Water System Pipeline Damage
Seattle Public Utilities Case Study

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ABSTRACT

Seattle Public Utilities (SPU) provides water to approximately 1.4 million people in the central Puget Sound area. In addition to providing direct service to approximately 700,000 residents, SPU wholesales water to 20 cities and water districts near Seattle.

SPU is completing an update of a 1990 seismic vulnerability assessment that was performed by Cygna Energy Services [1]. This assessment update accounts for changes in the understanding of the seismic hazards that threaten the Puget Sound region. The 2017 update emphasizes pipeline performance and overall system response.

The 2017 findings show that although some important "vertical" facilities such as reservoirs and pump stations are vulnerable, the most significant effect on water system response will be pipeline damage. Damage to transmission and distribution system pipeline damage is expected to severely disrupt system operation and delay system restoration. In order to mitigate the effects of this pipeline damage, SPU's mitigation strategy is to employ both short-term measures to manage the current vulnerability of the SPU water system and longer-term measures to reduce the vulnerability of the SPU water system. The five basic elements of SPU's mitigation approach are

Short Term

- Implement Isolation and Control Measures to Mitigate the Effects of Pipeline Damage on System-Wide Water Pressure
- Improve Earthquake Emergency Preparedness and Response Planning to Reduce Recovery Time

Long Term

- Construct an Earthquake-Resistant Transmission Pipeline That Will Supply Minimal Water Demand to SPU's Direct Service Area
- Use earthquake-resistant pipe in permanent ground displacement susceptible areas and for pipelines that are essential for fire-fighting or that serve critical facilities
- Seismically Upgrade Critical Reservoirs, Tanks, Pump Stations and Support Facilities

This paper summarizes the findings of SPU's seismic vulnerability study update and SPU's mitigation approach.

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INTRODUCTION/BACKGROUND

Seattle Public Utilities (SPU) provides treated water to 1.4 million residents in the Seattle area. Approximately half of these residents are in SPU's direct service area and the other half are served by 20 other cities and water districts. Total average daily demand is approximately 120 million gallons (450,000 cubic meters) per day.

Typically, two-thirds of SPU's water supply comes from the Cedar River Watershed which is located approximately 30 miles (50 kilometers) southeast of downtown Seattle in the Cascade Mountains. The Tolt River Watershed, located approximately 30 miles (50 kilometers) northeast of downtown Seattle in the Cascade Mountains, typically provides the other one-third of SPU's water supply. The Seattle Well Fields can provide an additional 10 million gallons (38,000 cubic meters) per day on an emergency basis for up to four months.

Approximately 193 miles (310 kilometers) of transmission pipelines convey water from the Landsburg Diversion on the Cedar River and the Tolt Reservoir to SPU's customers. Most of the Cedar River system transmission system consists of riveted or lock bar steel pipe with some alignments constructed from either concrete cylinder pipe or welded steel pipe. The newer Tolt 2 Pipeline is welded steel pipe with welded lap joints and the older, early 1960's vintage Tolt 1 pipeline is primarily concrete cylinder with some newer welded steel or ductile iron pipe.

SPU's direct service area is served by almost 1680 miles (2700 kilometers) of distribution pipelines. Cast iron mains comprise 79% of the distribution pipeline system with ductile iron pipe accounting for another 15%.

Chester Morse Lake and Lake Youngs provide storage for the Cedar River Watershed and the Tolt Reservoir and Regulating Basin provide storage for the Tolt Watershed. Storage within SPU's transmission and distribution system is provided by

- 10 below grade reservoirs ranging in capacity from 2.5 million gallons to 60 million gallons
- Three above grade concrete reservoirs
- Four elevated steel tanks
- Five steel standpipes
- Two surge tanks

Although most areas within SPU's direct service area can usually be served by gravity, SPU operates 31 transmission and distribution pump stations.

