Title: **Seattle Public Utilities - Water System Seismic Mitigation – The Sequel**

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Seattle Public Utilities – Water System Seismic Vulnerability Mitigation, The Sequel

William F. Heubach

ABSTRACT

Seattle Public Utilities (SPU) provides water to over 1.3 million people in the central Puget Sound area. Based on a 1990 seismic vulnerability assessment by Cygna Energy Services, many SPU water facilities were seismically upgraded. This assessment was focused on "vertical" facilities. Major transmission and distribution pipeline performance, and overall system response were only briefly considered.

Since 1990, earthquakes in Northridge, Kobe, Christchurch and the Tohoku regions, and hydraulic modeling done for a postulated earthquake in the Puget Sound regions have shown the effects that distribution pipeline failures can have on system response and recovery. Additionally, seismologists have determined that there are active surface faults running through the Puget Sound area that are capable of producing earthquakes of M7.0 or greater.

Consequently, SPU is re-evaluating the seismic vulnerability of its system and updating its seismic mitigation strategy. Five major objectives have been defined for this project:

1. Define post-earthquake water system level of service goals.
2. Perform seismic vulnerability assessments of SPU water system facilities.
3. Use hydraulic modeling to estimate post-earthquake system performance.
4. Develop planning level mitigation measures and cost estimates.
5. Develop seismic standards for new SPU water system facilities.

This paper describes the approach SPU is using to increase the seismic resiliency of its water system.

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INTRODUCTION

Seattle Public Utilities (SPU) provides potable water to over 1.3 million residents in the central Puget Sound region [1]. Approximately half of these residents are served directly by SPU. SPU wholesales water to nineteen other municipalities and special purpose districts, and to the Cascade Water Alliance, that serve the other residential customers. The average daily demand is approximately 135 million gallons (500,000 cubic meters).

Two watersheds in the Cascade Mountains east of Seattle are the sources of Seattle's water supply (see Figure 1). The Cedar River Watershed is located approximately 40 miles (65 kilometers) southeast of Seattle and provides approximately two-thirds of Seattle's water supply. Masonry Dam was constructed on the Cedar River in 1914 to raise Chester Morse Lake by approximately 35 feet (10 meters) and provide 13 billion gallons (50 million cubic meters) of usable storage. A pumping plant on the reservoir allows SPU to pump the reservoir even lower, if needed.

Water releases into the Cedar River from Chester Morse Lake are managed to provide water for the Cedar River fishery and for diversion into the SPU water transmission system at the Landsburg Diversion Dam, 14 miles (23 kilometers) downstream of Masonry Dam. Water diverted at the Landsburg Diversion Dam is piped to Lake Youngs which has an additional usable storage capacity of 1.5 billion gallons (5.5 million cubic meters). The Cedar River Water Treatment Plant at Lake Youngs uses ozonation and ultra violet processes to treat the water. The Cedar River Pipelines deliver treated water to SPU's direct service area and wholesale customers.

The Tolt River Watershed, located approximately 40 miles (65 kilometers) northeast of Seattle, was developed in 1962 to meet the rising water demands from population growth in the central Puget Sound region. The Tolt River Watershed supplies approximately one-third of SPU's water supply. The Tolt Reservoir provides approximately 18 billion gallons (70 million cubic meters) of storage. The Tolt River Water Filtration Plant, located approximately 5 miles (8 kilometers) downstream of the Tolt Reservoir, is used to treat Tolt Reservoir water. The Tolt pipelines are used to transport water to the northern portions of SPU's direct service area and wholesale customers.

In addition to the Tolt and Cedar River watersheds, SPU maintains two well fields approximately 10 miles (16 kilometers) south of downtown Seattle. The Riverton and Boulevard Park well fields can supply up to 10 mgd (40,000 cubic meters per day) in emergency and drought conditions.

