

# WASHINGTON STATE'S BRIDGE SEISMIC RETROFIT PROGRAM

## Abstract

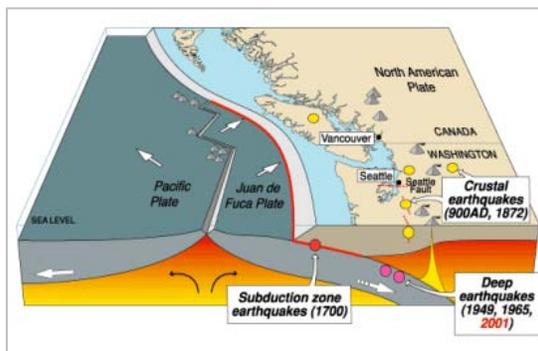
Earthquakes pose a serious risk to life and infrastructure in Washington State, particularly the Puget Sound region. Recognizing the earthquake risk to State owned bridges, the Washington State Department of Transportation (WSDOT) developed a bridge seismic retrofit program to address bridges that do not meet current seismic response design standards. The program is divided into three phases: Phase 1 addresses simply supported bridges and bridges with in-span hinges; Phase 2 addresses Major bridges and bridges with single column supports; Phase 3 addresses bridges with multiple columns. Nearly \$100 million has been spent to date to seismically retrofit bridges in high-risk zones that include: 191 bridges completely retrofitted; 15 bridges in progress; 716 bridges remaining.

## Washington State Facts and Earthquake Risks

Washington State has a variety of geographic features from the Pacific Ocean to the Cascade Mountains to the open Plains on the eastern side. The region that surrounds Seattle is known as the Puget Sound. Most of the seismic vulnerable bridges with high life-line importance are located in Western Washington and are concentrated near the metropolitan areas.

The State's total population is nearly 6.2 million with the largest city, Seattle, having a population of 572,600. The population of the three counties in the vicinity of Seattle is 3.2 million. The ports of Seattle and Tacoma are located in the Puget Sound Region and annually move more than half of all goods shipped internationally from the state (\$57 billion of the state's \$107 billion in 2001).

Washington is situated at the boundary between two tectonic plates. The Cascadia subduction zone, which is the convergent boundary between the North America plate and the Juan de Fuca plate, lies offshore from northernmost California to southernmost British Columbia. The two plates are converging at a rate of about 3-4 centimeters per year (about 2 inches per year). The northward-moving Pacific plate is pushing the Juan de Fuca plate north, causing complex seismic strain to accumulate. Earthquakes are caused by the abrupt release of this slowly accumulated strain.



WASHINGTON SEISMIC HISTORY MAP

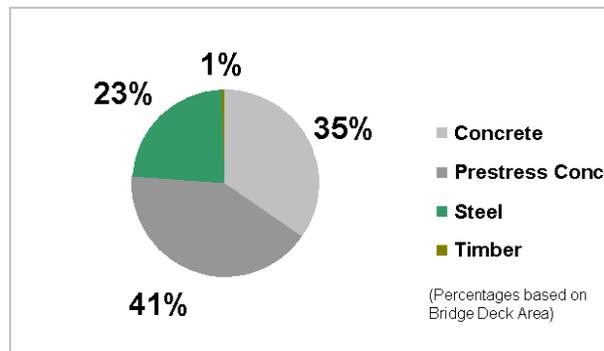
More than 1,000 earthquakes occur in the state annually. At least 20 damaging earthquakes have occurred during the past 125 years. Large earthquakes in 1949, 1965 and 2001 killed 15 people and caused

significant property damage. The most recent damaging earthquake was the 2001 Nisqually event, which caused one death, 320 injuries and over \$2 billion in damage.

A 2001 study by the Federal Emergency Management Agency found that Washington has the second highest risk of economic loss caused by earthquakes in the nation, behind only California. Recently, geologists have uncovered active surface fault zones near Seattle that are capable of generating major earthquakes in the Puget Sound region. The Earthquake Engineering Research Institute and the Washington Emergency Management Division summarized a Scenario for a Magnitude 6.7 earthquake on the “Seattle Fault” in a report published in June 2005.

### Washington State’s Bridge System

WSDOT is responsible for nearly 3,000 vehicular bridges on state owned highways. The bridges on state highways are made of either: concrete, prestressed concrete, steel or timber. Timber was generally used for bridges built prior to the 1950’s and represent 1% of the total. Steel has been used in both short and long span bridges and consists of 23% of the total. Concrete is the most common material used and represent 74% of the total number of state bridges. The average age of a state owned bridge is 39 years.



