THE REGIONAL RESILIENCY ASSESSMENT PROGRAM

March 2019

Resiliency Assessment

Washington State Transportation Systems

Homeland Security

> “Across western Washington, highway reopening times following a large magnitude CSZ earthquake are almost entirely contingent on highway bridges being safely reopened for emergency use.”

Executive Summary

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The Washington State Transportation Systems project assessed the resilience of Washington State's surface transportation systems to a Cascadia Subduction Zone (CSZ) earthquake, and the ability of those systems to support post-disaster response and recovery activities. This project was undertaken as part of the Department of Homeland Security (DHS) Cybersecurity and Infrastructure Security Agency (CISA) Regional Resiliency Assessment Program (RRAP), and in close coordination with the project's sponsor, the Washington Emergency Management Division (EMD), and other state, federal, regional, and local partners.

The primary purpose of this project was to prioritize highway transportation routes that will be best able to reopen quickly following a CSZ earthquake to establish post-disaster emergency supply chains between federally designated Incident Support Bases (ISBs) located in central and eastern Washington and Federal Staging Areas (FSAs) located in western Washington. These staging areas are critical locations in state and federal earthquake response plans for bringing life-saving and life-sustaining resources to affected communities. This RRAP project also assessed the earthquake hazard exposure of Washington State's maritime and rail transportation systems, and synthesized key findings from extensive stakeholder engagements from across surface transportation sectors.

A key outcome of this RRAP project was the identification of priority highway routes into western Washington with comparatively greater seismic resilience than similar routes, which will be better able to support the movement of resources into the affected area. Prioritized investment in these highway routes may further enhance their seismic resilience prior to a CSZ earthquake, and possibly accelerate their repair and reopening during post-disaster response activities. These findings are based on extensive network- and system-level assessments of highway transportation infrastructure, using seismic screening tools developed in direct collaboration with the Washington State Department of Transportation (WSDOT). Extensive geologic information that the Washington State Department of Natural Resources (DNR), the Washington Geological Survey (WGS), and the U.S. Geological Survey (USGS) provided further supports these analyses, and gives insight into additional environmental and geological modeling activities that could better support future seismic resilience studies.

A key finding of the maritime transportation systems analyses is that commercial ports in Washington State do not have a good understanding of their facilities' seismic vulnerability, and have not undertaken internal assessments of their seismic resilience. These gaps largely prevent the meaningful integration of commercial maritime transportation infrastructure systems into regional earthquake response plans. Washington State Ferries (WSF), in contrast, has undertaken a large seismic analysis and retrofit effort over the past decade to better understand and respond to the seismic vulnerabilities of their systems.

Rail transportation systems have the ability to move large volumes of goods efficiently, which could support post-disaster response activities, but the seismic resilience of Washington State's private-sector railway systems are largely unknown to state and other public officials. An earthquake hazards exposure analysis suggests that much of Washington State's rail transportation network, particularly in western Washington, will be exposed to significant seismic hazards. However, rail infrastructure seismic vulnerability information is largely unavailable, which prevents the meaningful integration of rail infrastructure into regional response plans.

The following report first offers background information on the RRAP as a program, the Washington State Transportation Systems project, and regional stakeholder engagement. It then discusses the analytical activities and outcomes that were undertaken as part of this RRAP project. These analytical activities focused only on surface transportation systems. Aviation facilities will likely serve an important role in post-disaster response activities, and should be the subject of future studies, but were outside of the scope of this analysis. This report concludes with a series of Key Findings that synthesize the project's analytical outcomes and offers a series of Resilience Enhancement Options that state, federal, and regional partners could undertake to increase the seismic resilience of Washington State's surface transportation systems. These actions could ultimately support more effective and efficient response and restoration activities following a major CSZ earthquake in the region.

Program Overview

The RRAP is a cooperative assessment of specific critical infrastructure within a designated geographic area and a regional analysis of the surrounding infrastructure that address a range of infrastructure resilience issues that could have regionally and nationally significant consequences. These voluntary, non-regulatory RRAP projects are led by the Infrastructure Security Division within DHS CISA, and are selected each year by the Department with input and guidance from federal, state, and local partners.

Program Goal and Participants

The goal of the RRAP is to generate greater understanding and action among public and private sector partners to improve the resilience of a region’s critical infrastructure. To accomplish this, the RRAP does the following:

- ☐ Resolves infrastructure security and resilience knowledge gaps;
- ☐ Informs risk management decisions;
- ☐ Identifies opportunities and strategies to enhance infrastructure resilience; and
- ☐ Improves critical partnerships among the public and private sectors.

Strong partnerships with federal, state, local, tribal, and territorial government officials and private sector organizations across multiple disciplines are essential to the RRAP process. These include private sector facility owners and operators, industry organizations, emergency response and recovery organizations, utility providers, transportation agencies and authorities, planning commissions, law enforcement, academic institutions, and research centers.

RRAP Activities and Results

Each RRAP project typically involves a year-long process to collect and analyze data on the critical infrastructure within the designated area, followed by continued technical assistance to enhance the infrastructure’s resilience. Individual projects can incorporate opportunities for valuable information and data exchanges, including voluntary facility security surveys, first responder capability assessments, targeted studies and modeling, and subject matter expert workshops.

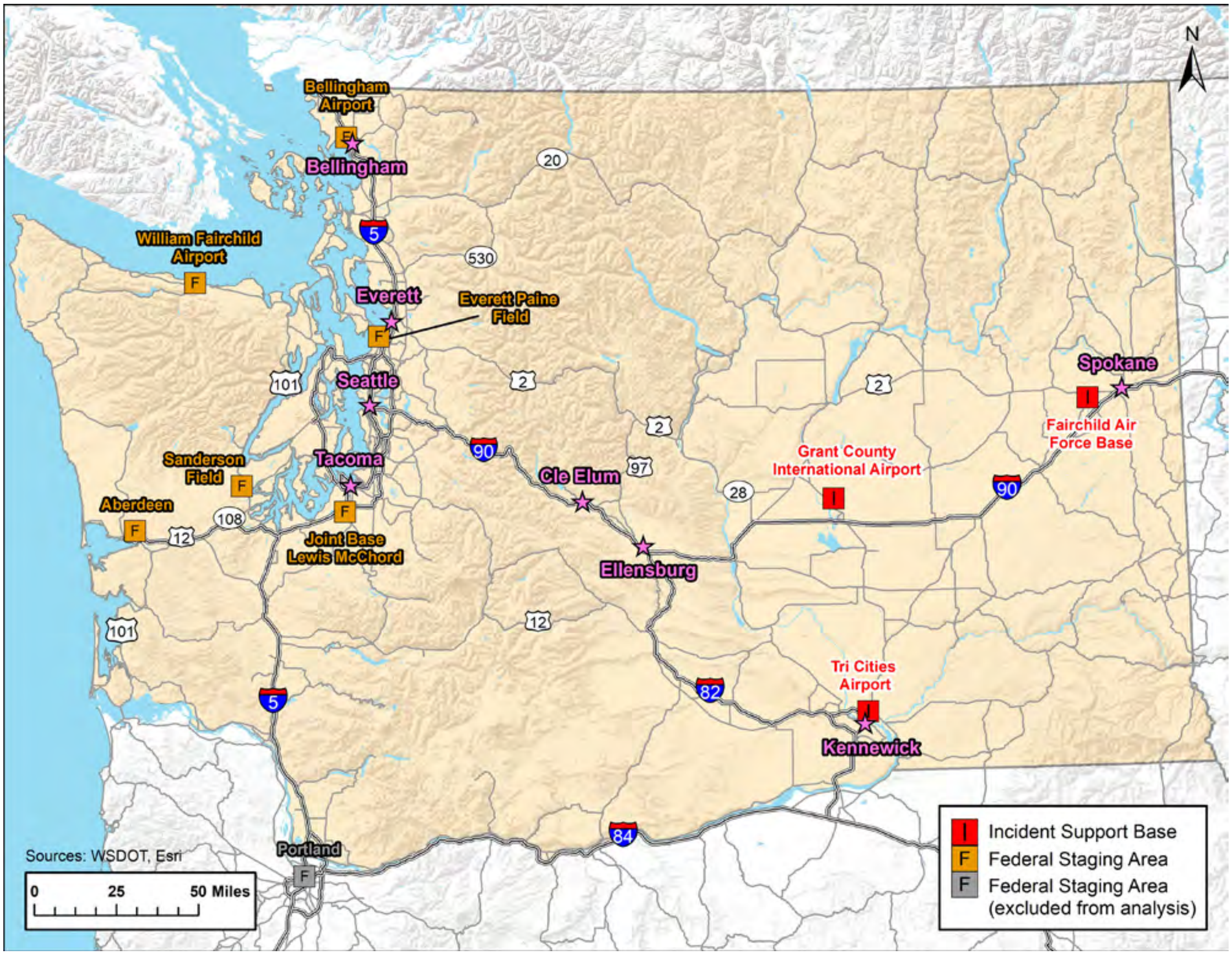
The culmination of RRAP activities, research, and analysis is presented in a Resiliency Assessment report documenting project results and findings, including key regional resilience gaps and options for addressing these shortfalls. Facility owners and operators, regional organizations, and government agencies can use the results to help guide strategic investments in equipment, planning, training, and infrastructure development to enhance the resilience and security of facilities, surrounding communities, and entire regions.

Project Overview

Project Description

Earthquakes are a central concern of emergency management personnel and infrastructure owners and operators in the Pacific Northwest. Since the early 1980s, concern has grown in Washington State about the potential for a Cascadia Subduction Zone (CSZ) earthquake that could cause severe damage and disruption throughout the region (CREW 2013). Such widespread impacts will necessitate massive response and recovery efforts to ensure that life-saving and life-sustaining resources are available to affected individuals and communities, particularly in the western part of the state where impacts are expected to be the greatest. However, state and regional exercises and studies have underscored the need to better understand the seismic vulnerability of regional transportation systems to a CSZ earthquake, and to take actions that enhance those systems' resilience (FEMA 2016, Resilient Washington State Subcommittee 2012). Following the outcomes of the joint multi-state and Federal Emergency Management Agency (FEMA) *Cascadia Rising* regional CSZ exercise in 2016, Washington's governor issued a directive instructing state agencies to strengthen regional transportation networks through improved review, planning, prioritization, and stakeholder engagement (Inslee 2016). Washington State and DHS officials have undertaken this Washington State Transportation Systems RRAP project to help emergency planners address several of the gaps in understanding of the CSZ-related seismic risks to transportation systems as identified through the outcomes of *Cascadia Rising* and in response to the governor's directive.

The state and federal agency response plan for a Magnitude 9.0 (M9.0) CSZ earthquake outlines a logistical response in which a series of disaster logistics staging areas serve as central hubs to receive and organize disaster relief supplies and equipment from around the country for transshipment to local communities (FEMA 2013). Incident response partners will activate staging areas following a disaster based on numerous factors (e.g., actual damage impacts, local government and disaster survivor needs, cooperation of facility owners and operators). However, FEMA has pre-identified potential locations in Washington State to serve as staging areas shown in figure 1. Under the FEMA plan, incident support bases (ISBs) will receive resources from across the United States, at locations outside of the area primarily impacted by the earthquake. Resources will then be transported to the federal staging areas (FSAs) located within the impacted areas for distribution to surrounding communities. Among the ISBs shown in figure 1, Grant County International Airport serves as the potential Primary ISB, Fairchild Air Force Base serves as the Secondary ISB, and Tri Cities Airport serves as the Tertiary ISB. It is important to note that ISB and FSA locations identified in this study are not inclusive of all the sites that state and federal agencies may possibly utilize as post-disaster staging areas; nor are they definitive staging locations. State and federal agencies will establish ISBs or FSAs post-disaster based on actual damage impacts along with local government and disaster survivor needs. The willingness of facility owners/operators to enter into a contract with the federal government post-disaster for the use of their facility as a staging area for an extended period will also influence ISB and FSA locations.



Sources: WSDOT, Esri

Figure 1: Potential Washington State Incident Support Base (ISB) and Federal Staging Area (FSA) Locations

The Washington State Transportation Systems RRAP project assessed the vulnerabilities and resilience of statewide surface transportation infrastructure systems to the anticipated impacts of a CSZ earthquake. These include both direct earthquake impacts (e.g., seismic forces) and secondary impacts (e.g., ground failure, tsunamis). The RRAP project also assessed the relative viability of statewide surface transportation systems to facilitate the movement of resources from the ISBs to the FSAs as part of the state and federal response and recovery effort. The primary analytical outcome of this RRAP project is a detailed finding that prioritizes state highway routes to act as transportation links between staging areas for response and recovery efforts. This includes a state-level screening of the seismic vulnerability of state highway bridges and pavements. Additional analytical outcomes of this RRAP project include an assessment of the hazard exposure, vulnerability, and resilience of maritime and rail transportation systems, to serve as a common point of departure for future studies and planning efforts.

Aviation transportation systems were not assessed as part of this RRAP project, which limited its scope to surface transportation systems only. Aviation transportation (e.g., airfields, navigation systems) will likely play an important role in post-disaster response and recovery activities, particularly in the earlier stages of response while surface transportation systems are broadly disrupted. Although not studied here, aviation transportation systems should be considered for future, in-depth study in the context of a CSZ earthquake disaster.

Criticality of Washington State Transportation Systems

An M9.0 CSZ earthquake will have a broad, regional impact area that extends over 700 miles from British Columbia to Northern California. Such widespread impacts will disrupt regional transportation at a systemic level. Direct seismic forces, ground failure, and tsunami flooding will damage extensively much of the region's road and rail networks, and port and airport facilities. In many cases, these systems are likely to be rendered unusable immediately after the initial earthquake, and could sustain additional damage from strong aftershocks, which are characteristic of subduction-zone-type earthquakes (CREW 2009). Such extensive damage to western Washington's transportation system will disrupt regional mobility and normal supply-chain operations, placing significant demand on the government and private-sector response to transport large volumes of basic commodities and other relief supplies into the region to sustain disaster survivors.