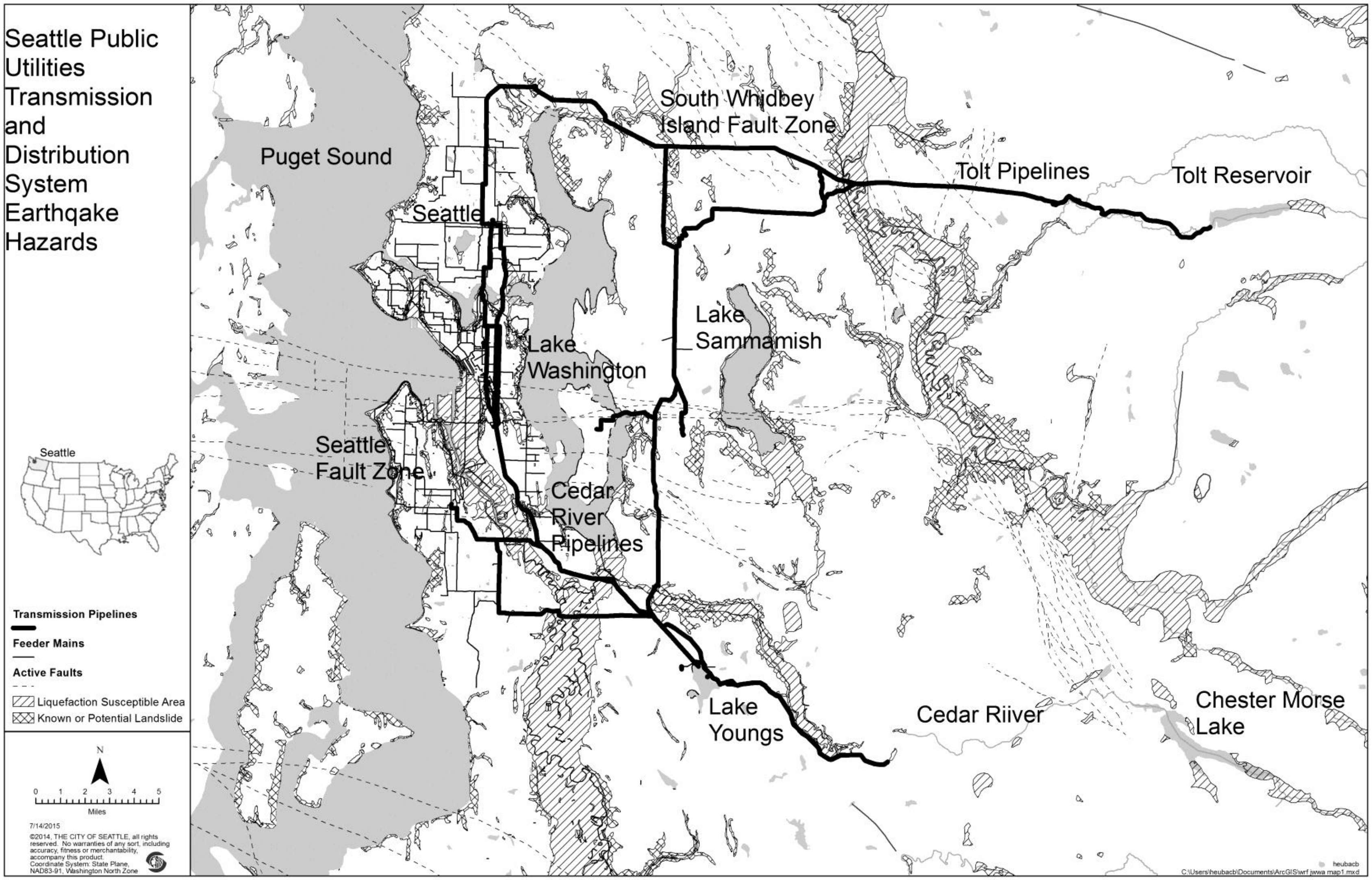


Figure 1. Seattle Public Utilities Transmission and Distribution System and Area Earthquake Hazards