WSDOT BRIDGES – MATERIAL TYPES

Nationally, the American Association of State Highway and Transportation Officials (AASHTO) adopted the first earthquake bridge design criterion in 1961. Modern seismic bridge design practice began in the mid-1970s after the 1971 San Fernando, CA earthquake. Significant improvements continued in 1983, followed by complete incorporation of new standards into the design code in the early 1990s. WSDOT’s seismic retrofit program addresses those concrete and steel bridges built from 1940 to 1983 that were constructed prior to current seismic design standards.

Many State bridges were constructed as part of the national interstate program that began in the 1950s. Interstate routes 5, 90 and 405 are the three primary interstate routes in the Puget Sound region that carry a large volume of the daily traffic. Many of these bridges were constructed prior to the current seismic design standards.



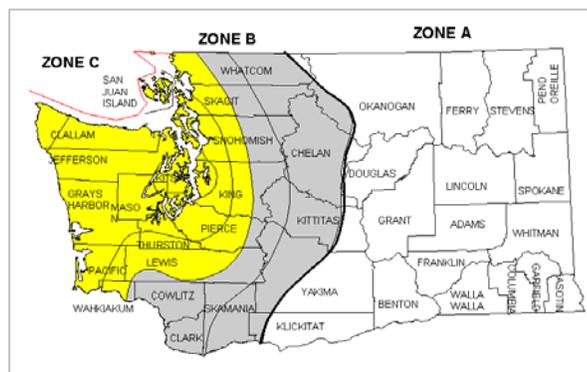
In the Seattle vicinity there are several major bridges on primary state routes. One of these is the Alaskan Way Viaduct on State Route 99. This

2 mile long structure was completed in 1953 and has an average daily traffic of 103,000 vehicles. Several studies and research projects have summarized the many seismic deficiencies and high risk of damage for this structure. In 1990, it was recognized that WSDOT's Seismic retrofit program would not include this bridge based on the high cost of retrofit and/or replacement.

## Program Summary

A Bridge Seismic Retrofit program in Washington State was developed by the Bridge and Structures Office in 1990 to address the seismic vulnerability of state highway bridges.

WSDOT uses a map to identify different seismic zones with peak ground accelerations (PGA) in Washington based on USGS information. "Zone C" is considered "High Risk" and covers the area with PGA greater than 0.20 times the force of gravity. "Zone B" is considered "Moderate Risk" and contains an area of PGA between 0.10 and 0.20 times the force of gravity. "Zone A" is considered "Low Risk" and contains an area of PGA less than 0.10 times the force of gravity.



**WSDOT SEISMIC ZONE MAP**

The bridge seismic retrofit program is based on the following objectives following a seismic event:

- Minimize risks of bridge collapse.
- Prioritize projects to minimize loss of life and disruption to commerce.
- Accept moderate damage.
- Make optimum use of available funding by addressing lower cost/highest benefit superstructure seismic retrofit needs first and follow with substructure retrofit needs.

To meet these objectives, bridges within the highest seismic risk area (old Zone C) were evaluated in 1990. These bridges are primarily located in the counties adjacent to Puget Sound region. Bridges located in the moderate seismic risk area (old Zone B), were screened and evaluated in 1994. The Bridges located in the lowest seismic risk area (old Zone A) have not been evaluated and have been excluded from the program.

The evaluation process included the following:

- Review of Zone C and B bridge plans.
- Identification of all seismic structural vulnerabilities.
- Development of a seismic retrofit prioritization methodology.
- Evaluation of retrofit techniques.
- Development of retrofit strategies and cost estimates.
- Development of a database to manage the program.

Bridge retrofit needs have been prioritized by first establishing groupings of bridges by the nature and extent of structural deficiencies. Then the bridges have been ranked according to the importance of the bridge. For superstructure retrofit ranking, Groups 1 and 2 were ranked together. For substructure retrofit ranking, Group 3 was ranked, then Group 4.