While regional response plans indicate reliance on air transportation in the initial stages of response, air transportation's ability to move the large volume of resources that will be necessary to sustain the affected population in the mid- to long-term is limited. Surface transportation modes (i.e., road, rail, maritime) are better able to move large volumes of goods and resources, and will become critical lifelines for the impacted region during ongoing response and recovery operations. Improved resilience of these surface transportation lifelines through infrastructure planning and investment is critical to meeting the post-earthquake public health and safety needs of affected populations. As noted in the report, *Resilient Washington State*, today's investments in these systems "can buy down tomorrow's recovery time and enhance public safety for generations to come" (Resilient Washington State Subcommittee 2012).

Washington State's surface transportation system is an essential component of the CSZ earthquake response and recovery plan and will serve as a vital lifeline for the individuals, communities, and critical facilities located within the earthquake-affected area. Washington's unique geography—with limited routes crossing the Cascade Mountains, numerous coastal and mountain communities with single or limited access routes, and island communities that rely on bridges or maritime systems for access—underscores the importance of transportation to response and recovery efforts. Ultimately, the ability of the state's surface transportation system to facilitate such activities is a direct function of its seismic resilience, and the ability of responders to reestablish transportation routes in the shortest possible amount of time.

Stakeholders

The Washington State Transportation Systems RRAP project facilitated collaboration among regional stakeholders to assess most effectively the seismic resilience of the state's surface transportation system. This approach ensured that analytical approaches and outcomes reflect current planning inputs and the best available science, and can most effectively inform state and regional planning efforts. The RRAP project team engaged stakeholders from federal, state, county, and municipal governments, as well as from the private sector, listed in the table on the next page. The Washington State Military Department's Emergency Management Division (EMD) was the regional sponsor for this RRAP project. In addition to EMD, four organizations participated as core stakeholders, offering input on the project's scope, approach, methodologies, analytical outcomes, and findings. This core stakeholder group included the following organizations:

- ☐ Washington State Department of Transportation (WSDOT)
- ☐ Federal Emergency Management Agency, Region 10 (FEMA Region 10)
- ☐ U.S. Coast Guard, District 13 (USCG District 13)
- ☐ U.S. Department of Transportation, Region 10 (USDOT Region 10)

Washington EMD and the core stakeholder group participated in kickoff meetings, quarterly progress reviews, and final reviews of the project outcomes and findings, including this report document. They also served as conduits to other state and regional partners that supported this RRAP project through stakeholder discussions, reviewing findings, and providing data, information or their expertise.

FEDERAL GOVERNMENT

- DHS
  - CISA
    - Infrastructure Security Division
    - National Risk Management Center
  - FEMA Region 10
  - USCG District 13
- U.S. Army Corps of Engineers
- U.S. Department of Energy
  - Pacific Northwest National Laboratory
  - Sandia National Laboratory
- U.S. Department of Transportation
- USGS

STATE GOVERNMENT

- Washington State Military Department
  - Washington Emergency Management Division
- WSDOT
  - Emergency Management
  - Bridge Office
  - Highway Maintenance
  - WSF
  - Rail Office
  - Materials Lab
  - Avalanche Management
- University of Washington
- Washington State DNR
  - Washington Geological Survey

REGIONAL, COUNTY, AND CITY GOVERNMENT

- City of Bellevue
  - Department of Transportation
- City of Seattle
  - Department of Transportation
- Grays Harbor County
  - Department of Emergency Management
- King County
  - Department of Transportation
- Pacific Northwest Economic Region
- Pierce County
  - Public Works
- Port of Bellingham
- Port of Everett
- Port of Grays Harbor
- Port of Port Angeles
- Port of Olympia
- Port of Seattle
- Port of Tacoma
- Port of Vancouver
- Puget Sound Regional Council
- Snohomish County
  - Public Works Department
  - Department of Emergency Management
- Tacoma Rail/Tacoma Public Utilities

PRIVATE SECTOR

- AMTRAK
- BNSF Railway Company
- Costco
- Safeway
- Union Pacific Railroad
- U.S. Foods

Analytic Outcomes

Analytic Outcomes

The analyses undertaken in this RRAP project are intended to enhance Washington State's understanding of its transportation system's resilience to a CSZ earthquake, identify gaps or needs, and complement prior planning efforts. In 2011, the DHS Homeland Infrastructure Threat and Risk Analysis Center (HITRAC) and National Infrastructure Simulation and Analysis Center (NISAC) undertook a regional study, *Analytical Baseline Study for the Cascadia Earthquake and Tsunami*, that provides a broad foundation for how an M9.0 CSZ earthquake could impact multiple infrastructure systems and sectors (NISAC 2011). This RRAP project assessed more specifically, and in greater detail, the surface transportation system's seismic vulnerabilities and resilience, and tailored outcomes to inform more directly state and federal CSZ logistical response plans. In addition, state and regional stakeholders stressed at the outset of this study the need for transparency and the ability to share this project's findings broadly with the community.

The following sections provide a brief background of the CSZ, discuss the primary hazards associated with a CSZ earthquake, and summarize the three areas of analysis conducted as part of this RRAP project. The hazards discussion identifies the data and information that supported the analyses, and identifies gaps within those data and information sources that could be strengthened to better support future analytical efforts. The three analysis areas include (1) an evaluation of state highway seismic vulnerabilities and identification of priority highway routes; (2) a hazard exposure analysis and summary of stakeholder engagement findings for maritime transportation infrastructure; and (3) a hazard exposure analysis and summary of findings for rail infrastructure.

Background on the CSZ

The CSZ is a megathrust fault zone located off of the west coast of North America that stretches approximately 700 miles from northern Vancouver Island, Canada, to Cape Mendocino, Calif. (figure 2). Along this fault, three regional tectonic plates—the Explorer, Juan de Fuca, and Gorda plates—are pulling away from the larger Pacific plate and moving towards the North American plate. At the North American plate boundary, these three regional plates are descending—or subducting—underneath the North American plate (figure 3). As this subduction occurs, "a large portion of the boundary between the subducting and overriding plates resists the convergent motion, until this part of the boundary breaks in a great earthquake" (CREW 2013). Historic records suggest that the last such great earthquake along the CSZ boundary occurred in January 1700 with an estimated magnitude of 8.7-9.2 (Atwater et al. 2015). Furthermore, paleoseismology studies looking at centuries of seismic history in the region have identified numerous prior earthquakes that occurred as early as 1400 BC (Atwater et al. 2003). These studies place the likelihood of a major CSZ earthquake occurring in the next 50 years at approximately 10 percent[1] (Goldfinger et al. 2012).

Scientists project that a CSZ earthquake could occur with a magnitude of 9.0 and that the ground could shake for several minutes, releasing tremendous amounts of energy that could damage infrastructure and affect communities along the west coast of the United States and Canada. Since the mid-twentieth century, several other subduction zone earthquakes have occurred around the Pacific region that provide context for what the Pacific Northwest region could experience during a CSZ earthquake. These include an M9.2 earthquake in Prince William Sound, Alaska (1964); an M9.1 earthquake in Aceh-Andaman, Sumatra (2004); an M8.8 earthquake in Maule, Chile (2010); and an M9.0 earthquake in Tohoku, Japan (2011) (CREW 2013).

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[1] *Goldfinger et al. (2012) note that "time-independent probabilities for segmented ruptures range from 7–12 percent in 50 years for full or nearly full margin ruptures to ~21 percent in 50 years for a southern-margin rupture. Time-dependent probabilities are similar for northern margin events at ~7–12 percent and 37–42 percent in 50 years for the southern margin."*

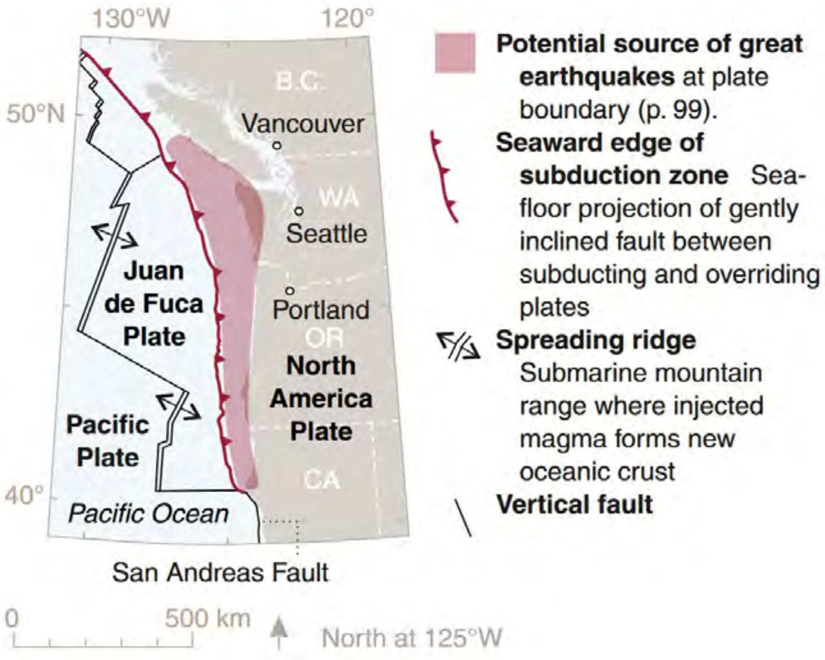

Figure 2: Cascadia Subduction Zone (CSZ) Geographical Extent (Atwater et al. 2015)

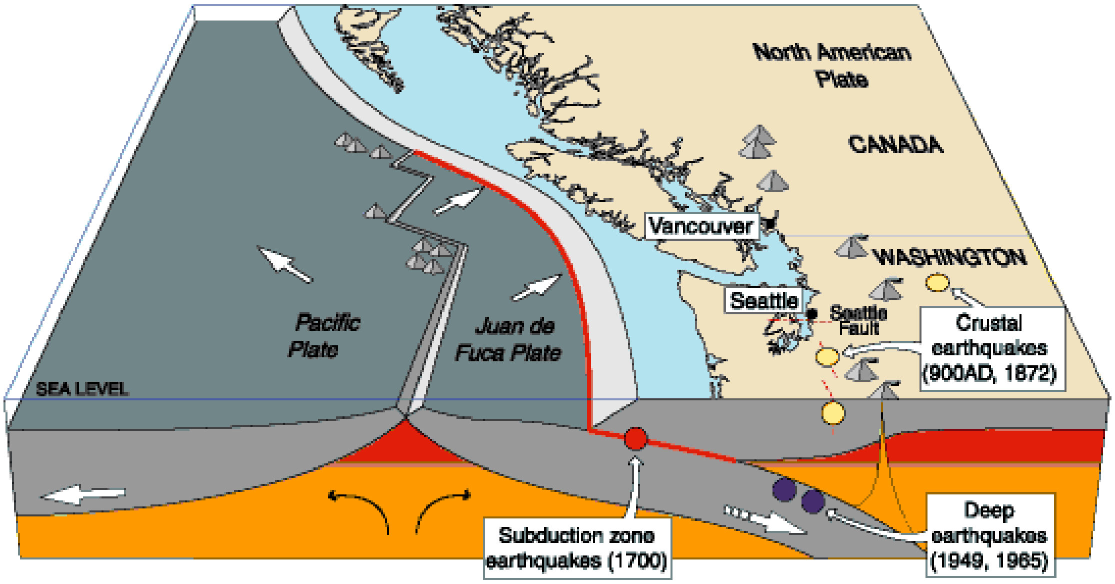

Figure 3: Plate Tectonics in the Cascadia Subduction Zone (CSZ) (Wells et al. 2016)

CSZ Seismic and Secondary Hazards

The primary hazard associated with a CSZ earthquake is strong and prolonged shaking, or ground motion, and the forces that such shaking can impart on infrastructure and the built environment. However, the primary earthquake can also trigger several secondary hazards associated with a CSZ earthquake. These include ground failure (e.g., landslides, ground displacement or deformation), tsunamis, and—particularly in winter months—avalanches. Both the primary and secondary hazards associated with a CSZ earthquake can cause significant damage to statewide transportation systems and can adversely affect their ability to facilitate response and recovery efforts. This section discusses the several hazards associated with a CSZ earthquake that this RRAP project considered, the supporting hazard data and information available that was used to inform this study's analysis, as well as any gaps in the available data and information that should be addressed in future work. While not all seismic and secondary hazards considered for this RRAP project were ultimately integrated into the analysis, they are discussed here to provide context for their exclusion, and identify actions that could be taken to better integrate them into future analyses.