The Great Seattle Fire of 1889 was the impetus for developing a reliable water system for Seattle. Consequently, some SPU water system facilities are more than 100 years old. Currently, SPU's distribution system consists of

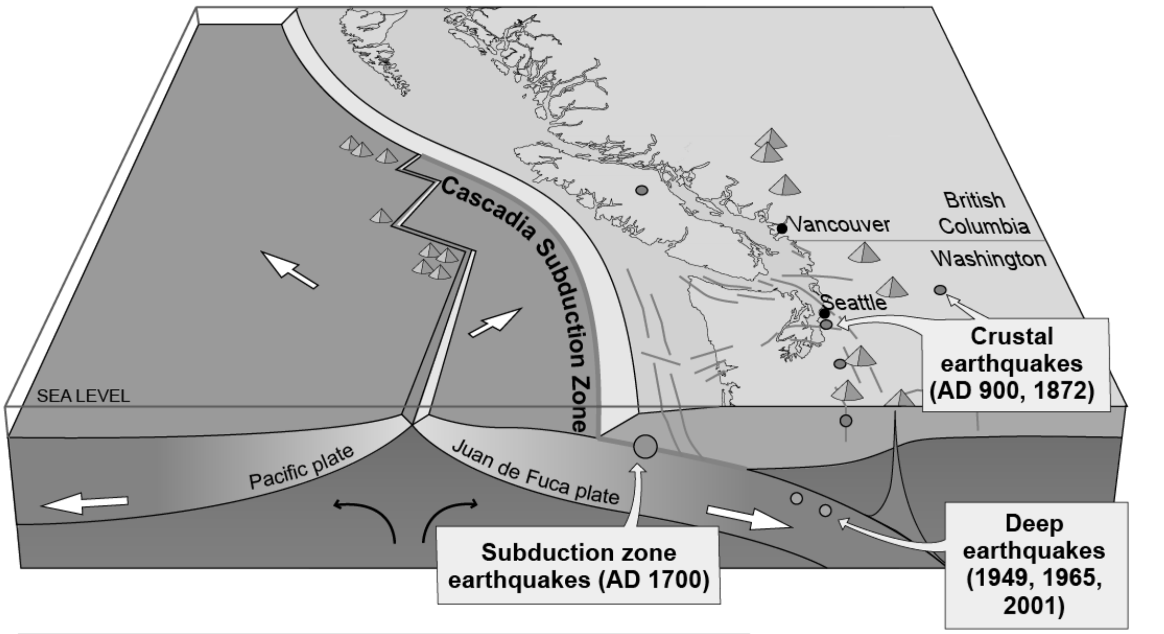
- 1700 miles (2700 kilometers) of distribution pipelines
- Ten at-grade terminal storage reservoirs ranging in size from 5 million gallons to 60 million gallons (19,000 cubic meters to 227,000 cubic meters)
- Six standpipes and elevated tanks
- Sixteen pump stations
- 21,000 valves
- 19,000 fire hydrants

PUGET SOUND REGION SEISMICITY

The SPU water transmission and distribution system lies over a subduction zone. As Figure 2 shows, there are three earthquake mechanisms that threaten the Puget Sound region:

- Deep intraplate earthquakes in the Juan de Fuca plate are caused by fracturing of the Juan de Fuca Plate as it is being subducted below the North American Plate and the Puget Sound. The M7.1 1949 Olympia, M6.5 1965 Seattle and M6.8 2001 Nisqually Earthquakes were intraplate earthquakes. Although the epicenters of these three earthquakes were located within the Puget Sound region, the hypocenters of Juan de Fuca intraplate earthquakes are typically 30 to 80 kilometers (20 to 50 miles) below the earth's surface. Consequently, peak ground accelerations in most locations are less than 0.2g. Damage from these earthquakes to SPU water system facilities has been minimal and has not significantly affected water system functionality.
- Megathrust subduction earthquakes are possible below the Pacific Northwest coastal zone where the Juan de Fuca Plate is being subducted by the North American Plate. The locked boundary between the North American Plate and Juan de Fuca plate extends more than 700 miles (1100 kilometers) and is capable of producing earthquakes of M9.0 or greater. Because the interplate fault rupture would not occur in the immediate vicinity of Seattle, peak ground accelerations would likely only be on the order of 0.2g to 0.3g in SPU's service and transmission area. However, strong ground shaking may last as long as three or four minutes and would increase the likelihood and extent of soil liquefaction, damage to buried pipelines and above ground structures. Under the worst case scenario, the western regions from Northern California to Southern British Columbia would be significantly impacted.
- Several active surface fault systems in the Puget Sound region have produced M7.0 to M7.5 earthquakes. Although these surface faults are responsible for most of the earthquakes in the Puget Sound area, most of these earthquakes are too small to produce significant damage. The last major earthquake from a surface fault in the Puget Sound area is believed to have occurred over 1100 years ago in the Seattle

Fault Zone. The Seattle Fault Zone runs directly through Seattle and possibly all the way east to the Cedar River Watershed. In addition to strong ground shaking that may exceed 0.6g, the Seattle Fault Zone may produce surface expressions of faulting.



Source	Max. Size	Recurrence
Subduction zone	M 9+	200–600 years
Deep Juan de Fuca plate	M 7+	30–50 years
Crustal faults	M 7+	Hundreds of years?

*figure modified from USGS Cascadia earthquake graphics at http://geomaps.wr.usgs.gov/pacnw/pacnweq/index.html

Figure 2. Puget Sound Earthquake Source Zones (Source: USGS [2] and Washington State Department of Natural Resources [3])

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE PAST

Cygna Energy Services [4] was hired by SPU to perform a seismic vulnerability assessment of SPU's water system facilities in the late 1980's. Almost all of SPU's water system facilities were assessed by Cygna. Seismic hazards were identified by Shannon and Wilson, a geotechnical engineering consultant.

Although some surface faults had been identified in the Puget Sound region prior to 1990, these faults were not considered capable of producing large, damaging earthquakes at the time. Although the Cascadia interplate subduction zone had been identified prior to 1990, Cascadia interplate subduction earthquakes were believed to be limited to approximately M8.0 to M8.5. Cygna evaluated SPU's facilities for two levels of ground shaking:

- 0.50 probability of exceedance in 50 years ground motions (72 year average return interval)
- 0.10 probability of exceedance in 50 years ground motions (475 year average return interval)

The postulated mechanisms for these ground motions were M6.5 and M7.5 intraplate earthquakes that would occur 30 to 50 miles directly below the facilities that were assessed.

The Cygna study focused on distinct water system facilities and a few discrete transmission pipeline locations. Based on the Cygna study, several facilities were seismically upgraded. These upgrades ranged from improving structural component connections at pump stations to installing seismic base isolators on two elevated tanks. Additional emergency preparedness measures such as purchasing flexible hose to use as temporary water mains and water blivets that could be used to provide temporary drinking water sources were also implemented.

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE PRESENT

In 2014, SPU decided to take a fresh look at the seismic vulnerability of its water system and to develop a long term mitigation plan. There were several reasons behind SPU decision to re-evaluate the seismic vulnerability of its water system. First, in many of the several large earthquakes since the 1990 study was completed, water systems had continued to perform poorly. Complete restoration of water system service has taken upwards of two months in some instances. The indirect economic effects on Seattle's businesses and industries would be enormous if complete water system restoration took two months or more. If the post-earthquake recovery took too long, Seattle could risk outward migration of both businesses and residents.