In 2015, SPU initiated a comprehensive seismic vulnerability assessment update. The purpose of this update was to re-evaluate the seismic vulnerability of SPU's facilities with the current understanding of the seismic risks in the Puget Sound region and with an emphasis on pipeline and overall system performance.

PUGET SOUND SEISMICITY

There are three source zones that are capable of producing damaging earthquakes in the Puget Sound region (see Figure 1). The subduction of the Juan de Fuca Plate by the North American Plate has produced M9.0 subduction earthquakes with an average return interval of 500 years. The fault rupture can extend 700 miles (1100 kilometers) along the Pacific Northwest coast from Northern California to southern British Columbia. Since it has been 300 years since the last full rupture of the interface between the Juan de Fuca and North American Plates, seismologists estimate there is a 0.14 probability that this interface will rupture in the next 50 years. Ground motions between 0.2g and 0.3g would be expected in SPU's transmission and distribution area. Ground shaking would be expected to last several minutes.

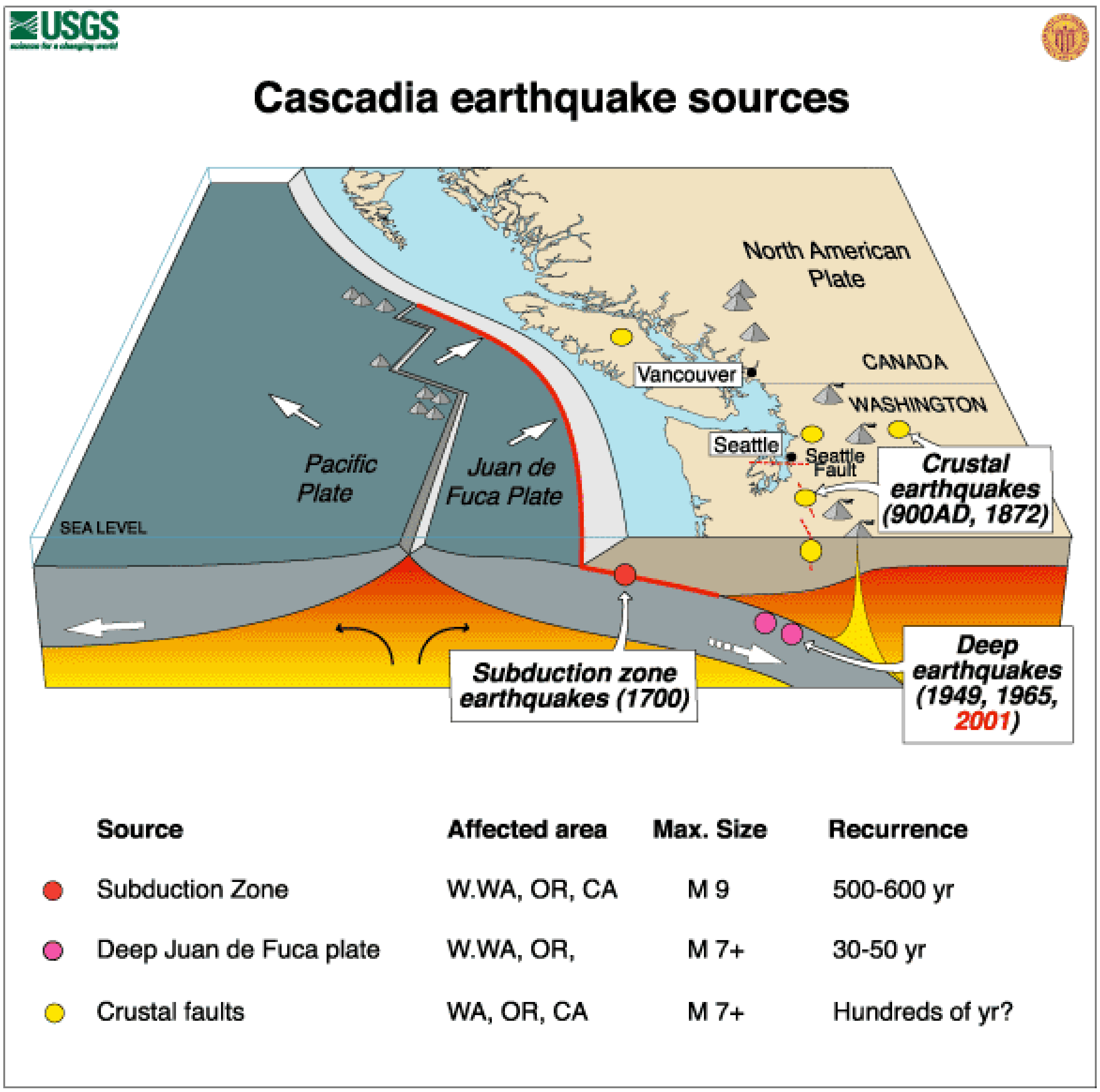

Figure 1. Puget Sound Earthquake Source Zones [2]

Every 25 to 30 years, M6.0 or greater earthquakes occur in the subducted Juan de Fuca Plate as it fractures below the Puget Sound region. Although these intraplate earthquakes can occur directly below SPU's service area, the hypocenters are typically 20 to 50 miles (30 to 80 kilometers) deep. In most areas, peak ground accelerations at the earth's surface are less than 0.2g. Although some SPU facilities were damaged during the 1949 M7.1, 1965 M6.5 and 2001 M7.1 Puget Sound earthquakes, water system operation was not significantly affected during either of these three earthquakes.

Crustal blocks within the North American Plate are being dragged northward by the Pacific Plate. These crustal blocks are colliding with a fixed portion of the North American Plate that lies in Canada. This compression has produced a complex set of shallow faults in Western Washington. One of these fault zones, the Seattle Fault zone, runs directly through Seattle and has produced earthquakes of M7.0 or greater in the Seattle area. These surface faults are capable of producing peak ground accelerations in excess of 0.6g. The determination that these surface faults are active only occurred in the last 25 to 30 years so most older facilities are not designed to resist these larger ground motions. Seismologists estimate there is a 0.05 probability of a M6.5 or larger Seattle Fault event in the next 50 years.