Ground Motion

Ground motion is the most apparent and direct hazard associated with an earthquake. The size of an earthquake is expressed most commonly (by USGS and others) using the Moment Magnitude Scale (MMS), which quantifies the amount of energy that an earthquake releases (USGS Undated[a]). In this RRAP project, the core stakeholder group agreed that the "USGS M9.0 Scenario Earthquake – Cascadia M9.0 Scenario (mean value)" should form the basis for all analysis (USGS 2017). This USGS CSZ scenario is a 2017 update to an earlier 2011 USGS scenario that the Cascadia Region Earthquake Workgroup identified for use in regional catastrophic planning (CREW 2013). Earlier versions of this USGS CSZ scenario were also used in the HITRAC/NISAC study, the *Cascadia Rising* 2016 exercise, and FEMA's *Cascadia Subduction Zone (CSZ) Catastrophic Earthquake and Tsunami Response Plan (Ver. 2.0)* (FEMA 2013, 2015, NISAC 2011).[2]

Peak ground acceleration (PGA) is a quantitative measure of shaking intensity that is commonly used in infrastructure seismic design specifications and building codes. Whereas MMS is a measure of an earthquake's overall size, PGA is a location-specific measure of ground shaking intensity that can be used to approximate the seismic forces that a specific location or structure will experience during an earthquake.[3] PGA is the primary metric for earthquake intensity used in this study to assess the vulnerability of Washington State's surface transportation system to ground motion. Figure 4 shows the geographic information system (GIS) data collected from the USGS for PGA projected across Washington State under the USGS M9.0 CSZ scenario. The strongest shaking is projected to occur in the coastal, Olympic Peninsula, and southwestern parts of the state, and it will generally diminish moving east across the state. The USGS scenario study area ends at approximately 118° west longitude (just west of Spokane) with projected PGA values of approximately 0.04g. Minor shaking of 0.04g or less could still be expected to occur east of the USGS scenario study area in eastern Washington.

Subduction earthquakes, in general, typically experience a longer duration of shaking as compared with other types of earthquakes, which increases the potential for structures to sustain damage or to fail. The duration of shaking for a CSZ earthquake is projected to range from 2-6 minutes (CREW 2013, Resilient Washington State Subcommittee 2012). However, the effects of longer duration shaking on structures have not been widely studied and current seismic design specifications and codes do not explicitly consider shaking duration in structural design and assessment practices (Chandramohan 2016). This RRAP project incorporates some findings from this nascent field of research to account for the effects of longer duration shaking on transportation systems (see the accompanying report, *Washington State Highway Bridge Seismic Screening Tool – Technical Report*). However, significant additional research will be required to quantify the effects of long duration shaking on structural systems and to characterize more fully potential CSZ impacts in Washington State.

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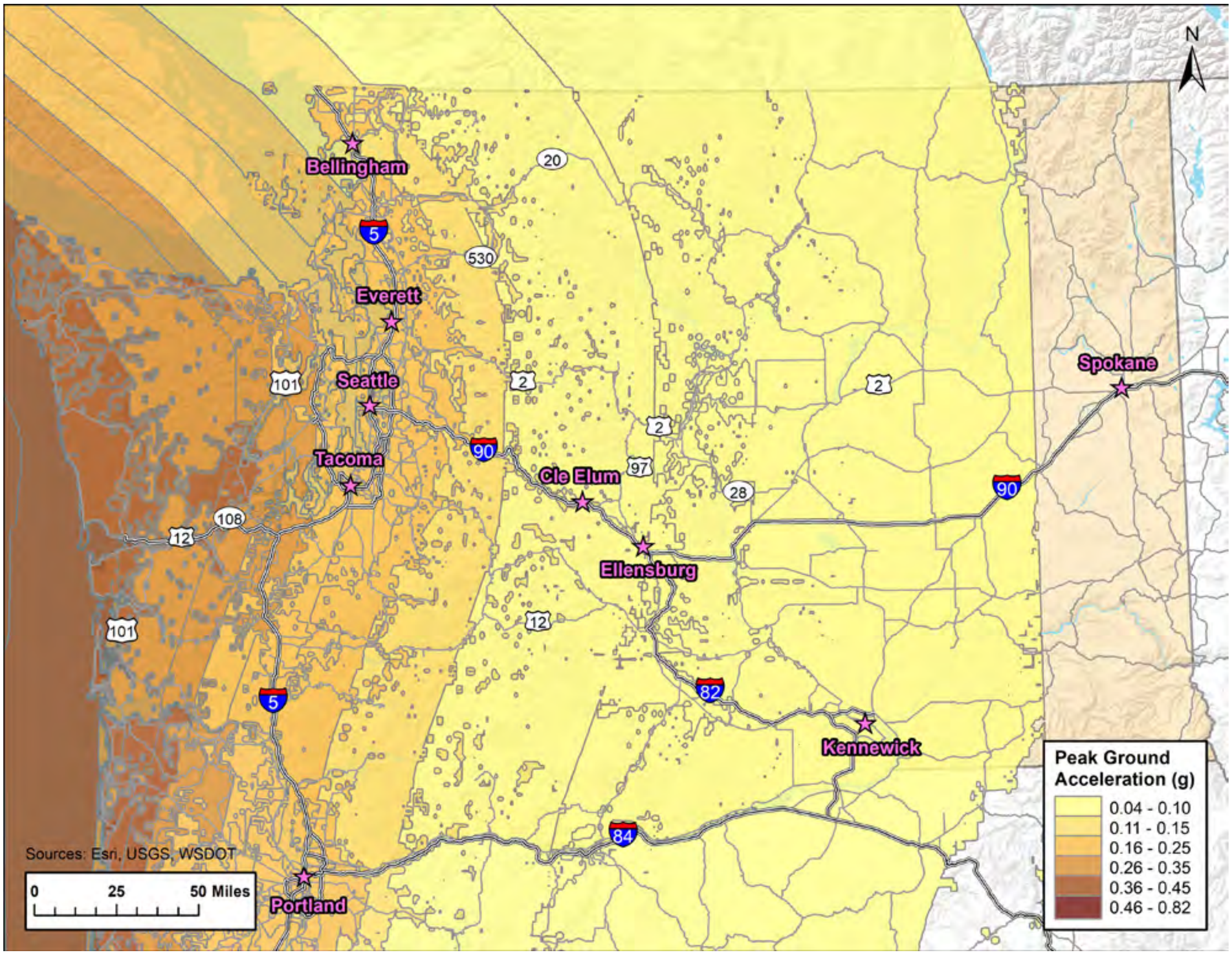
[2] *The University of Washington and the USGS's current "M9 Project" will offer improved characterization of a CSZ earthquake using dozens of scenarios, but was not available at the time of this RRAP study (Sherrod 2017, University of Washington 2018).*

[3] *PGA is expressed as an acceleration in units of **g**; 1 g is the Earth's gravitational acceleration, or 9.81 m/s^2*



Sources: Esri, USGS, WSDOT

Figure 4: Projected Peak Ground Acceleration (PGA) for Washington State under the USGS M9.0 CSZ Scenario

Strong aftershocks commonly occur in the hours, days, and weeks following subduction earthquakes. It is likely that strong aftershocks following a CSZ earthquake will cause additional damage to structures in the region; however, the occurrence of aftershocks and their impacts to already degraded infrastructure is impossible to predict. For these reasons, the core stakeholder group agreed that this study would focus on assessing impacts and vulnerabilities associated with the primary M9.0 earthquake and not attempt to address the impacts of aftershocks on Washington State's surface transportation system.

Ground Failure

Ground failure refers to a range of secondary hazards that can be triggered by an earthquake, in which ground and soils become unstable, shift, flow, or lose their load-bearing capacity and ability support structures.

Soil Liquefaction

Soil liquefaction (also referred to as liquefiable soils) refers to the phenomenon where certain types of soils that are saturated with water can behave like a liquid when they experience seismic shaking. Liquefaction can result in the loss of support for surface structures (e.g., buildings and bridges), soil flows on even very gentle slopes, and large differential settlements where areas of the ground surface sink in comparison to nearby or surrounding soils. Soil liquefaction occurs typically in alluvial soils—loose sand and silty soils that are characteristic of river valleys, river deltas, and other areas with flowing water (USGS 2006). DNR maintains a statewide geospatial database that characterizes soil liquefaction susceptibility in the top-most layer of soil for all of Washington State (figure 5) (DNR 2010). This dataset served as the primary basis for analyzing seismic-related ground failure impacts to the statewide surface transportation system in Washington State.

As shown in figure 5, highly liquefiable soils in Washington State occur most frequently along river valleys, with some broader concentration of soils with very low to low liquefaction susceptibility in the low-lying areas surrounding these rivers and streams. Soils with some liquefaction susceptibility— ranging from very low to high—underlay much of the Puget Sound region. Furthermore, approximately 80 percent of the more than 7,000 centerline miles of state-owned highways in Washington State are built on soils with some liquefaction susceptibility; and approximately 23 percent are built on soils with moderate-to-high or high liquefaction susceptibility.

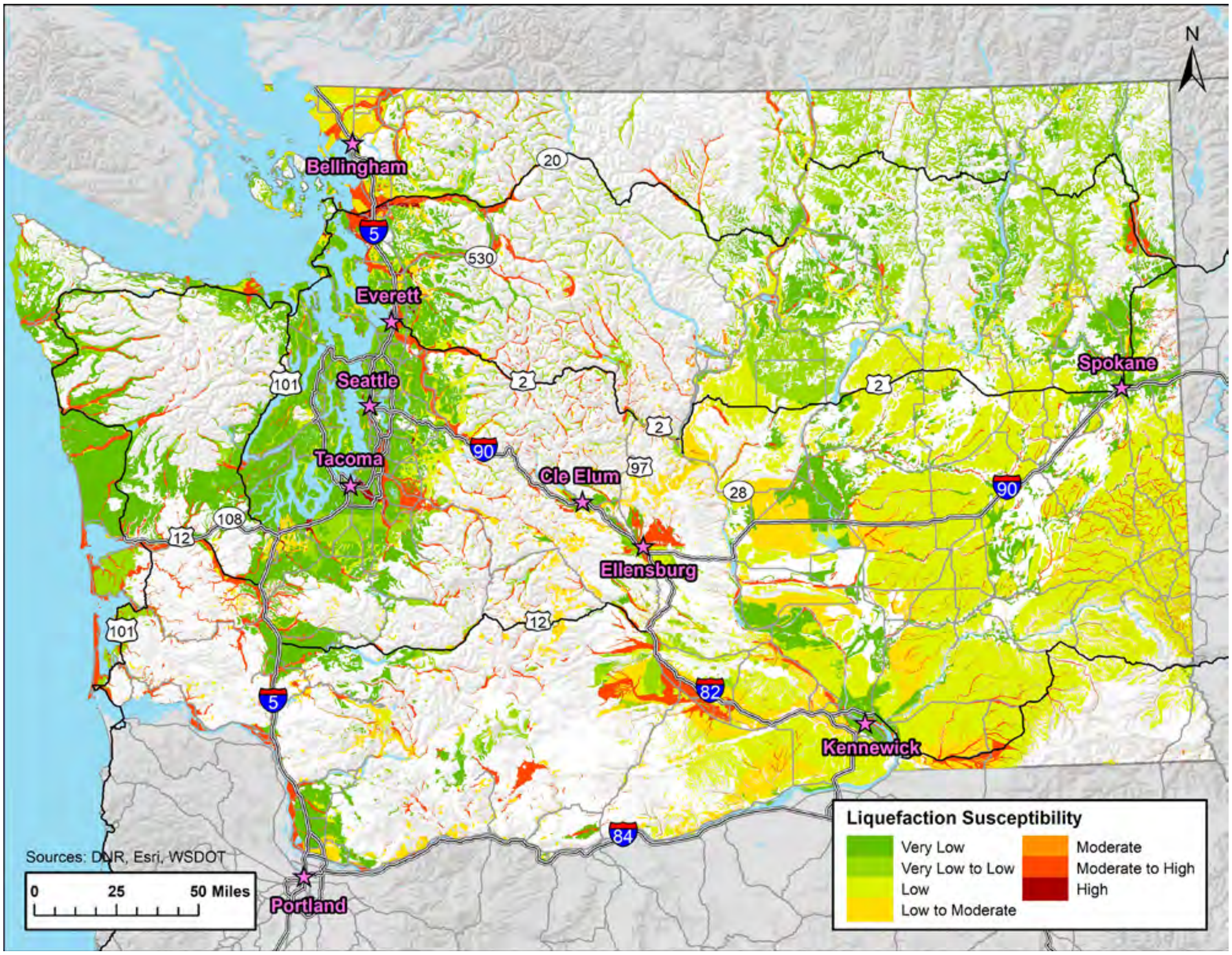


Figure 5: Soil Liquefaction Susceptibility in Washington State

The impacts of seismic-induced soil liquefaction to infrastructure is commonly quantified as permanent ground deformation (PGD), which refers to the vertical and lateral deformation of soil resulting from soil liquefaction, as measured in inches or feet of displacement. PGD can create significant disruptions to regional transportation systems. For highways, bridge foundations can fail leading to bridge failure, roadbeds and pavements can sink or shift creating significant cracking or discontinuities in the driving surface, and slopes or earth retaining structures adjacent to highways can fail. For rail infrastructure, rail lines can shift and buckle, rail yards can experience significant deformation or differential settlement, and rail bridges can experience impacts similar to highway bridges. Lastly, port and maritime infrastructure can experience differential settlement or liquefaction resulting in submarine landslides that can affect navigation channels, and also the potential failure of seawalls supporting port infrastructure.

FEMA’s HAZUS natural disaster risk model uses PGD as the primary measure of seismic-induced ground failure to evaluate infrastructure impacts. Accordingly, PGD is used in this study as the primary metric for ground failure to assess the State surface transportation system’s vulnerability to seismically induced soil liquefaction. PGD is calculated in this study using a method developed by Bardet, Mace, and Tobita (1999), which is described in greater detail in the accompanying report, *Washington State Highway Seismic Screening Tool—Technical Report*. However, using this method with the data currently available from DNR and WSDOT requires some analytical assumptions that introduce uncertainty into the analysis. Two of the primary inputs to calculating PGD are the local ground slope and the thickness of saturated soils where PGD is being calculated.

