seismic safety. As such, the societal implications of the Nisqually earthquake for concern about seismic risk in this region are uncertain.

8 Summary and Conclusions

The following preliminary conclusions can be drawn from the information in this report:

- A magnitude 6.8 earthquake struck the Puget Sound region of Washington State at 10:54:32 a.m. local time, February 28, 2001. The earthquake's epicenter was located near the Nisqually delta area of southern Puget Sound, at 47.149N, 122.727W and 52 km depth. Ground motions were moderate, with most strong motion recording stations showing peak ground accelerations of less than 0.2g.
- This type of earthquake (Wadati-Benioff zone earthquake) is one of the three characteristic event types already considered in current seismic hazard assessments for the region.
- Geotechnical damage was unexpectedly light in many areas; a number of soil deposits considered highly susceptible to liquefaction showed little or no evidence of ground deformation. Nonetheless, permanent ground deformations included landslides on the order of 100 ft.
- Damage to structures, lifelines, and other facilities was correlated to soil conditions, with most damage occurring in areas underlain by loose, saturated soils.
- Structural damage to buildings was not widespread. Modern buildings and those that had been recently seismically upgraded performed well structurally. Most of the structural damage to buildings occurred in older, unretrofitted, unreinforced masonry structures, or on structures founded on soft soils.
- Significant non-structural damage was observed in all types of buildings.
- With at least one exception, significant damage to bridges was limited to older structures. Most bridges suffered only minor damage and were not closed for a significant length of time.
- Lifelines in general performed well. Damage to airports caused some of the most significant interruptions to service in the region.
- Emergency and healthcare response systems were not highly stressed by this event, and they seemed to work well.
- The retrofit measures that have been undertaken over the past decade, in both buildings and bridges, undoubtedly reduced the amount of damage and loss of life that would otherwise have occurred. However, many unretrofitted structures were undamaged as well.

- While structural damage to businesses was relatively limited, nonstructural damage and the associated business disruption caused significant economic losses.

The damage and economic loss that occurred demonstrate that continued retrofit and disaster planning efforts are essential. This earthquake is not the largest event possible in the Puget Sound area. Citizens and officials should not be lulled into a false sense of security concerning seismic safety.