SEISMIC HAZARD ESTIMATION

SPU's facilities are spread over a larger geographical area. In addition to the probabilistic ground motions that are used by building codes, ground motions and seismic hazards were estimated for M7.0 Seattle Fault earthquake and M9.0 Cascadia Subduction earthquake scenarios.

The average of five NGA-West2 ground motion prediction equations were used to estimate ground motions for the Seattle Fault M 7.0 earthquake [3]. The BC Hyrdo ground motion prediction equation [4] was used to estimate ground motions for the M9 Cascadia Subduction earthquake.

Permanent ground displacements were estimated for liquefaction- and landslide-susceptible areas for both scenario earthquakes. These displacement estimates are used as input to pipeline damage algorithms developed by the American Lifelines Alliance [5]. The regional permanent ground displacement estimates are intended to produce averages over wide geographical areas and are not intended for site-specific analysis. The actual displacements at some sites may significantly differ from the regional estimates.

The liquefaction-susceptibility and soil units identified by the Washington State Department of Natural Resources [6] and the estimated ground shaking intensity and duration were used in conjunction with liquefaction displacement models to estimate the liquefaction displacements. Three components of liquefaction displacement were estimated [7]:

- PGD_h, the horizontal component due to lateral spread
- $PGD_{v\text{-}vol}$, the vertical component due to ground settlement and ejecta
- $PGD_{v\text{-}dev}$, the vertical component due to deviatoric strains cause by lateral displacement

The total permanent ground displacement from liquefaction was estimated as

$$PGD_{total} = \sqrt{[(PGD_h)^2 + (PGD_{v-vol} + PGD_{v-dev})^2]} \quad (1)$$

The areal extent of liquefaction in a particular region was estimated as a function of the soil properties and ground shaking intensity. Shaking duration was considered by applying a magnitude scaling factor.