Bridges are placed in one of the following groups according to their structural deficiencies:

<u>Superstructure Group</u>	<u>Type of Deficiency</u>
1.	Bridges with in-span hinges.
2.	Bridges simply supported at piers.
<u>Substructure Group</u>	
3.	Bridges with single-column piers.
4.	Bridges with multi-column piers having substructure deficiencies.
<u>Major/Special Bridges</u>	Bridges that require further structural analysis to assess whether seismic retrofit is warranted. These are essentially large or unusual type structures

### **Structural Vulnerability**

The seismic risk associated with each bridge site was evaluated in terms of ground acceleration and type of foundation material. The vulnerability of the structures themselves was evaluated for adequacy of superstructure support length and apparent capacity of supporting elements. The structural details evaluated consisted of the following: Structure Type, Bearings, Type of Restraint, Pier Type, Column Type and Details, Column-to-Footing Anchorage Details, Footing Type, Abutment Type

Collapse of a superstructure is typically related to inadequate support length which allows the superstructure to fall off its supports or failure of an in-span hinge. The demand-to-capacity evaluations for support length have been determined using the

criteria specified in the FHWA's 1983 Seismic Retrofit Guidelines for Highway Bridges, and 1987 Seismic Design and Retrofit Manual for Highway Bridges.

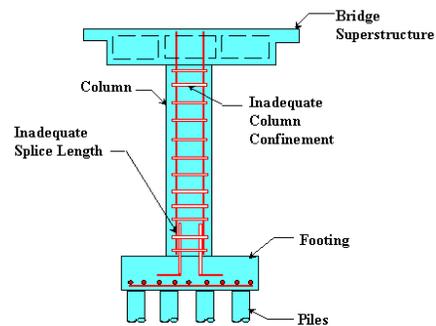
In-span hinges are considered to be the highest seismic retrofit priority because of the potential for collapse during relatively modest earthquakes. There are ten basic types of in-span hinges that have been used on state bridges. Most hinges have less support length than required by current AASHTO standards. Some superstructures with in-span hinges could collapse due to greater than designed movement, and others would only be susceptible to collapse if the hinge were to fail structurally; both types of deficiencies required retrofit to ensure structural safety.

Bridges that are simply supported at piers or abutments are vulnerable where the support length is inadequate and adequate restraint is not provided in either the longitudinal and transverse direction.

Bridge design criteria and structural details to accommodate dynamic seismic loading have changed dramatically over the past 20 years, based largely on lessons learned from earthquakes in California like those that occurred in 1971 at San Fernando and in 1989 at Loma Prieta.

The principal areas of substructure deficiency of older bridges when compared to current design criteria are as follows:

1. Inadequate confinement reinforcement for main longitudinal reinforcing steel in concrete columns.
2. Inadequate splice length of main longitudinal column reinforcing to footing dowels.
3. Inadequate development length of footing dowels (footing embedment).
4. Absence of reinforcement in the tops of footings.
5. Inadequate footing support capacity.



**TYPICAL COLUMN DEFICIENCIES**

The first three items were easily identified by a review of the bridge plans. Splice and confinement reinforcing, design, and detailing practices have changed so significantly that vulnerability is more of a yes or no determination rather than a degree of deficiency. The same is true of reinforcing in the tops of footings. Footing support adequacy is a function of the column retrofit scheme selected and existing footing's capacity to withstand the forces from a design earthquake. Footing retrofit techniques are expensive relative to the cost of retrofitting superstructures and columns.

Bridges with substructure deficiencies have been divided into the following priority groups:

- Bridges with single column piers.
- Bridges with multi-column piers having one more types of substructure deficiencies.

## Retrofit Techniques

### Superstructure

The design criteria and nature of the retrofit construction details have continued to improve through lessons learned from earthquakes of the past three decades, and the vast amount of research and physical testing performed in California, Washington, and throughout the world.

Techniques for restraining longitudinal and transverse movement of bridge superstructures typically include various combinations of restraining bars, hold downs, and reinforced concrete stops and thrust blocks. Replacement or modification of vulnerable bearing types have also been done. Bridges requiring this work are essentially done.



**LONGITUDINAL  
RESTRAINER**

### Substructure

Past earthquakes and experimental tests have shown that concrete columns on pre-1983 bridges are vulnerable to brittle failure if exposed to a significant seismic event. Column jacketing permits ductile behavior of the bridge during an earthquake by providing additional shear capacity and confinement thus allowing the formation of plastic hinges at one or both ends of the column.



**COLUMN RETROFIT STEEL**

The primary material used by WSDOT to retrofit concrete columns is welded steel jackets. The process includes using two steel sections that are attached around a column and then welded together. Thickness of the steel jacket is determined by the size of the existing columns. Composite materials such as carbon fiber and fiber reinforced polymers (FRP) were installed on 9 bridges but was discontinued since the cost was 2 to 3 times more than steel.