Ground slope can be readily approximated across the state using GIS software and a USGS-published digital elevation model dataset (USGS Undated[b]). This dataset expresses land surface elevations using a 10 meter grid, which is sufficient to calculate general slope trends. In some areas, however, slope calculations using this dataset may be underestimated where local embankments or slopes fall within the 10 meter grid. By comparison, determining the thickness of saturated soils is difficult. DNR catalogs the topmost layer of soils in Washington State according to its liquefaction susceptibility, but it does not categorize the liquefaction susceptibility of deeper or underlying soil layers. As the thickness of saturated or liquefiable soils is not known, the thickness of liquefiable soils throughout the state must be assumed in order to approximate PGDs. The RRAP research team discussed and agreed upon these assumptions with the WSDOT State Geotechnical Engineer and DNR Assistant State Geologist, who also indicated that collaborative efforts are ongoing between their two departments to better catalog historical and ongoing subsurface exploration and boring projects across the state. A more complete catalog of subsurface conditions will reduce the uncertainty in liquefaction vulnerability and PGD projections for infrastructure systems throughout the state.

Landslides, Debris Flows, and Rock Falls

Landslides, debris flows, and rock falls are three types of slope failures that earthquakes can trigger. These types of slope failures occur along state highways in Washington even under normal conditions, and WSDOT mitigates them as part of ongoing highway operations and maintenance. However, a major CSZ earthquake could cause significant additional slope failures to occur. The RRAP research team reviewed the available landslide data in WSDOT’s Unstable Slope Management Program (WSDOT 2017a). However, WSDOT’s Chief Engineering Geologist, and Safety and Emergency Operations Manager stressed during discussions that the Unstable Slope Management Program only addresses known slope hazards—that is, historic or chronic slope failures across the state. The current database does not include any considerations of seismic-related impacts, nor does it catalog *potential* unstable slopes or slope failures that a major earthquake or other natural event could trigger (WSDOT 2017b). WSDOT did note that some known landslides could prove quite time consuming to clear, but that the number of such landslides is relatively small and that the severity of their impacts following a CSZ is uncertain and difficult to predict. Given these uncertainties and the shorter amount of time required to clear landslide debris for the majority of individual slides, as compared with bridge repair and reopening times, the RRAP research team excluded such slope failure hazards from this analysis of statewide surface transportation seismic vulnerability.

Tsunamis

A tsunami is a large sea wave (or series of waves) that occurs when some incident or disruption displaces a large volume of water. In the context of a CSZ earthquake, displacements in the ocean floor associated with a fault rupture will propagate an ocean wave; the amplitude of the wave will increase as it travels out from the fault line and approaches shallower water near the coastline. The first CSZ tsunami wave is projected to reach the coastline within 20 to 30 minutes of the initial earthquake with wave heights up to 30 to 40 feet. Given the experiences of similar coastal subduction zone earthquakes around the world, this initial tsunami wave could be followed by subsequent waves in the hours following the earthquake (CREW 2013).

Tsunamis can affect coastal transportation infrastructure systems in a number of ways. The large volume of water moving inland can inundate infrastructure for hours or days until floodwaters drain and subside. Tsunami waves can impose tremendous lateral and uplift forces on structures, such as bridges, docks or other marine structures, which can cause structural damage or failure. Similarly, the swift movement of tsunami inundation water around bridge columns or piers can rapidly deteriorate or remove the soils that support bridge pier foundations—a condition referred to as bridge scour—increasing the potential for structural failure. WSDOT maintenance personnel also indicated that if flooding is prolonged, water infiltration into road subgrades and bridge abutments could lead to the accelerated deterioration of pavement structures.

Tsunamis also create strong currents and wave forces that can dislodge and carry large quantities of floating debris and suspended sediments. Debris can collect near structures, such as bridges and docks, exerting additional lateral forces on the supporting superstructure, or block waterway access to coastal infrastructure, such as ferry terminals and commercial ports. Sediments can collect in shallower waterways and coastal areas restricting the draft of vessels that can operate in those waterways and access nearby maritime facilities. Debris must be removed before marine vessels can resume operations and waterways may require dredging to remove sediments and restore operating depths.

DNR publishes two GIS datasets representing tsunami impacts along Washington State's shorelines, each of which aggregate a number of smaller studies conducted along portions of the state's coastline. The first dataset, the 1A Scenario, contains projected tsunami inundation data associated with a 500-year tsunami event; the second dataset, the L1 Scenario, contains projected tsunami inundation data associated with a 2,500-year event. The 1A Scenario dataset is limited only to information projecting the geospatial extent of tsunami inundation. That is, it does not contain information about inundation depth, flow velocity, or other metrics that could be useful to planners and engineers. Furthermore, the 1A Scenario dataset covers a relatively small portion of Washington's coastlines, focusing primarily on those areas with coastal communities or populations. The L1 Scenario dataset, in contrast, contains more information characterizing tsunami hazards, including inundation depth and flow velocity; it also models a significantly larger extent of Washington's coastlines than does the 1A scenario (see figure 6 for a comparison of coverage areas).

At the beginning of this RRAP study, DNR had only published the 1A Scenario dataset. As a result, the 1A Scenario formed the basis for early analysis activities in this study, particularly those focused on highway bridge structure impacts. DNR later published the L1 Scenario dataset after a substantial portion of this study's analysis was completed, and therefore use of the L1 Scenario was limited primarily to analysis of inundation impacts to coastal port facilities. However, a review of tsunami impacts to bridges found that only five highway bridges within the 1A and L1 Scenario study areas were at risk of significant scour-related impacts along the Pacific coast, where the two scenario study areas are very similar. Therefore, the RRAP research team estimates that the impacts of using the 1A Scenario instead of the L1 Scenario for bridge impact analyses is minimal.

As noted, neither the 1A nor the L1 Scenario datasets comprehensively characterize tsunami impacts to Washington coastlines, but instead focus primarily on the more populace portions of the coastline. While the L1 Scenario dataset characterizes a comparatively greater extent of coastline than does the 1A Scenario dataset, some infrastructure systems still fall outside of their current modeling extents, such as coastal roadways, bridges, ferry terminals, and some commercial ports. These data gaps prevent analysis of tsunami impacts to surface transportation infrastructure located outside of the tsunami study areas. Through discussions with the RRAP research team, DNR indicated that additional tsunami modeling efforts are planned for portions of the coastline not currently modeled in the 1A or L1 Scenario datasets. The outcomes of these future studies could provide significant additional insight into coastal and maritime infrastructure seismic vulnerability assessments, and should be integrated into such studies when modeling is complete.

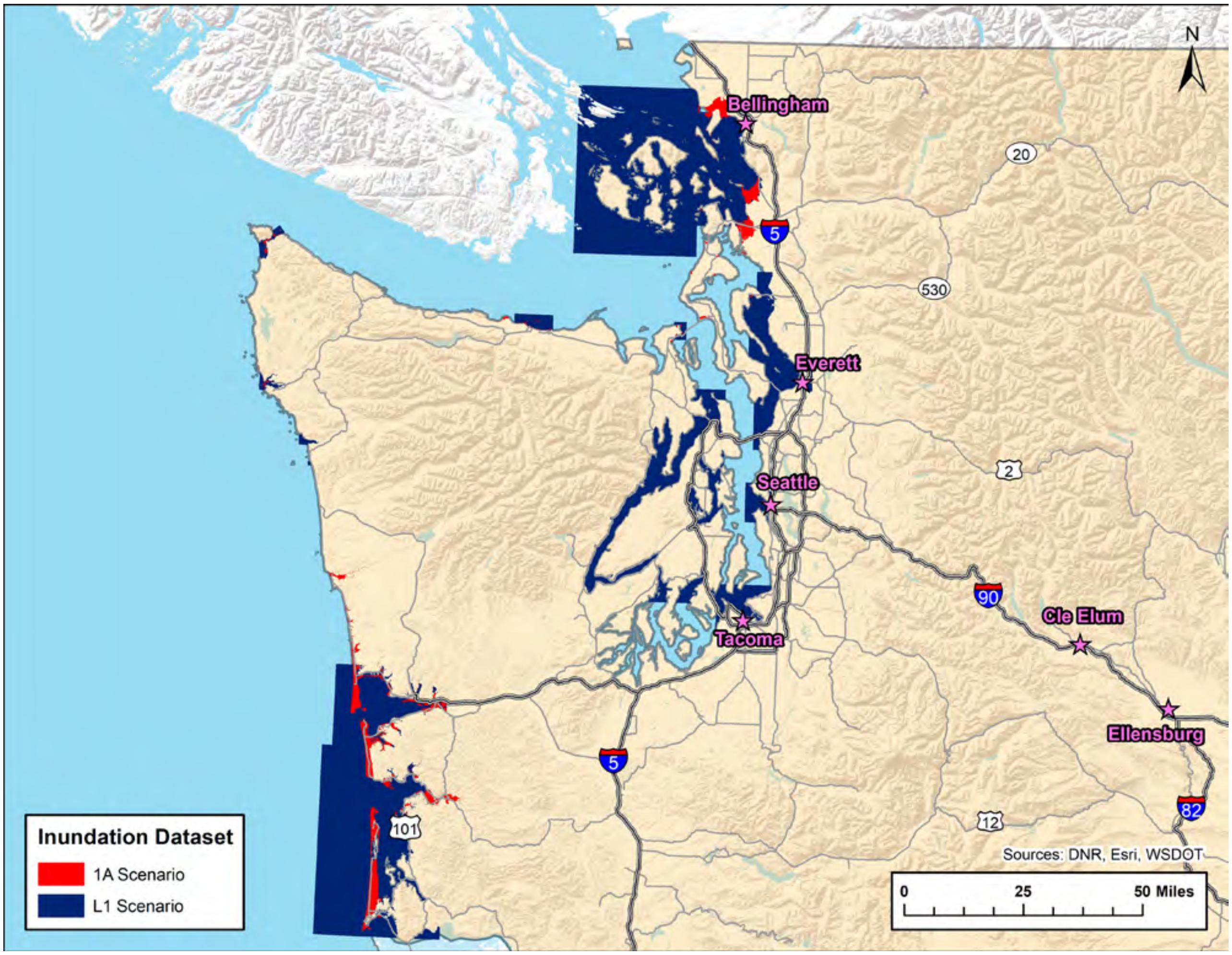


Figure 6: Washington State DNR Tsunami Inundation Datasets Coverage Comparison

Avalanches

The Cascade Mountains experience significant seasonal snowfall that has historically affected transportation routes traversing between the western and eastern parts of the state. Throughout the fall and winter months, WSDOT actively forecasts and manages avalanches along major state highways (WSDOT 2015a). WSDOT catalogs and maintains GIS datasets that characterize known or historic avalanche paths across the state to aid in avalanche management and control. The RRAP team discussed with WSDOT the potential to include avalanches in this study, but it ultimately excluded them from this analysis. WSDOT avalanche management staff indicated that avalanches typically only affect highway operations, and not the underlying infrastructure itself. That is, once avalanche snow is removed from roadways, no underlying physical impacts typically require repair before highways are reopened. Furthermore, the amount of time required to clear avalanche snow—even when that snow is mixed with rocks, vegetation, or other debris—is very short in comparison to the time required to repair other infrastructure physically damaged during a CSZ earthquake.

Highway Vulnerability Analysis and Prioritization

The primary analytical objective of this RRAP project was to evaluate the seismic vulnerabilities of state highway infrastructure to a CSZ earthquake and to identify priority routes that may be reopened most quickly following a disaster to reestablish connections between the ISBs and FSAs. These priority routes constitute highways that, based upon the analysis conducted, are less vulnerable to the hazards associated with a CSZ earthquake and therefore may have a shorter reopening time in comparison to other state highways. Identifying priority routes will enable state officials to focus infrastructure investment on those state highway routes to harden or increase their resilience to seismic impacts, or to target post-earthquake response and restoration activities along those routes to most efficiently reestablish supply lines into the affected region.

To determine the priority highway routes in the state, the RRAP research team conducted a system-level assessment of state highway infrastructure to assess its seismic vulnerability to a CSZ earthquake. The assessment then determined approximate reopening times for highway routes based on the projected level of damage that they will experience. To accomplish this, the RRAP research team first subdivided the entire state highway network into a series of 21,356 discrete segments and identified the infrastructure assets (i.e., bridges and pavements) that comprise those highway segments. The team then evaluated the impacts of seismic hazards to those transportation system assets and determined the approximate reopening times for each of these individual segments based on the projected damage to their bridges and highway pavements. These segment-based reopening times then fed into a mixed-integer linear programming model that computed the optimal path connecting the primary ISB and all FSAs that has the lowest aggregate reopening time. The following sections describe the methodology and results for the bridge and highway assessments that fed into the prioritization model, and then the highway network optimization/prioritization model itself.

This study focused on *reopening* times instead of *restoration* times. While restoration time generally refers to the amount of time required to restore facilities to a fully operable, pre-disaster state of repair, reopening time simply refers to the amount of time required to bring transportation infrastructure and facilities back to a minimally acceptable state of repair. That minimally acceptable state of repair is intended to be sufficient to enable the initial movement of emergency response vehicles and resources into the affected region, but not to support broader inter- and intra-regional mobility. The RRAP sponsor and core stakeholders recommended this use of reopening times given this study's focus on the immediate response to a CSZ earthquake and the reestablishment of emergency supply lines into western Washington.

Restoration vs. Reopening Time

In a post-disaster emergency environment, ***restoration time*** refers to the amount of time needed to return an asset or facility to its pre-disaster condition. For example, highway bridges would be replaced or returned to a condition sufficient to allow the traveling public to use that bridge safely, and without any temporary restrictions on weight or other operating factors.

In contrast, ***reopening time***, as it is used in the context of post-disaster activities in this study, refers simply to the time required to repair an asset or facility to a minimum safe condition that would enable emergency responders to use the facility, but not sufficient for broader or unrestricted use by the general traveling public.