The factor of safety for landslides in Seattle under static conditions was estimated by Harp et al [8] in a previous study. Using a simplified sliding block model and assumed ranges of slope, the landslide probability was estimated as a function peak ground acceleration for each of the factor of safety ranges defined by Harp et. al. The Makdisi and Seed [9] relationships between the peak ground acceleration, k_{y-max}, the acceleration that triggers landsliding, k_y, and the earthquake magnitude was used to estimate permanent ground displacement from landslides [10].

FACILITY ASSESSMENT APPROACH AND FINDINGS

Over 100 SPU facilities were evaluated [11]. The facilities were evaluated with regards to expected post-earthquake functionality. The evaluation methodology was a function of the facility criticality. For most facilities, an ASCE 41-13 [12] Tier 1 assessment was conducted [13]. For many of the above ground reservoirs, pseudo static analyses were performed [14]. To address some structural issues that had been identified, detailed soil-structure interaction (SSI) analyses were performed for four of the below grade reinforced concrete terminal reservoirs [15-18].

Many of the simpler buildings were found to be seismically rugged even though they were designed and constructed before modern seismic codes were adopted. As expected, when there were deficiencies in the lateral force resisting system, they often involved inadequate detailing in the roof-to-wall connections and/or shear walls.

The reservoirs and tanks were more likely to have significant seismic concerns. Insufficient lateral strength and inadequate anchorage were common tank and reservoir deficiencies. The roof-to-wall connections were inadequate for many of the ground-supported concrete tanks.

Based on the SSI model findings, four below grade reservoirs were seismically upgraded. For all four reservoirs, the perimeter floor slabs were thickened to keep water loss from any cracking less than 100 gallons (380 liters) per minute. Wall sealants were used to control leakage from wall cracking in three of the reservoirs. In a fourth reservoir, the wall was thickened.

PIPELINE ASSESSMENT APPROACH AND FINDINGS

As Figure 2 shows, SPU's transmission and distribution pipeline alignments are exposed to numerous seismic hazards. In addition to crossing several areas of unstable soils, the Cedar River transmission system traverses through the Seattle Fault zone as it travels north through Seattle. The Seattle Fault is a complex fault system that is approximately 50 miles (80 kilometers) long and as wide as five miles (eight kilometers) [19]. Uplift of up to 20 feet (six meters) may occur in the northern part of the Seattle Fault zone meters) may occur in the northern part of the Seattle Fault zone while three to ten feet (one to three meters) of surface displacement may occur in the southern portion of the zone. Similarly, the Tolt transmission system must traverse the Sound Whidbey Island Fault zone that is as wide as 12 miles (20 kilometers).