## **Program Status**

Phase 1 (Superstructure Retrofits) – *Complete*

Phase 2 (Single Column Retrofits and Major Bridges) – *In Progress*

Bridges with Single Columns

- 99 bridges completed / 10 bridges with a project in progress / 51 bridges remaining (19 west of Cascades / 32 east of Cascades).

Major Bridges

- 18 bridges completed / 4 bridges remaining / 3 bridges excluded due to future replacement planned.

Phase 3 (multiple Column Retrofits) – *Future*

- 19 bridges completed.
- 605 bridges remaining.
- 2005 Transportation Partnership Program new revenue package funded retrofit on 172 of the 604 bridges in the Puget Sound region.

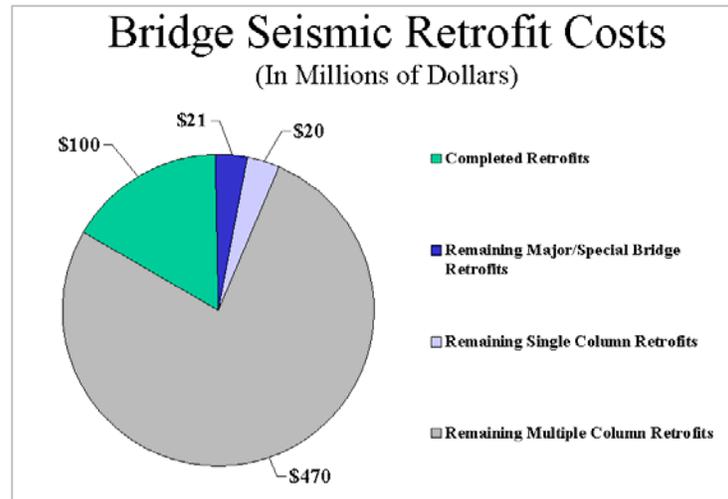
## **Program Numbers**

Total number of bridges requiring retrofit = 895

- Bridges Complete = 217
- In-Progress = 19
- Partially Complete = 153
- Remaining = 506 (Total Remaining = 506 + 153 = 659)

## Program Funding

To date the program has spent approximately \$100 million. Completion of the major bridges and bridges with single columns is expected to cost \$41 million. The current cost estimate for the final phase to retrofit bridges with multiple columns is estimated to be \$470 million. Future structural reviews and research may show that some of these bridges do not require retrofit thus lowering the total cost of this phase.



SEISMIC PROGRAM - FUNDING SUMMARY

Since the legislature's approval of the Seismic Risk Reduction Program in 1991, funding for the seismic retrofit, or replacement of the Alaskan Way Viaduct, Bridges with hollow core columns (which includes several bridges on SR520) or bridges with potential foundation risks such as liquefaction have not been included in the State's bridge seismic retrofit program.

### Funding History

- 1991 - The legislature approved funding for a systematic program to seismically retrofit bridges statewide. Funding was \$3 million a year.
- 1994 - The legislature increased funding to \$5 million a year, following the California North Ridge earthquake.
- 1997 - Funding was increased to about \$7 million a year for the 1997-99 biennium.
- 1999 - The Highway System Plan established a target of \$15 million a year funding level for the 1999-01 biennium.
- 2000 - The funding level for the remaining 1999-01 and 2001-03 biennium's was reduced to \$11 million per year following the passage of Initiative-695 which caused a reduction in the overall funding for statewide bridge preservation projects.
- 2003 - The funding level for the 2003-05 biennium was \$8.45 million per year.
- 2005 - The funding level for the 2005-07 biennium is \$4.65 million per year.
- 2005 - Transportation Partnership Program provides \$87 million to complete 172 "High" and "Moderate" risk bridges in the Puget Sound vicinity. This work would be completed in 8 years beginning July 1, 2007.

## Major Bridges

WSDOT has identified 25 bridges with unique structural features that required an in-depth analysis to determine the seismic vulnerabilities and possible retrofit options. All of these bridges have been reviewed and most have had some or all identified seismic retrofit work completed. One major bridge that has been excluded from any seismic retrofit is the Alaskan Way Viaduct.