While this study approximated reopening times for individual assets (e.g., bridges, pavement segments), it did so at a system-level using infrastructure screening tools. While these screening tools used facility-specific asset management information, they did not conduct detailed, asset-level engineering analysis of individual facilities. These results can inform system- or network-level optimization analyses, state asset management activities, or identify where additional, asset-level engineering analyses may be needed, but they do not predict the specific seismic impacts and damage states of individual assets from a CSZ earthquake.

Bridge Seismic Screening Analysis

WSDOT owns and manages 3,495 highway bridges across Washington State, which serve as critical links within the state highway system across otherwise impassable rivers, terrain, and other roadways or obstacles. When damaged, bridges can require significant time and resources to reopen and reestablish these connections, which can contribute significantly to the overall reopening time of highway routes. Accordingly, an important part of this RRAP project's system-level assessment was to assess the seismic vulnerability of state highway bridges to a CSZ earthquake. To accomplish this, the RRAP research team worked collaboratively with

WSDOT bridge engineers to develop the Bridge Seismic Screening Tool (BSST) that assessed the potential impacts that a CSZ earthquake could have on state highway bridges and determined approximate reopening times for each bridge. This section provides an overview of the BSST and presents the screening analysis results that inform the optimization analysis. The supplemental document, *Washington State Highway Bridge Seismic Screening Tool – Technical Report*, provides a more detailed discussion of the development, implementation, and data supporting the BSST.

The BSST analysis focused on 2,717 highway bridges that WSDOT owns and manages in western and central Washington. While WSDOT owns a total of 3,495 bridges, WSDOT and the RRAP team agreed to exclude from this analysis bridges located in the state's eastern-most counties,[4] which are not projected to experience PGA levels sufficient to cause serious damage.

The BSST methodology, shown in figure 7, began by evaluating each bridge's structural configuration, separating out those "special bridges" with non-standard design configurations. These 35 special bridges include, for example, suspension bridges, moveable bridges (e.g., draw bridges), and floating bridges, which are evaluated separately on an individual basis using the expert opinion and input of WSDOT bridge engineers. The remaining 2,682 bridge were then evaluated with respect to the seismic design of their superstructure. This first considered whether a bridge was built or retrofitted (under WSDOT's statewide seismic retrofit program) using design standards that incorporate seismic design considerations (WSDOT 2015b). If a bridge was built using seismic design standards, the BSST then evaluated whether the PGA that a bridge is projected to experience during a CSZ earthquake will exceed the PGA specified by the prevailing design standard that was in use when the bridge was either built or retrofitted. This seismic design assessment also incorporated a PGA adjustment factor to account for the effects of longer-duration shaking on bridge seismic performance.

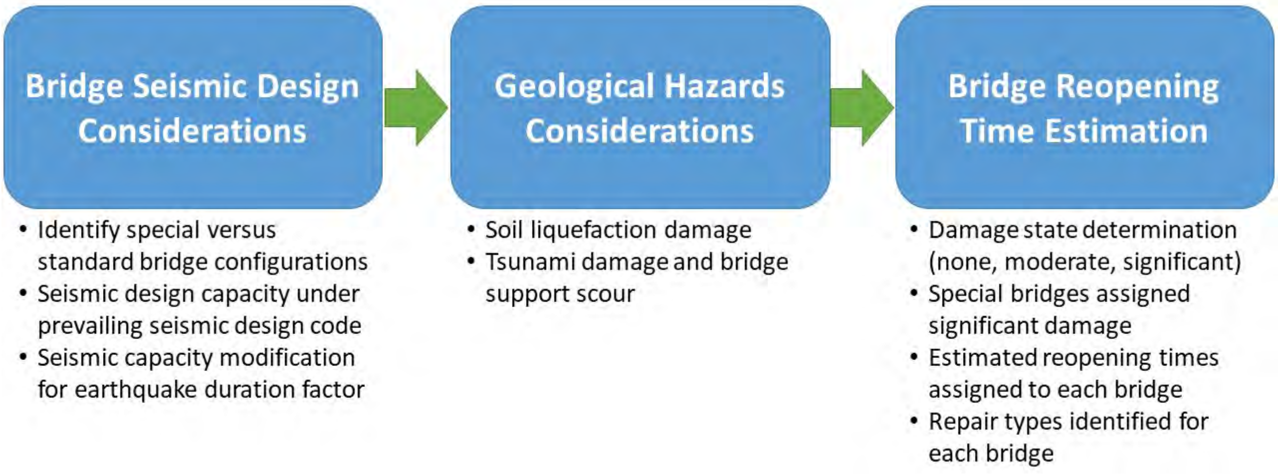


Figure 7: Bridge Seismic Screening Tool (BSST) Methodology

The BSST then evaluated the vulnerability of bridges to two primary geological hazards associated with a CSZ earthquake—soil liquefaction and tsunami inundation. Soil liquefaction was evaluated by comparing the PGA that a bridge is projected to experience during a CSZ earthquake with the liquefaction susceptibility data that DNR provided, and several PGA liquefaction thresholds that were determined in consultation with WSDOT's State Materials Laboratory and State Geotechnical Engineer. Tsunami vulnerability was evaluated by looking at bridge overtopping by a tsunami wave or related flooding, and scour damage potential to the supporting substructure.

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[4] *These counties include Adams, Asotin, Benton, Columbia, Ferry, Franklin, Garfield, Lincoln, Pend Oreille, Stevens, Spokane, Walla Walla, and Whitman.*

Finally, the BSST assigned approximate reopening times to bridges using damage types calculated during the seismic design analysis, liquefaction and scour considerations, and additional bridge characteristic information such as bridge length and the obstacle that the bridge traverses (e.g., river, ravine, surface roadway). The RRAP team developed and agreed upon the damage types and approximate reopening times shown in table 1 in collaboration with WSDOT's bridge office. State bridge engineers emphasized that that these bridge damage estimates and reopening times likely constitute a worst-case scenario for bridge seismic performance and damage outcomes. The BSST also provides some broad information about the types of actions that may be needed to reopen bridges or reestablish connections at those locations, as shown in table 1. These include the possibility of local temporary bypass roads around collapsed bridges (e.g., highway overpasses) and whether soil liquefaction is projected to be a contributing factor to damage that could require subsurface strengthening prior to reopening.

Table 1: Bridge Reopening Times and Repair Types Criteria

Damage Level	Damage Type	Consideration	Bridge Length (ft)	Reopening Time	Repair Type
None	None	None	N/A	0 days	None
Moderate	Minor or None	None	N/A	2 weeks	Bridge inspection and minor or no repairs
Significant	Any significant damage type	Bridge not over waterway or impassable topography	> 50	2 weeks per 50 ft. of bridge length	Temporary road
			≤ 50	2 weeks	
	Significant damage without soil liquefaction	Bridge over waterway or impassable topography	> 150	2 years	Major bridge rehabilitation or replacement
			≤ 150, > 50	14 months	
			≤ 50	7 months	
	Significant damage with soil liquefaction	Bridge over waterway or impassable topography	> 150	2.5 years	Major bridge rehabilitation or replacement and subsurface strengthening
			≤ 150, > 50	1.5 years	
			≤ 50	8 months	

Bridge Seismic Screening Results

The BSST results project damage types on the basis of damage level (None, Moderate, Significant), bridge characteristics (e.g., special bridge, bridge length), and the types of damage that the bridge will experience (see the *Washington State Highway Bridge Seismic Screening Tool – Technical Report* for a full discussion of damage type results). These BSST damage type results for the CSZ scenario earthquake are shown in figure 8. While a large number of bridges evaluated are projected to experience no damage (621 bridges), nearly 76 percent of the bridges evaluated are projected to experience some level of damage (excluding special bridges). Of those bridges projected to experience some level of damage, over 32 percent (670 bridges) are projected to experience significant damage as a direct result of inadequate seismic design (i.e., the seismic demand exceeds the bridge's current seismic design capacity).

Furthermore, nearly 32 percent of the bridges projected to experience significant damage will do so as a combined result of inadequate seismic design and potential soil liquefaction affecting the bridge's substructure. In fact, soil liquefaction affects nearly 40 percent of the bridges projected to experience significant damage as a result of the CSZ scenario earthquake.

In western Washington and the Puget Sound region, results indicate a high concentration of bridges with damage types related to inadequate seismic design (PGA) and combined inadequate seismic design and potential soil liquefaction (PGA/liquefaction). However, moving eastward along the primary routes crossing the Cascade Mountains, potential soil liquefaction becomes the predominant projected damage type despite adequate superstructure seismic design. This transition is particularly evident on Interstate 90, US Route 2, State Route 20 and State Route 530, which are largely built in river valleys. East of the Cascades, a significantly greater number of bridges are projected to experience no damage. Of the bridges east of the Cascades that are projected to experience some damage, most only experience moderate damage. Although many of these bridges do not experience PGAs exceeding their seismic design capacities, PGAs could still cause moderate damage to structures requiring repairs before reopening.

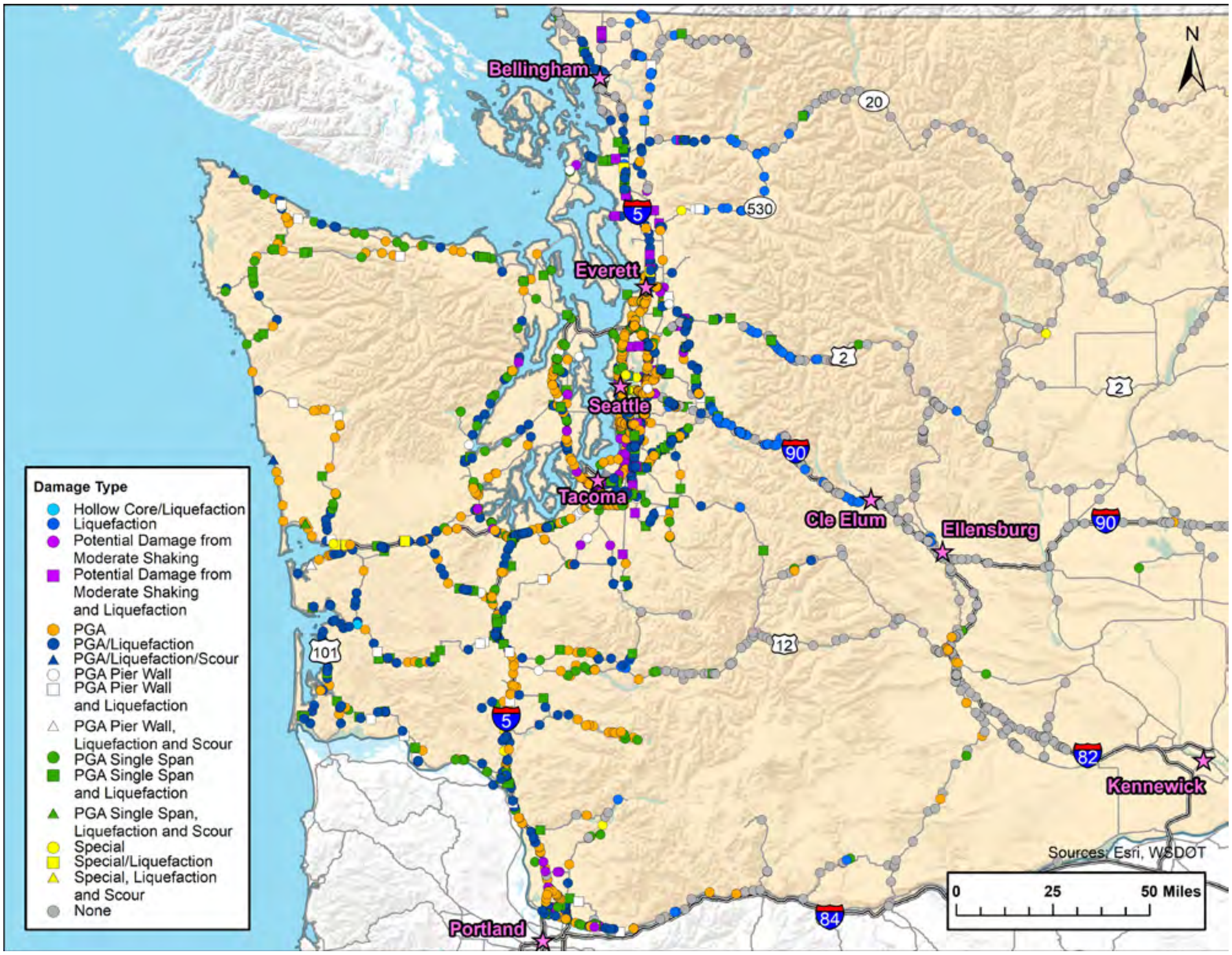

Figure 8: Bridge Seismic Screening Tool (BSST) Projected Damage Types for Highway Bridges in Washington from the CSZ Scenario Earthquake

Encouragingly, this analysis projected that no highway bridges will suffer damage due to tsunami overtopping following the CSZ scenario earthquake, and that only five highway bridges could suffer significant scour damage from an earthquake-induced tsunami. However, limitations of the methodology used for assessing bridge vulnerability to overtopping during tsunamis may underestimate tsunami risks, and these results should be tested further using the L1 tsunami scenario dataset. Additionally, both the 1A scenario used in this bridge analysis, and the L1 scenario proposed for future use, do not offer comprehensive coverage of Washington coastlines, and only bridges on the state highway system within the 1A tsunami study areas were assessed. Therefore, it is possible that bridges outside of the current tsunami study zones, and also non-highway bridges (e.g., county, city, or privately-owned bridges) that were not considered in this analysis, could be affected by tsunami impacts.