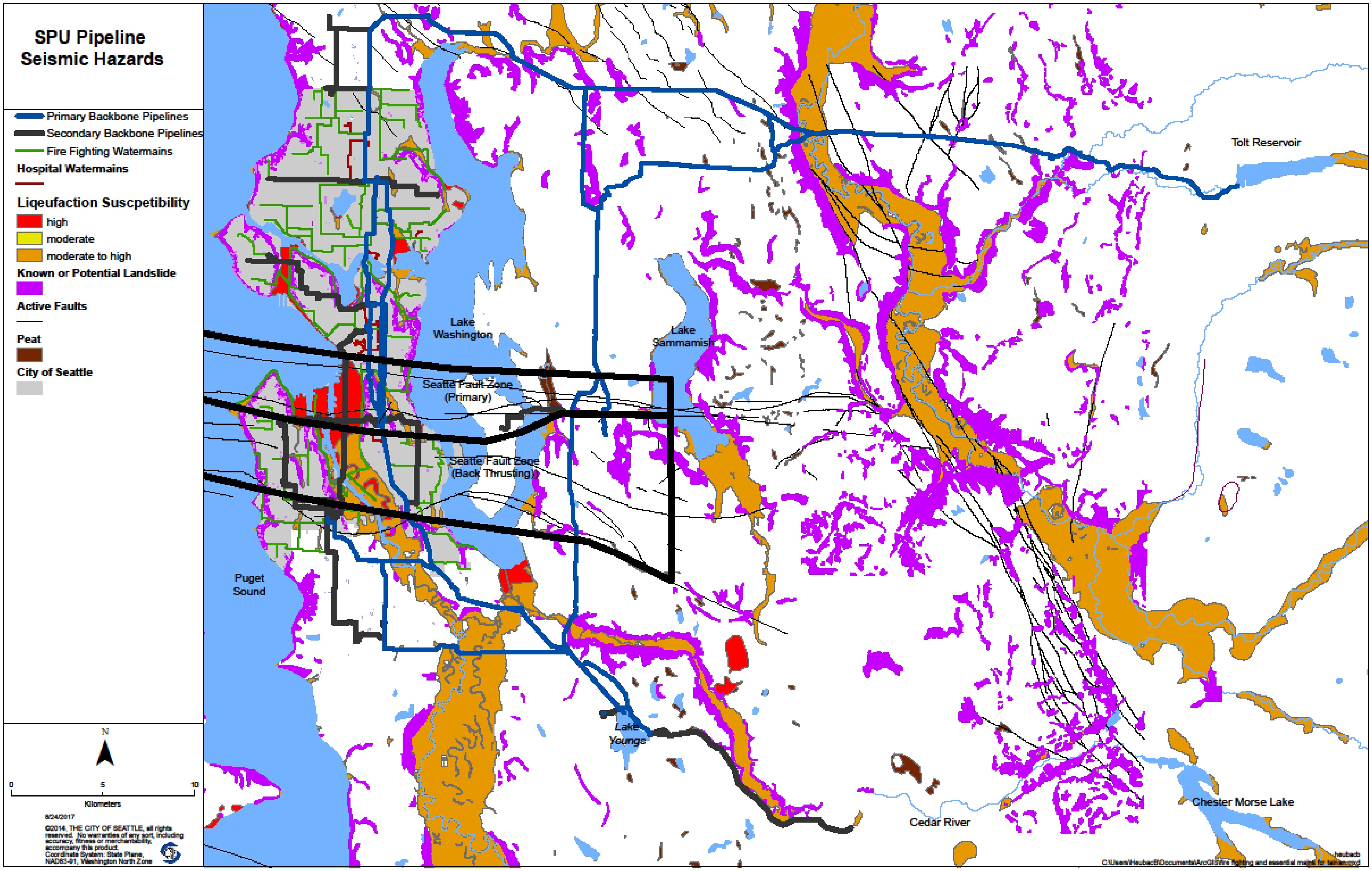

Figure 2. Seattle Public Utilities Pipeline Hazards

Distribution Pipelines

Two separate approaches were used to assess the distribution piping system and transmission piping system. The American Lifelines Alliance pipeline fragility models [5] were used to estimate distribution pipe breakage. These models take the form of

$$RR_{PGV} = K_1 \text{ X } 0.00187 \text{ X } PGV \quad (2)$$

and

$$RR_{PGD} = K_2 \text{ X } 1.06 \text{ X } PGD^{0.319} \quad (3)$$

where

RR_{PGV} = number of repairs per 1000 feet (305 meters) caused by seismic wave propagation effects

K_1 = constant dependent on the pipe material and joint system

PGV = the peak ground velocity expressed in inches per second

RR_{PGD} = number of repairs per 1000 feet (305 meters) caused by permanent ground displacement effects

K_2 = constant dependent on the pipe material and joint system

PGD = the permanent ground displacement expressed in inches

K_1 and K_2 range from 0.15 for ductile pipe to 1.4 for brittle pipe.