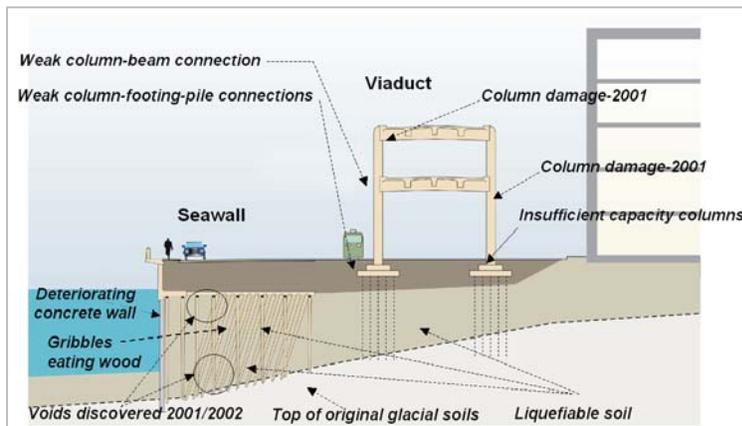
### State Route 99 - Alaskan Way Viaduct

Studies in the mid-1990s showed that the 1950s-era viaduct was nearing the end of its useful life. In early 2001, a team of design and seismic experts began work to determine whether it was feasible and cost-effective to strengthen the viaduct by retrofitting it. In the midst of this investigation, the 6.8 magnitude

Nisqually earthquake shook the Puget Sound region. The earthquake damaged the viaduct, forcing the Washington State Department of Transportation (WSDOT) to temporarily shut it down.

Post-earthquake inspections of the viaduct revealed both good and bad news concerning its condition. The good news was that the viaduct survived the 6.8 magnitude earthquake. The bad news was the earthquake caused damage to the viaduct's joints and columns, further weakening the structure and revealing its severe vulnerability. The team of experts concluded that it was not cost-effective to fully retrofit the majority of the viaduct; rather, the viaduct would need to be rebuilt or replaced.

Immediate repairs were made to four viaduct sections in the Pioneer Square area near S. Washington Street. WSDOT also imposed roadway restrictions that remain in effect today. These restrictions are for vehicles that weigh over 10,000 pounds. They include reduced travel speeds for large vehicles (from 50 miles per hour to 40 miles per hour) and require large vehicles to use only the right-hand lane of the viaduct. Ongoing inspections have revealed other increased cracks, exposed rebar, and weakening concrete; all signs that the viaduct is aging and continuing to deteriorate. Replacement of this structure is currently in the planning phase.



**ALASKAN WAY VIADUCT – VUNERABILITY AREAS**

## State Route 99 – George Washington Bridge

The George Washington Bridge is a long-span cantilever truss structure spanning the Lake Washington ship canal at the entrance to Lake Union in Seattle. The structure was designed and built between 1929 and 1931. The 800 ft. long main span is one of Seattle's longest and tallest spans and is currently registered as one of four Historic Bridges in King County. The bridge carries 6 lanes of arterial traffic averaging 73,836 vehicles a day. The Aurora Bridge has been designated as a critical emergency route and is considered an essential bridge by the Seattle Engineering Department Traffic Section.



**GEORGE WASHINGTON BRIDGE**

A “Seismic Vulnerability Assessment and Retrofit Concept Study” completed in 1995 identified areas of seismic vulnerability in the bridge and provided recommendations for a seismic retrofit project. This study recommended substructure retrofit that would have required significant soil removal and pier modifications that would have changed the esthetic look of the main bridge piers. In order to minimize work to the main piers, WSDOT initiated another study in 2001 to evaluate the use of new base isolation bearings. The total cost to complete all retrofit work was estimated to be \$12.4 million

WSDOT decided to address the seismic deficiencies in three separate projects due to the total retrofit cost. The first stage project added restrainers to the bridge and was completed in 2000 at a cost of \$2.1 million. The second stage retrofit work included replacing 24 existing rocker bearings with friction pendulum base isolation bearings. These bearings are designed to mitigate the deficiencies of columns at piers S-3 to N-3 (inclusive) and deficient members in the main truss spans. The expansion joints were replaced to allow greater movement in a seismic event. A couple of the lower cord truss members were also replaced. The second stage project was completed in 2004 at a cost of \$7.3 million.



**FRICTION PENDULUM BEARING**

The future stage 3 retrofit project will address the seismic deficiencies in the north and south approaches, which will include; strengthen concrete columns with steel column jackets, modifications to the longitudinal girders and floor beams. The estimated cost of this phase is \$3.0 million.