There were also several important lessons learned in these earthquakes [5]. Although water distribution pipelines continued to perform poorly, particularly in areas were permanent ground displacement occurred, some distribution pipelines such as those made from earthquake resistant ductile iron pipe performed exceptionally well. Other United States utilities have conducted pilot projects with earthquake resistant ductile iron pipe and United States pipe manufacturers have begun developing their own earthquake-resistant water distribution pipe.

Although facility criticality was considered in the Cygna study, overall water system performance was not considered. As the 1994 Northridge, 1995 Kobe, and 2011 Christchurch and Tohoku earthquake demonstrated, distribution system pipeline breaks can have a major effect on water system reliability and restoration. A 1988 USGS sponsored study [6] looked at how distribution pipelines might affect system response in a portion of the SPU water system. As part of a Water Research Foundation study [7], SPU evaluated the effect of distribution pipeline damage on the entire water system. As Figures 3 and 4 show, it will likely take only a few hours for large areas of the SPU direct service system to lose water pressure after a major earthquake. Six to ten hours after an earthquake, most of the system could lose water pressure.

Finally, the understanding of the seismicity of the Puget Sound region has changed dramatically since 1990. Earthquake design codes have undergone significant revision. When the 1990 SPU seismic study was completed, the only two mechanisms believed capable of producing damaging earthquake in the Puget Sound region were the Cascadia interplate and intraplate zones. Although the most common type of earthquake in Western Washington are small, shallow earthquakes and a shallow M7.2 earthquake occurred in Eastern Washington in 1872, in 1990 it was not believed that large, shallow earthquakes were likely in Western Washington. However, since 1990, paleoseismic evidence has been discovered that indicates that large shall earthquakes have occurred in Western Washington in the past and will occur in the future. One of the active surface fault zones that seismologists have identified, the Seattle Fault Zone, runs directly through Seattle and bisects the Cedar River pipelines and the Eastside Supply Line, the transmission pipeline that supplies SPU's eastside wholesale customers. Another fault zone, the South Whidbey Island Fault Zone, bisects the Tolt River pipelines.

Figure 3. Estimated SPU System Water Pressure Three Hours After Major Earthquake (Darkest Areas Denote Water Pressure = 0)

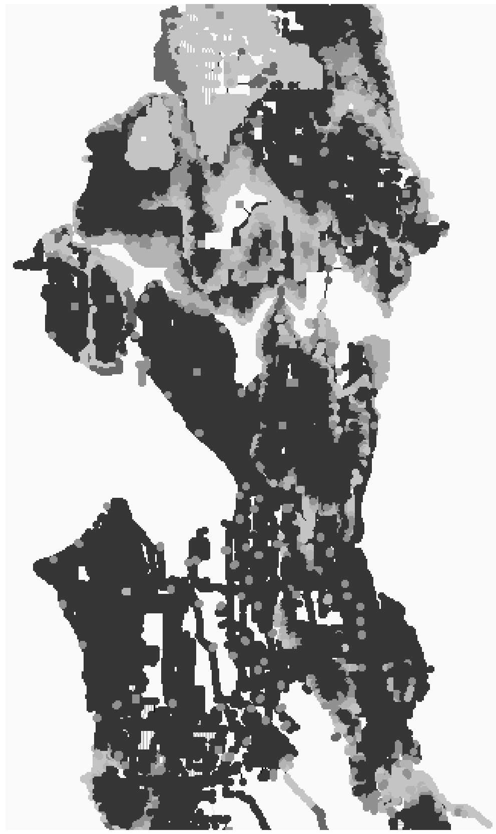


Figure 4. Estimated SPU System Water Pressure Ten Hours After Major Earthquake (Darkest Areas Denote Water Pressure = 0)

In addition to possible surface expression of faulting that could damage SPU water system facilities, the Seattle and South Whidbey Island fault complexes have dramatically increased the ground motions. Additionally, the building codes [8] have gravitated from considering 0.10 probability of exceedance in 50 years (475 year average return interval) ground motions to 0.02 probability of exceedance in 50 years (2475 year average return interval) ground motions. Consequently, the design level ground motions for SPU water system facilities has increased from approximately 0.2 to 0.3g, to 0.5 to 0.6g.