Peak ground velocities were estimated with the ground motion prediction equations referenced earlier [3 and 4]. The methodology described in the seismic hazards section was used to estimate the permanent ground displacements and areal extent of permanent ground displacement.

For the M9 Cascadia Subduction earthquake scenario, approximately 1400 pipe repairs are forecasted. In the M7 Seattle Fault scenario, approximately 2000 pipe repairs are forecasted. Figure 3 shows the repair rates for the Seattle Fault scenario. As the models suggest, the highest rates occur where permanent ground displacements are expected.

The models used to estimate distribution pipe are very approximate and do not show exact locations where pipe breakage is expected to occur. Instead, these models provide a gross estimate of the overall number of failures that might be expected.

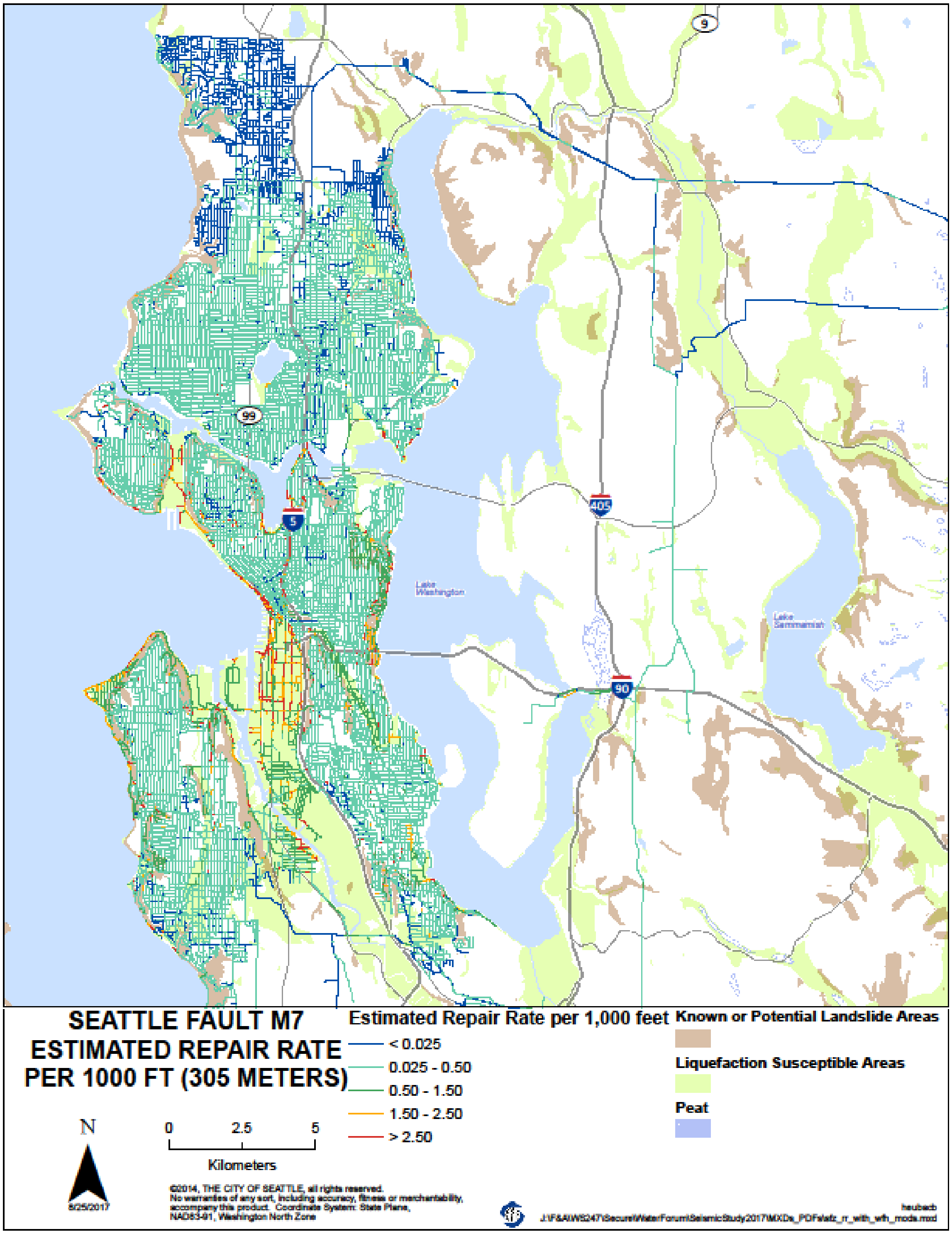

Figure 3. Estimated Distribution Pipeline Failure Rates for M7 Seattle Fault Earthquake

Transmission Pipelines

A more site-specific approach but still "high level" approach was used to evaluate transmission pipeline vulnerability. Previous findings from the 1990 Cygna report, SPU staff input and comparison of geotechnical hazard maps were used to identify those areas of most concern along the transmission pipeline alignments. For those sites believed to be most critical, available site specific geotechnical information was reviewed. Based on the transmission pipeline characteristics and the available geotechnical information, an expert panel estimated the pipeline performance for each of the three scenarios.

The assessment identified multiple locations along the Cedar River and Tolt transmission pipelines with potentially unstable soils. Additionally, the Cedar River transmission pipelines must cross the Seattle Fault zone and the Tolt transmission pipelines must cross the South Whidbey Island Fault zone.

The assessment concluded that under the M7.0 Seattle Fault scenario and M9 Cascadia Subduction Zone scenario, both transmission pipeline systems would likely suffer damage and would be unable to convey water into SPU's service areas. The transmission pipeline systems could be damaged in multiple areas and restoration could be difficult.