## Bridges with Prestressed Hollow Core Piles



**SR520 – EVERGREEN PT FLOATING BRIDGE AND APPROACHES**

There are 22 bridges on Interstates 5, 405 and State Route 520 that were built in the early 1960's that have precast/prestressed hollow core concrete piles. Hollow-core piles do not provide necessary ductility for high seismic loading, and have been generally discontinued from use in higher seismic hazard zones like the Zone C that is typical in western Washington.

One of the primary problems (non-ductile performance) occurs in the top several feet of the piles (a length equivalent to the pile diameter) where plastic hinging develops in the pile-to-pile cap connection. Tests performed to verify effectiveness of retrofits in this area have shown that while providing addition confinement and longitudinal reinforcing in this area improves shear capacity, it actually reduces pile ductility by driving the plastic hinging region to the mid height of the pile.

A second, and possibly more severe deficiency could result from spalling of the interior surface of the piles at fairly low lateral displacements and modest pile curvature (flexural rotation induced by lateral seismic loads). The concrete inner surface is unconfined and under compressive strains as low as 0.004, the concrete spalls. These thin walled piles (typically five inches thick on these circa 1960s bridges) rapidly loose vertical load capacity with any amount of spalling, unlike conventional solid columns which are indifferent to spalls so long as the concrete core and reinforcing that confines the main longitudinal steel are intact.



**TYPICAL PRESTRESSED CONCRETE HOLLOW COLUMN**

The results of a series of tests at the University Of California at San Diego tests on retrofitted and unretrofitted hollow core piles shows that displacements equal to that required to initiate yielding of the main pile reinforcing steel initiate cracking, and at 2.5-4 times that displacement a non-ductile failure, best described as instantaneous implosion, occurred. By comparison, WSDOT typically uses column retrofit methods that ensure ductile performance up to eight times yield displacement. There is no established method for effectively retrofitting hollow-core piles to improve ductile performance for high seismic loading.

## 2001 Nisqually Earthquake

On February 28, 2001 at 10:54 AM local time a magnitude 6.8 earthquake occurred on a normal fault on the Juan de Fuca plate. The epicenter was approximately 17.6 km Northeast of Olympia, 23.7 km SW of Tacoma, and 57.5 km SW of Seattle, Washington. The earthquake was named “Nisqually” due to its location near a prominent delta in the south Puget Sound Region. The location of the earthquake was very near a 7.1 magnitude event that happened in 1949. The Nisqually earthquake occurred deep below the earth’s surface with a depth of the hypocenter, approximately 52.4 km.



**I-5 BEACON-HOLGATE BR**

and four located in the Southwest region, near Centralia, Morton and Kalama. Reports poured in from the field – regional maintenance crews, traffic maintenance crews, state patrol, local police and jurisdictions – indicating where damage was suspected and which bridges had been closed.

It was soon determined that structures within a 73-mile radius of the epicenter would need to be checked, which translated to the inspection of 1,456 bridges. It was determined that 78 bridges had been damaged as a result of the Nisqually earthquake with the majority (46) of these bridges owned and maintained by WSDOT. The city of Seattle reported damage to eighteen bridges.

The numbers of bridges damaged based on their design type were: Reinforced concrete bridges (36); Prestressed concrete bridges (20); Steel bridges (16); Movable bridges (6). No damage was reported to timber or masonry bridges. The most common type of reported damage (48 bridges) consisted of concrete cracking and spalling. The Alaskan Way Viaduct sustained significant damage, which required temporary shoring. The total cost to repair the damage to state bridges was approximately \$5 million.



**ALASKAN WAY VIADUCT SHORING**

Throughout the department, at all levels, the focus was on rapid response to the emergency situation. In the first minutes, it was difficult to know the size of the earthquake or where it was centered and thus, the size of the emergency. It was clear that a major event had occurred and damage to the transportation system was likely.

Following the earthquake, nine state bridges were closed because of suspected damage. This included three bridges in Seattle, two in Bremerton

## **Research**

Considerable WSDOT sponsored bridge seismic research has been completed with a few projects still in progress. Much of the research has been conducted by the University of Washington and the Washington State University as part of the Washington State Transportation Center (TRAC). Their web page address is <http://depts.washington.edu/trac/>. A list of bridge seismic related research is available on the TRAC internet site through their searchable database.