SEATTLE PUBLIC UTILITIES SEISMIC PROGRAM – THE FUTURE

Recognizing the current seismic vulnerability of SPU water system, SPU has established five objectives for its seismic program/study.

Post-Earthquake Level of Service Goals

Clear, concise post-earthquake water system performance objectives are being defined. The purposes of these objectives are to define obtainable goals and to communicate these goals to SPU's stakeholders. The performance objectives need to be realistic in terms of available funding. The objectives also need to recognize that due to the high costs, it will take many years to upgrade SPU's water system to meet the objectives. Consequently, the objectives will be divided into (relatively) near-term objectives for the next 20 years and longer term objectives for the next 50 to 60 years.

The different SPU stakeholders have been identified and their input is being solicited. Major stakeholder groups include

- Seattle Fire Department
- Retail Customers
- Wholesale Customers
- City and SPU Leadership
- SPU Staff

Stakeholder engagement includes meeting with stakeholders and soliciting their input. Because any mitigation strategy that is implemented by SPU will require some level of rate-based funding, a choice experiment will be developed to help determine retail customer willingness-to-pay for improved water system seismic performance.

Water System Facility Seismic Vulnerability Assessments

The seismic vulnerability of each SPU water system facility will be assessed. The facilities will be evaluated with three different sets of criteria: two scenario events and the code level 0.02 probability of exceedance in 50 years (2475 year average return interval) ground motions. The first scenario event is a postulated M9.0 Cascadia interplate subduction earthquake that would occur off the Washington coast. Fault rupture could extend over 700 miles (1100 miles) from Southern British Columbia to Northern California. Although the 0.2 to 0.3g ground shaking intensity in the SPU transmission and distribution area is similar to the shaking intensity used in the 1990 Cygna study, strong ground shaking may last for three or four minutes. The long ground shaking duration has significant implications for less ductile facilities that may not be able to withstand repeated excursions into the inelastic range. Additionally, the long duration ground motions will likely result in more widespread liquefaction and landslides, larger permanent ground displacements and more extensive pipe damage. The M9.0 Cascadia scenario is believed to be representative of a scenario with an approximately 500 year average return interval.

The second scenario is a M6.7 Seattle Fault Zone earthquake. The Seattle Fault Zone will be assumed to rupture within SPU's direct service area. In addition to strong ground motions in the vicinity of the fault rupture, the fault ruptures surface expression will be assumed to sever the Cedar River pipelines. This M6.7 Seattle Fault Zone scenario is consistent with the type of event that may be expected to occur every 1000 to 2500 years.

Each facility will also be assessed in accordance with current building code and standard ground shaking levels. Although the current U.S. codes are in the process of migrating from 0.02 probability of exceedance in 50 years ground motions to 0.01 probability of collapse in 50 years ground motions, the 0.02 probability of exceedance ground motions, which will likely be similar to the 0.01 probability of collapse ground motions in the Puget Sound region.

Although all SPU facilities will be considered, the level of analysis for each facility will vary. Facilities that have been recently constructed and/or upgraded to current codes will be assumed to remain functional during the scenario and code level analyses. Whenever possible, information and analyses developed by Cygna or other seismic evaluations will be used in the assessments. Critical facilities that have not been previously analyzed for the current ground motions will be analyzed in most detail. ASCE 41-13 procedures [9] will be used as a guideline. Site-specific evaluations will be conducted for critical transmission pipelines. Distribution pipeline damage will be estimated with the American Lifelines Alliance (ALA) water distribution system pipeline fragility models [10]. The fragility models will be modified to reflect SPU water distribution pipeline characteristics and lessons learned about water distribution pipeline damage since the 2001 ALA guidelines were published.