The projected repair types offer some insight into the types of conditions that WSDOT may need to address to reopen bridges to a minimum level of functionality that enables their use for emergency response. These results are shown in figure 9. A large number of the bridges evaluated (951 bridges, or 35 percent) can be reopened by establishing a temporary roadway that bypasses the bridge. However, of the bridges that require some level of intervention greater than inspection and minor repair, the majority (797 bridges) are crossings over water that could require a new bridge to be built. In addition, 662 of these crossings are also proximate to liquefiable soils that could require subsurface stabilization or strengthening prior to the construction of a new bridge. Constructing new bridges across waterways requires the greatest amount of reopening time, particularly at wide crossings. Consequently, efforts to strengthen or enhance the resilience of such crossings could have the greatest returns in buying down bridge reopening times, and ultimately the reopening times for entire corridors.

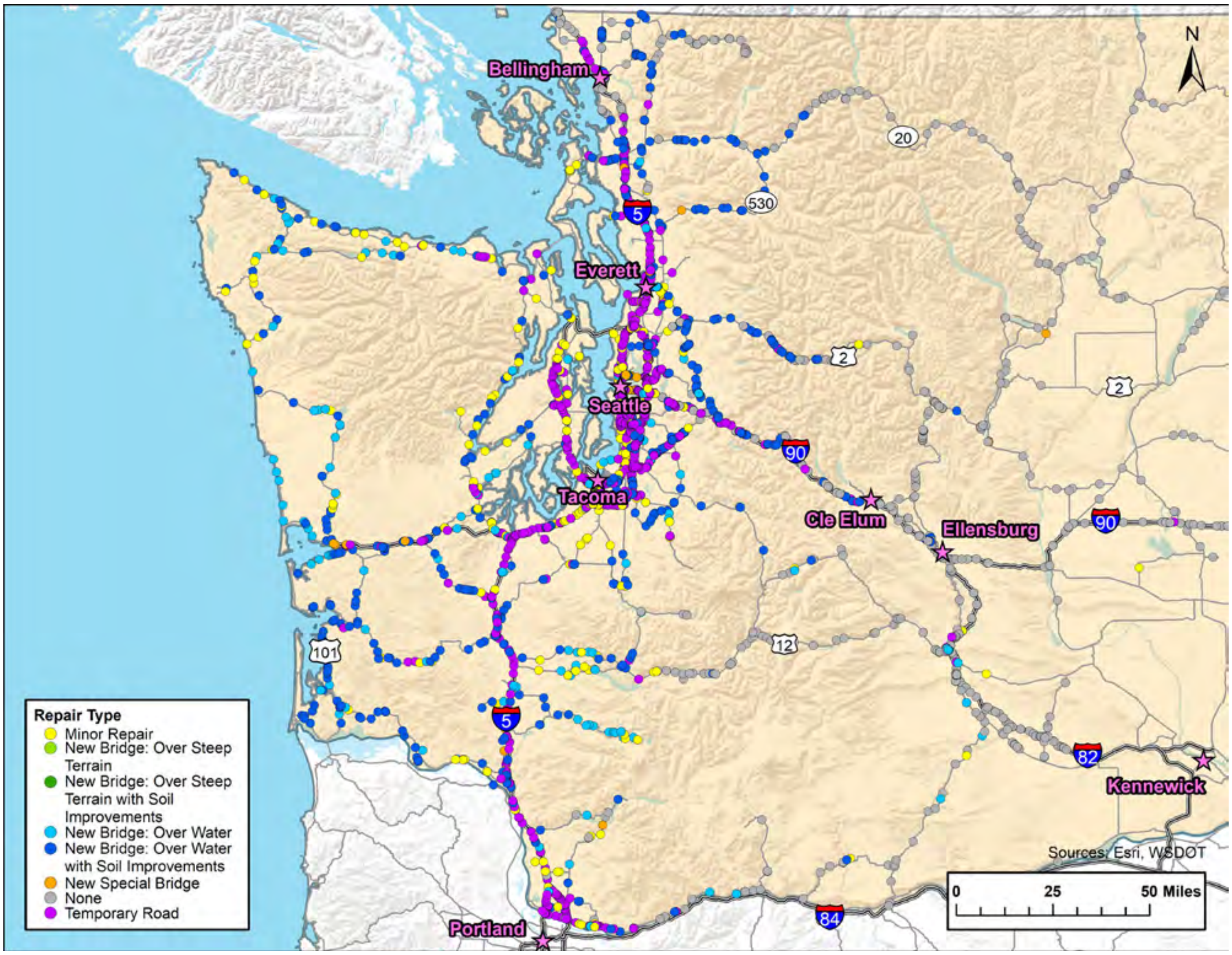

Figure 9: Bridge seismic Screening Tool (BSST) Projected Reopening Repair Types for Highway Bridges in Washington after the CSZ Scenario Earthquake

Along the Interstate 5 corridor, the dominant repair type required to reopen bridges is the construction of temporary bypass roadways. However, a substantial number of bridges along that same corridor are also projected to require new bridges over waterways, in many cases with soil improvements. The dominant repair type projected for bridges located on the major routes crossing the Cascade Mountains is also new bridges over waterways, again, in most cases with soil improvement. This finding is consistent with the results discussed earlier, as many of these routes follow river valleys leading into the mountains from western Washington. On the Olympic Peninsula and in much of southwestern Washington, where bridges frequently cross rivers and other water features, the majority of bridges are also projected to require new bridges over water. Particularly along the southern coastal region, many of these bridge repairs may also require subsurface strengthening or improvement given the prevalence of liquefiable soils.

Figure 10 shows the results of the reopening times approximation from the BSST; these reopening times are also summarized in Table 2. While 621 bridges are projected to sustain no damage, and therefore have no projected delay in reopening from a structural perspective, it is important to note that WSDOT may still choose to conduct inspections on many of these bridge structures prior to reopening, which could cause minor delays. Nonetheless, 13 percent of bridges (or 363 structures) could be reopened within the first month after the earthquake occurs following inspections and minor repairs. Conversely, 782 bridges, or nearly 29 percent of those bridges evaluated would require over 1 year to reopen, and in many cases, 2 years or more. Repair and reopening times are greatest in the Puget Sound and southwestern coastal regions of the state, and on the Olympic Peninsula.

These results are generally consistent with the higher PGAs that will be experienced in these regions given their proximity to the fault line. On the Olympic Peninsula and in the southwestern coastal region, these longer repair and reopening times are also consistent with repairs requiring the construction of new bridges over water, and frequently with soil improvements.

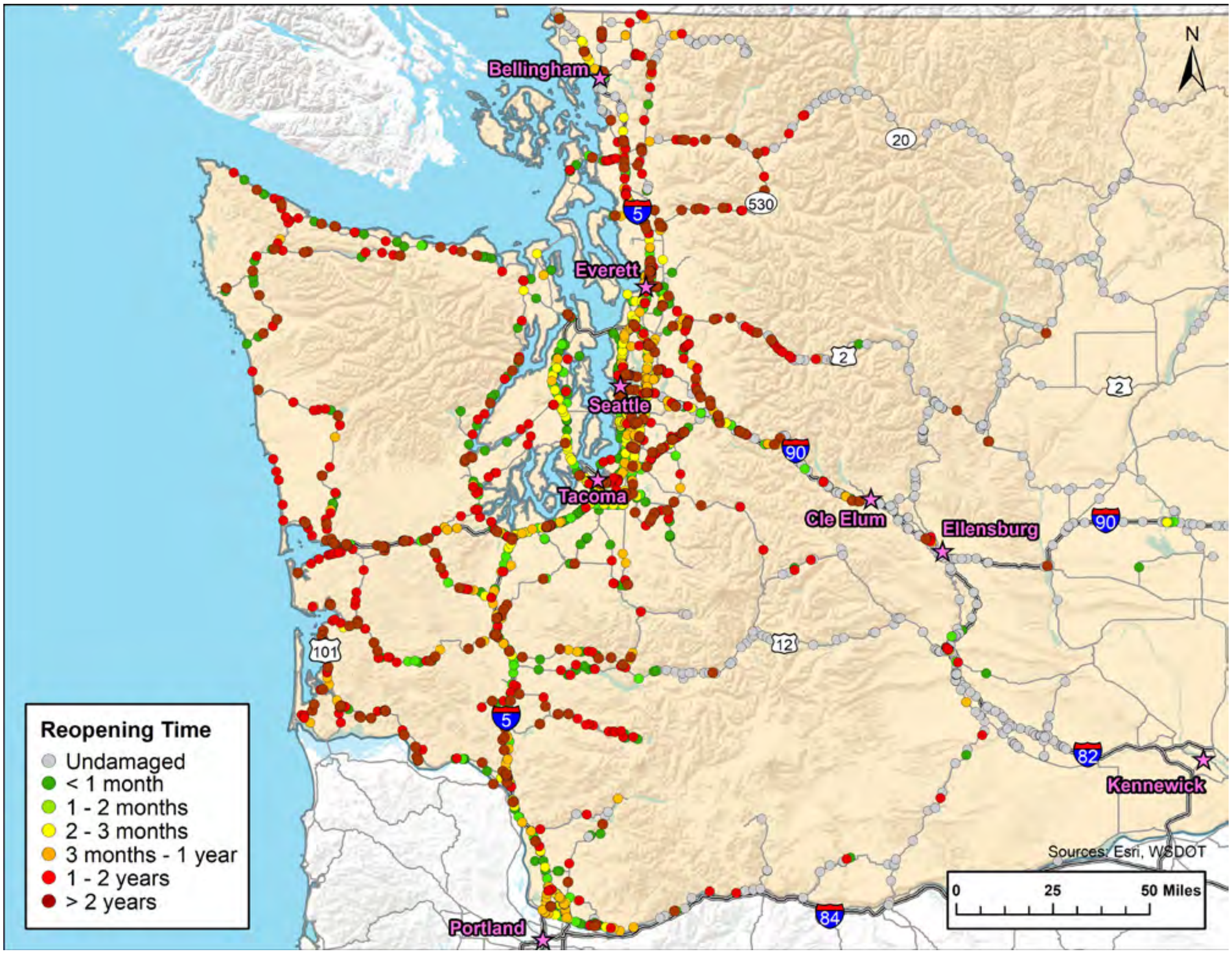

Figure 10: Bridge Seismic Screening Tool (BSST) Projected Reopening Times of Highway Bridges in Washington after the CSZ Scenario Earthquake

Table 2: Summary of Bridge Seismic Screening Tool (BSST) Projected Reopening Times of Highway Bridges in Washington after the CSZ Scenario Earthquake

Reopening Time	Number of Bridges
None	621
1–14 days	317
2–4 weeks	46
1–3 months	627
3–6 months	165
6–12 months	159
1–1.5 years	304
1.5–2 years	120
2–2.5 years	352
> 2.5 years	6

Highway Seismic Screening Analysis and Results

The Washington State highway system comprises 7,050 centerline miles of highways owned and managed by WSDOT.[5] During a CSZ earthquake, these highways may be exposed to ground failures that could result in significant damage to the highway surface or supporting soils, rendering the highway impassable. The RRAP research team worked collaboratively with WSDOT's Maintenance Office and pavement engineers to develop the Highway Seismic Screening Tool (HSST) to assess the potential impacts that a CSZ earthquake could have on highway pavements, and to determine approximate per-mile reopening times for highway segments. The HSST calculates PGD on an individualized basis for each highway segment in the state highway network to assess the damage to pavements from CSZ earthquake-induced liquefaction in the underlying soils. This section provides an overview of the HSST development, implementation, and results that inform the larger highway network optimization and prioritization analysis. The supplemental document, *Washington State Highway Seismic Screening Tool—Technical Report*, provides a more detailed discussion of the development, implementation, and data supporting the HSST, including a detailed discussion of PGD calculations and assumptions.

The HSST analysis focused on all 7,050 miles of state highways, as well as adjacent on-/off-ramps to intersecting roadways. The HSST methodology, shown in figure 11, began by subdividing the state highway network into discrete segments, which vary in length from several hundred feet to several miles, for analysis. Segments endpoints were identified at intersections between interstates, state highways, and primary roadways; transitions of the highway into and out of regions with liquefaction-prone soils; and transitions of the highway into and out of areas of known landslides. The resulting highway network, which included on- and off-ramps, consisted of 21,356 segments covering more than 9,425 miles.

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[5] *This excludes on-ramps, off-ramps and other connections to non-WSDOT-owned roadways.*

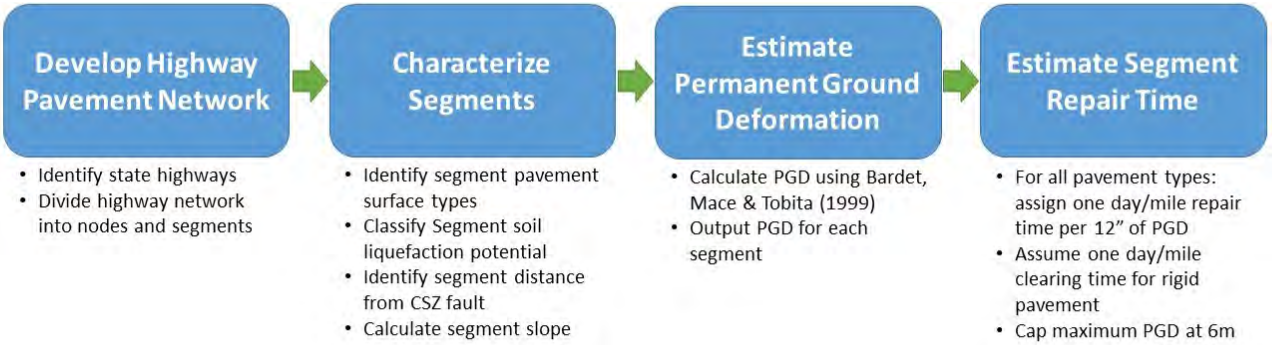

Figure 11: Highway Seismic Screening Tool (HSST) Methodology

The HSST characterized each segment in the highway network according to four factors: segment soil liquefaction potential, distance from the CSZ fault, relative ground slope, and segment pavement type (using WSDOT's Washington State Pavement Management System Surface Type dataset [WSDOT 2016]). These four factors were then used to calculate PGD values for each segment using the method outlined by Bardet, Mace, and Tobita (1999), and estimated segment repair and reopening times using metrics developed in close collaboration with WSDOT's Maintenance Office. As with bridges, an important underlying assumption in these repair and reopening times was that they specify the amount of time necessary to repair pavements to a minimum acceptable state of repair to facilitate the movement of emergency response and supply vehicles, and not restoration to a pre-disaster state of repair. WSDOT and the RRAP research team agreed that a temporary wearing surface composed of compacted crushed gravel would provide a sufficient surface for such activities, and assumed that a single lane of travel would be sufficient for initial response operations, but could be expanded later during the ongoing response.