SYSTEM ASSESSMENT APPROACH

In order to develop a strategic mitigation approach, the facility and pipeline assessment results were applied to a system hydraulic model to estimate post-earthquake system performance. In addition to current system performance, the hydraulic model is being run for multiple mitigation approaches to determine the most-effective approaches that are consistent with SPU's post-earthquake performance goals.

In previous post-earthquake assessments, SPU has used a detailed EPANet system model to assess post-earthquake system performance. Because of all of the demands that a seismic event creates on the system, the full system model rapidly becomes unstable and has trouble converging. Consequently, a skeletonized model was used for this analysis. Instead of modeling every pipeline, the skeletonized model models most pressure zones with only a few nodes.

The FEMA Hazus [20] assumptions were used to estimate the severity of the pipeline failures. Breaks are defined to occur when a pipeline can no longer carry water. A leak is defined to occur when water is escaping from the pipeline but the pipeline can still convey flow. Permanent ground displacement failures were assumed to consist of 80% breaks and 20% leaks. Conversely, 20% of the wave propagation failures were assumed to be complete breaks and the other 80% were assumed to be pipeline leaks.

The individual flow rate through a break was estimated as the amount of flow that could be provided at the end of a 2000-foot (600 meters) open pipe that is supplied with water at 60 psi (400 kPa). The water flow through an average leak was estimated as the flow through a circumferential opening of 0.04 inches (1 millimeter) at 60 psi (400 kPa). These assumptions are based on the assumptions used by Kennedy/Jenks/Chilton in a study sponsored by the United States Geological Survey [21].

Because nearby pipeline failures will influence the volume of water that can be flow out of each failure, the effective volume of water that will be lost was reduced in each pressure zone once the failure rate exceeded one failure per 10,000 feet (3000 meters). The effective water loss was assumed to decrease exponentially below the water loss that would occur if all of the failures were independent.