Water System Post-Earthquake Response

Water system performance in past earthquakes has shown that distribution pipeline breaks can heavily influence post-earthquake water system performance and recovery. Unmitigated, distribution pipeline damage can quickly drain reservoirs and lead to loss of system pressurization. This behavior is consistent with the hydraulic modeling results from the 2009 Water Research Foundation study. Consequently, the facility earthquake scenario vulnerability assessment results will be used to estimate overall system response. A "skeletonized" system hydraulic model will be used to hydraulically model the system response. The major difference between the approach used in this study and the 2009 Water Research Foundation study is that a "skeletonized" hydraulic model that essentially models each pressure zone as a single node will be used in this study. With the full system EPANet model used in the previous Water Research Foundation study, EPANet has trouble converging and remaining stable once pressures reach 0 psi in large areas of the system. A simpler EPANet model is expected to remain more stable under the extreme conditions created by a large earthquake.

In addition to assessing the current water system vulnerability, the hydraulic model will also be used evaluate the effect of mitigation options on system response. Hydraulic modeling of the system response to various mitigation solutions will help identify cost effective mitigation strategies that are consistent with the post-earthquake level of service goals.

Earthquake Mitigation Strategy Development

Mitigation solutions will be developed that are consistent with the post-earthquake level of service goals. If the mitigation solutions are unrealistically expensive, there will be some iteration/modification of the post-earthquake level of service goals. As mentioned previously, there will be a near-term set of post-earthquake level of service goals and a longer term set of post-earthquake level of service goals.

Because SPU has committed to limit rate increases through 2020, the near term mitigation measures are expected to include less expensive strategies such as improvement of emergency preparedness and response procedures, and implementation of post-earthquake operation and control strategies.

Seismic Standard Development for New Water System Facilities

As part of the long-term approach to reducing the seismic vulnerability of SPU's water system, an important component of SPU's current seismic study is to develop seismic standards for new water system facilities. Because buildings, building contents and reservoirs are already covered by existing codes and standards, the emphasis will be on the development of standards for pipelines. It's expected that the standards for distribution system pipelines will be largely prescriptive. That is, in areas where permanent ground displacement is possible, some type of earthquake resistant pipe will be required. As pipe criticality and size increases, the level of analysis will increase. For transmission pipelines, the requirement of a complete seismic analysis is anticipated.

Previous earthquakes experienced by other water utilities and the 2009 Water Research Foundation study suggest that SPU would likely experience more than 1000 distribution pipeline failures in a major earthquake. Because it is not practical to replace large amounts of vulnerable distribution piping in a short amount of time, one purpose of the standards will be to ensure that as SPU replaces pipelines as part its normal replacement process, seismic resistant pipelines are installed so the vulnerability of SPU's pipeline system can gradually be reduced.

SUMMARY

Seattle Public Utilities is reevaluating the seismic vulnerability of its water system and developing a new mitigation strategy because:

- The understanding of the seismicity of the Puget Sound region has changed dramatically since SPU's 1990 study.
- Recent earthquakes have shown that although water systems remain seismically vulnerable, there are practical strategies that can be used to decrease vulnerability.
- In addition to individual facility evaluation, the response of the entire water system needs to be considered.

The objectives of SPU's seismic program are to:

- Define post-earthquake water system level of service goals
- Evaluate the seismic vulnerability, consistent with the current understanding of seismicity in the Puget Sound region, of SPU's water system facilities
- Estimate SPU's water system response to two earthquake scenarios
- Develop a mitigation strategy and program to enable SPU to meet its post-earthquake level of service goals
- Define seismic design standards for water system facilities with an emphasis on design standards for pipelines.

Ultimately, over time, SPU is aiming to develop a seismically resilient water system that is able to function as needed after a major earthquake so that life safety and property damage effects are minimized. Additionally, the time fully restore the system should be minimized to reduce societal impacts.

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