The results of the highway seismic analysis indicate that although 8,434 of the segments evaluated are located on liquefiable soils, the majority of highways will experience relatively low PGD—74.1 percent of highway miles will experience less than 6 inches of PGD, with approximately 31 percent of those miles experiencing none at all. As shown in figure 12, the highest average per-mile repair and reopening times coincide with high PGD values projected to occur from the Interstate 5 corridor to the west, with the most significant PGD occurring in southwestern Washington and on the Olympic Peninsula. Moderate to minor PGD is projected to occur along highways leading into the Cascade Mountains, heading east from the Interstate 5 corridor up to the topographic divide, where average, per-mile repair and reopening times become comparatively lower. A few locations with higher PGD values occur in the river valleys along the major east-west routes. PGD east of the Cascades is projected to be at either very minor or insignificant levels.

The repair and reopening times for highway pavements largely mirror the results of projected PGD magnitudes; however, some variability appears in repair times given the varying types and thicknesses of highway pavement structures. The analysis projects that the longest highway repair and reopening times will occur in southwestern Washington and the Olympic Peninsula, with comparatively shorter times in the Puget Sound area. Interstate 90 shows slightly longer repair and reopening times in comparison with parallel routes crossing the Cascades Mountains, which is likely due to the presence of rigid concrete pavements on that highway that will necessitate additional time for removal prior to repaving.

The overall distribution of average per-mile repair and reopening times for highway pavements on liquefiable soils are shown in table 3. The majority of highway segments have an average per-mile repair time of 0.5 days, with only 13 percent of affected highway mileage requiring more than 2 days per mile to repair.

Differences in repair and reopening times associated with different pavement types have a negligible impact on average repair and reopening times. Even with the increased time to clear away rigid pavement (i.e., Portland cement concrete) debris before placing fill, rigid pavements require, on average, 0.9 days per mile to repair, whereas flexible pavements (i.e., asphalt concrete) require, on average, 1.4 days per mile to repair. The similarity of average per-mile repair times between flexible- and rigid-surfaced pavements occurs in large part because hundreds of miles of rigid pavements are located further east in the state, where the ground shaking will be less intense, and the flexible pavements include hundreds of miles on the Olympic peninsula and in southwestern Washington State, where PGD impacts will be greater.

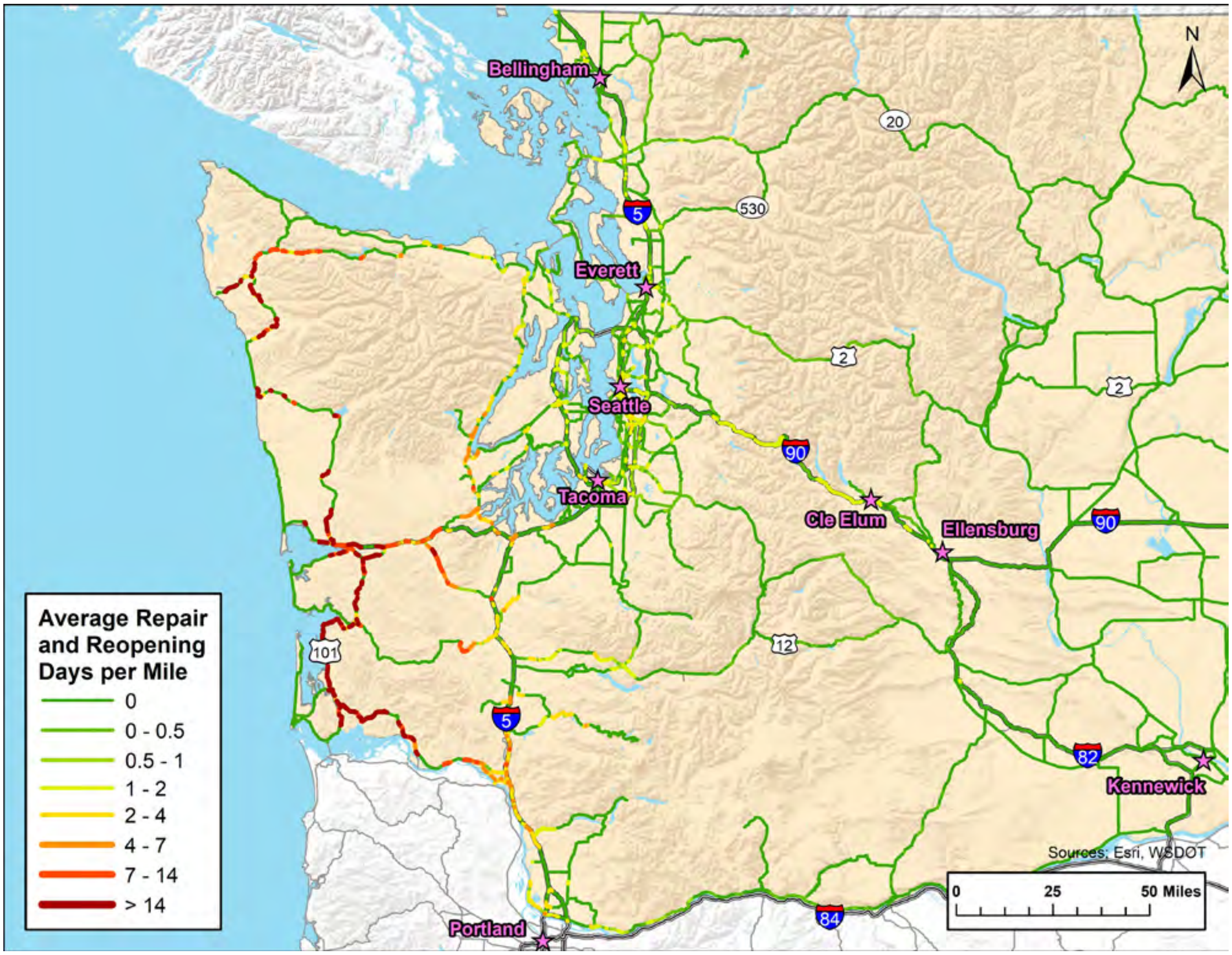

Figure 12: Highway Seismic Screening Tool (HSST) Projections of Statewide Average Per-mile Reopening Times for Highway Pavements

*Table 3: Highway Seismic Screening Tool (HSST) Projected Average Repair and Reopening Days per Mile for Highway Pavements Located on Liquefiable Soils**

Repair and Reopening Days/Mile	Miles	% of Total	Cumulative %
0 days	1,280.9	43%	43%
>0 to 0.5 days	754.7	25%	68%
>0.5 to 1 day	162.7	5%	73%
>1 to 2 days	400.0	13%	87%
>2 to 4 days	187.3	6%	93%
>4 to 7 days	54.5	2%	95%
>7 to 14 day	55.8	2%	97%
>14 days	97.3	3%	100%
TOTAL MILES	**2,993.3**		

**Excludes highways not located on liquefiable soils, for which reopening time in the HSST is 0 days per mile*

Aggregated Highway Bridge and Pavement Reopening Results

The RRAP research team combined the results from the BSST and HSST analyses to determine the aggregate reopening times for statewide highways from both bridge and pavement repairs on a per-mile basis, as shown in figure 13. These results were combined by dividing the entire state highway network into uniform one-mile-long segments and assigning individual bridge and pavement segment reopening times to the coinciding one-mile highway segments. In cases where HSST model segments (which are not uniform in length) did not align with the uniform, one-mile highway segments used here for aggregation, the HSST model output segments were either combined (in the case of HSST segments shorter than one mile) or split between adjoining one-mile segments and proportionally weighted to preserve their per-mile reopening times (in the case of HSST segments longer than one mile).

One notable feature of the combined BSST and HSST results is the strong influence that bridge reopening times have on the aggregate per-mile reopening times. A visual comparison of the BSST results (figure 10) and the aggregated BSST and HSST results (figure 13) show a strong correlation between segments with longer reopening times (i.e., greater than 6 months) and the locations of bridges with similarly long reopening times. In fact, of the 1,305 one-mile highway segments with combined reopening times of 2 weeks or greater, bridge reopening times contributed more than 90 percent of the combined per-mile reopening times in all but 71 cases (or 5.4 percent of segments).

Other trends from the BSST and HSST results are also evident in the combined dataset. For example, the extent of highway segments with longer reopening times are greater on the Olympic Peninsula and in southwestern Washington. Similarly, combined reopening times along highways leading east from the Interstate 5 corridor into the Cascade Mountains are generally longer owing to the location of highways in river valleys. As discussed earlier, these locations have a generally higher occurrence of liquefiable soils that can lead to greater pavement damage and also necessitate bridges over waterways, which have comparatively longer reopening times.

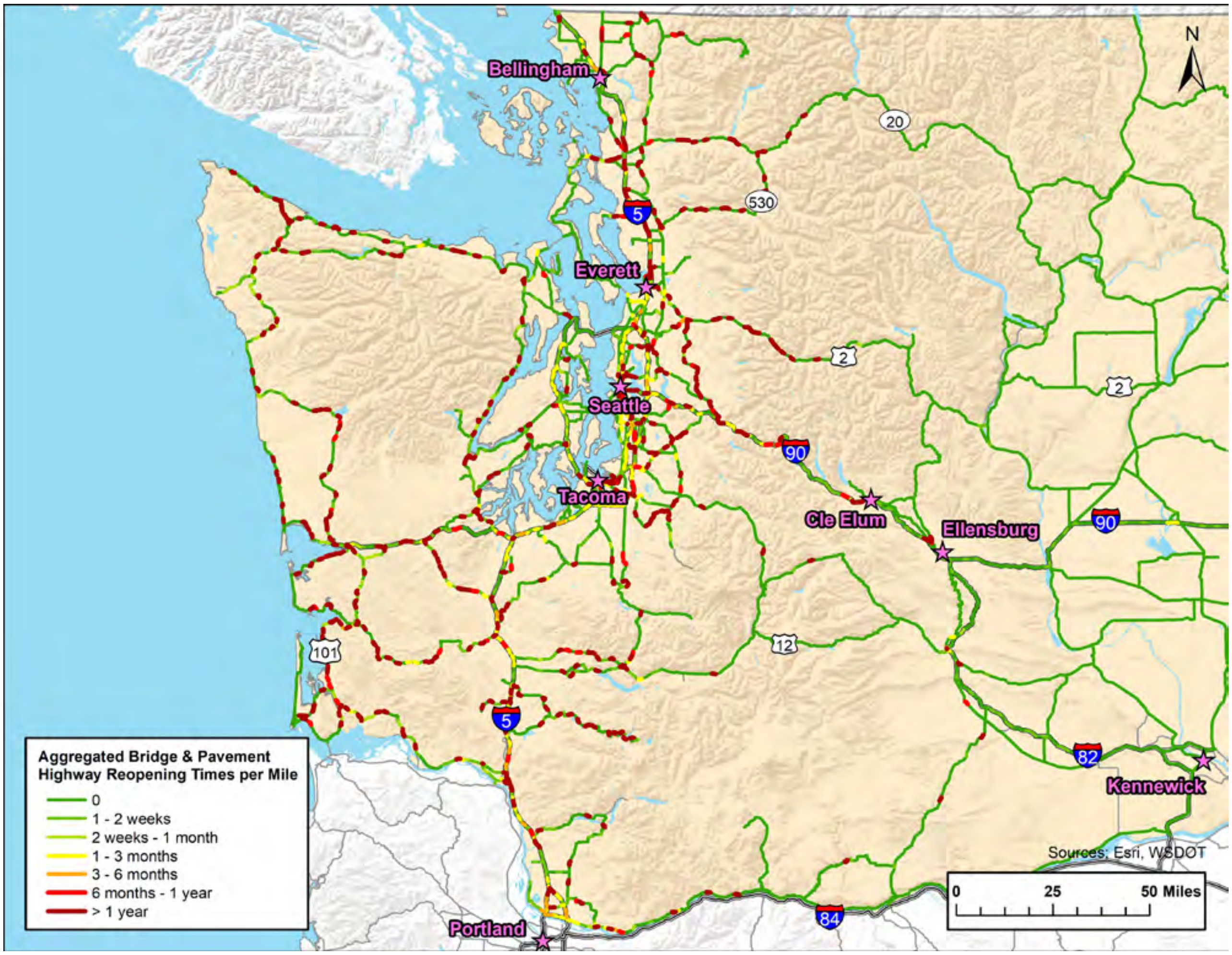

Figure 13: Aggregated Bridge and Pavement Projections of Statewide Highway Reopening Times per Mile

Highway Optimization Modeling and Prioritization

The goal of the highway optimization model was to identify those state highway routes that will be able to quickly reestablish connections between the primary ISB and the six FSAs, and begin supporting the movement of emergency response and recovery resources into the region. By identifying these routes that are the least vulnerable and quickest to reopen, state officials can begin to integrate those routes into pre-disaster planning activities. For instance, they could prioritize highway investments along those routes to harden or increase the resilience of highways and bridges, or emphasize post-disaster assessment and reopening of those routes to establish post-disaster emergency supply chains into the affected region more quickly.