Once the water loss for each pressure zone or node was estimated, the emitter coefficients were calculated and applied to the EPANet model. The emitter coefficients were calculated from the equation [22]

$$Q = Cp^{\gamma} \tag{4}$$

where
Q = the flow rate
C = the emitter coefficient
p = the pressure
γ = the pressure coefficient (assumed to be 0.5)

The results of the system analyses showed that much of SPU's direct service area would lose water pressure within 12 hours of either a M7 Seattle Fault or M9 Cascadia Subduction earthquake. It would likely take at least 2 months to restore minimal water service to all areas within the direct service area. It would likely take several years before pre-earthquake levels of service could be restored to the direct service area.

MITIGATION APPROACH

With input being provided by stakeholders such as SPU's ratepayers, the Fire Department and wholesale customers, SPU is currently establishing post-earthquake performance goals. The primary criteria the performance goals address are:

- Firefighting water availability immediately after a seismic event
- Maintaining and/or restoring water pressure within the distribution area and wholesale turnouts
- Mitigating life-safety risks

Given the number of vulnerable facilities, budgetary and workload realities make it unrealistic to immediately meet the performance goals. Consequently, one set of performance goals is being set for 20 years in the future and another set of performance goals is being established for 50 years in the future. The general approach SPU is taking is to over the short term, use isolation and control strategies, and emergency preparedness and response planning to mitigate the effects of facility damage on water system performance. As facilities are made more seismically rugged, overall facility seismic resiliency will gradually increase. In this regard, five mitigation strategies are being developed:

1. Construct a seismic resistant transmission pipeline from the Cedar River supply to Seattle that would be highly likely to survive a major earthquake so there would be at least minimal (fight fires and basic needs but not enough for landscaping or other non-critical uses) water flowing into town. The Cedar River system was chosen over the Tolt system because it is easier to supply water from the Cedar River system throughout the SPU service area than the Tolt system. This "seismic-resistant" transmission pipeline would be constructed over a 50-year time frame.

2. Install more isolation and control systems that would allow SPU to prevent pipe breakage from draining reservoirs and to allow SPU to isolate heavily damaged areas so the system could be restored faster. This mitigation measure will be implemented over a 10-year time frame and is intended to mitigate the failure effects of some of the current system facilities.
3. When new pipelines are installed or replaced in areas that are susceptible to permanent ground displacements, use earthquake-resistant pipe. Regardless of the known permanent ground displacement susceptibility, use earthquake-resistant pipe on all mains that necessary for fire fighting, serve critical facilities such as hospitals and facilities needed for emergency response, and pipelines that supply distribution tanks and large service areas. The estimated time frame to install earthquake-resistant pipelines in these situations is approximately 100 years.
4. Seismically retrofit the most critical facilities (tanks, pump stations, etc.). It is expected that less critical facilities will not be seismically upgraded, particularly those facilities with shorter remaining "useful" lives. The probability of the occurrence of a major earthquake before these facilities are replaced is relatively small and it is more cost-effective to use limited resource to address the seismic vulnerability of more critical facilities that have a bigger impact on system performance. These upgrades will be done over a 20- to 50-year time frame.
5. Improve emergency preparedness and response planning. Needed repair materials and resources will be identified and methods to obtain these materials and resources after an emergency will be identified. Strategies and resources needed to provide emergency drinking water after an earthquake will be augmented. These plans and procedures will be implemented over a 10-year time frame.

SUMMARY

Seismic vulnerabilities have been identified in the SPU water system. These vulnerabilities would likely lead to loss of water pressure in much of SPU's direct service area after a major earthquake. Restoration of minimal water service to all areas would likely take as long as two months. In order improve the seismic resiliency of the SPU water system, SPU plans to implement five mitigation approaches. Two of the approaches, using isolation and control measures and improving emergency preparedness and response to mitigate facility damage effects, are intended to improve system response in the short term. Over the longer term, constructing an earthquake-resistant transmission pipeline, replacing aging distribution watermains with earthquake-resistant mains and upgrading critical, seismically vulnerable facilities will increase the seismic resiliency and performance of the SPU water system.

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