To evaluate and identify optimal highway routes, the optimization model used the outputs of the BSST and HSST to define the post-CSZ earthquake reopening times for the 21,356 highway segments and the 2,717 highway bridges assessed. The model then evaluated the segments and bridges using a branch-and-cut algorithm available in the commercial optimization software, CPLEX. This algorithm identified a series of successive highway segments and bridges that form pathways between the primary ISB and FSAs with the shortest aggregate reopening time. This algorithm has been used in similar applications to assess and prioritize other networked infrastructure systems—for example, the electric grid and other networked energy infrastructure (Verner, Kim, and Petit 2017).

This optimization analysis made several underlying assumptions in identifying the optimal routes. First, all FSAs were given equal weighting in the analysis. That is, no one FSA was given greater priority than any other, which could affect the optimization outcomes by prioritizing routes that more directly connect to higher priority FSAs. Second, the model did not distinguish the highways' direction of travel, and it included both on-/off-ramps and over/underpasses. This enabled the model to both bypass collapsed overpasses by using on-/off-ramps and to switch between parallel directions of travel on the same highway. For example, if a northbound span of a bridge is disrupted on Interstate 5, but the parallel southbound span is useable, the model could switch from the northbound to southbound lanes of travel at an earlier interchange to make the crossing on the southbound bridge span. Given that Interstate 90 is the only divided highway crossing the Cascades Mountains, a similar approach was taken to allow the optimization model to cross traversable medians between eastbound and westbound lanes on that interstate.

Finally, the model assumed that bridges and highways must be reopened successively along priority pathways, meaning that a highway segment must be reopened first before the bridges or highways lying beyond that segment can be repaired and reopened. This could lead to aggregate reopening times for the priority routes that are unrealistically long. However, the purpose of this assessment is not to attempt to approximate the actual reopening time of the priority routes, but rather to evaluate and compare among multiple routing options to identify the most optimal path from the alternatives available. Therefore, the impacts of this assumption are likely minimal and were applied consistently across the analysis. It is possible that post-earthquake response and construction activities could be able to address multiple affected segments in parallel, or could occur more quickly than projected in this analysis, resulting in shorter aggregate reopening times, but this is difficult to predict with any certainty, as construction resource constraints are unknown.

The RRAP research team conducted several runs of the optimization model that evaluated different route options across the Cascade Mountains, and identified that two potential routes offered the most efficient paths across the mountains, with similar results: Interstate 90 over Snoqualmie Pass, and US 12 over White Pass. The model results show that the optimal solution using Interstate 90 has an aggregate reopening time that is 7.9 percent greater than the US 12-based solution. Discussion with WSDOT experts identified that Interstate 90 is preferred between the two solutions for several reasons. These include comparatively smaller highway size and capacity on US 12, greater frequency of landslides and rock-falls along US 12, planned seismic retrofit activities on Interstate 90 that will further enhance its seismic resilience, and the design of Interstate 90 as two parallel highways (eastbound and westbound) that give it greater redundancy along portions of that corridor.

The results of the optimization model as applied to the entire Washington State highway network, and utilizing Snoqualmie Pass over Interstate 90, are shown in figure 14. The optimal route, highlighted in green, connects the primary ISB located at Grant County International Airport near Moses Lake with the six potential FSAs located in western Washington.

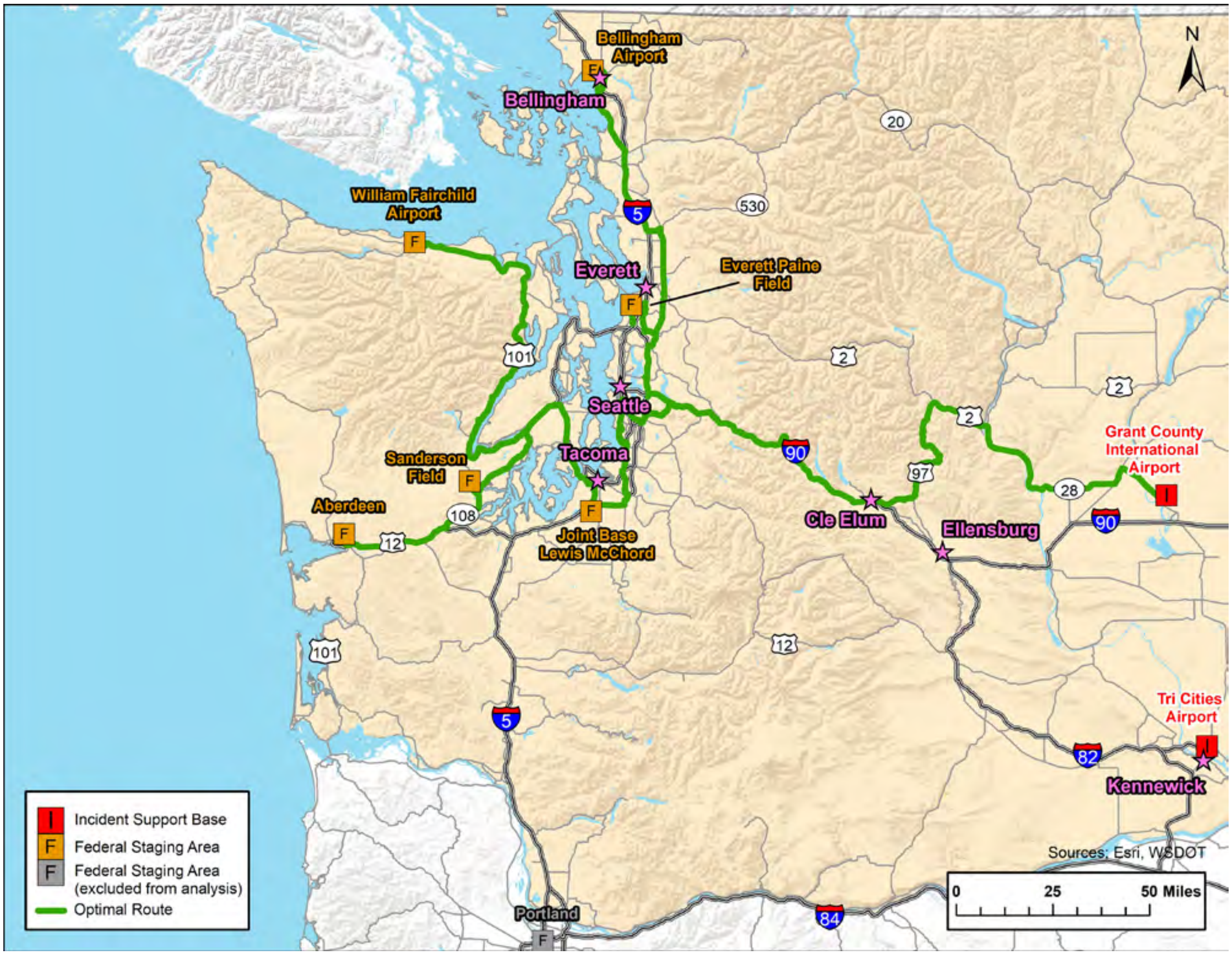

Figure 14: Optimization Model Results Showing Prioritized Routes Connecting the Primary Incident Support Base (ISB) with Federal Staging Areas (FSAs)

There are several notable features of the optimal highway routing solution. The first is that the route leaving the ISB at Grant County International Airport does not immediately follow Interstate 90, but instead follows a combination of state routes and US routes north before rejoining Interstate 90 near Cle Elum, Wash. The RRAP team compared the two routes connecting the ISB with Cle Elum and found that using only Interstate 90 resulted in a near doubling of the reopening time along that corridor. This alternative is due to several bridges on Interstate 90 that cross the Yakima River west of Ellensburg, Wash., which were identified through the BSST process as having substantial reopening times (figure 15). A series of local detours around these bridges were also evaluated; however, bridge impacts on those alternate routes would result in at least an 86 percent increase in reopening time along that corridor connecting the ISB with Cle Elum as compared with the current priority corridor between those two locations.

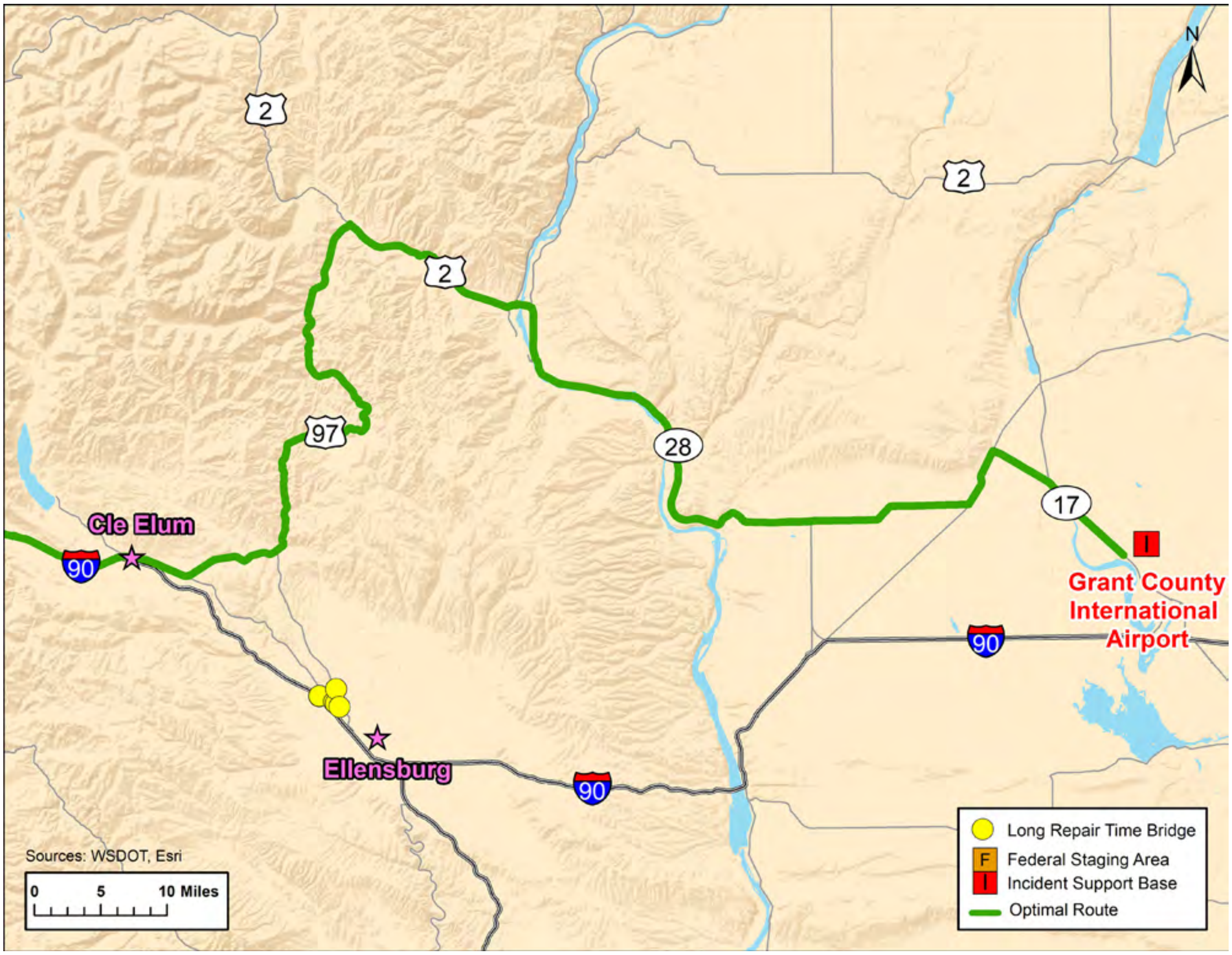

Figure 15: Interstate 90 Bridges with High Repair and Reopening Times near Ellensburg, Wash.

Another notable feature is that the optimal route solution that connects the FSA at Joint Base Lewis McChord to three coastal and Olympic Peninsula FSAs uses the Tacoma Narrows Bridge and a series of State and US Routes beyond, instead of a more physically direct connection around the southern portion of Puget Sound along Interstate 5, US 101, and State Route 8. The RRAP team compared these two potential routing options and found that, similar to the case with Interstate 90, a series of bridges located on Interstate 5 and State Route 8 near Olympia, Wash., resulted in a 12.3 percent increase in reopening times along that more direct route (see figure 16).

Both highway bridge and pavement reopening times influenced the optimization model results. However, the RRAP research team investigated further the contributions of both highway bridges and pavements along select corridors, finding that the influence of bridges reopening times significantly outweighed those of pavements. For example, examining two corridors along the priority routes—one from Ellensburg to the Interstate 405 junction, and one connecting Redmond and Arlington, Wash.—highway pavements contributed less than 1 percent to the aggregate reopening time of both corridors. This suggests that the reopening times of bridges control nearly completely the determination of optimal routes using this study’s methodology. As noted in the BSST discussion, the results of the bridge screening analysis likely constitute the worst-case scenario for bridge reopening times. Nonetheless, even with significant improvements in bridge reopening times, bridges would likely continue to control in the optimization model.

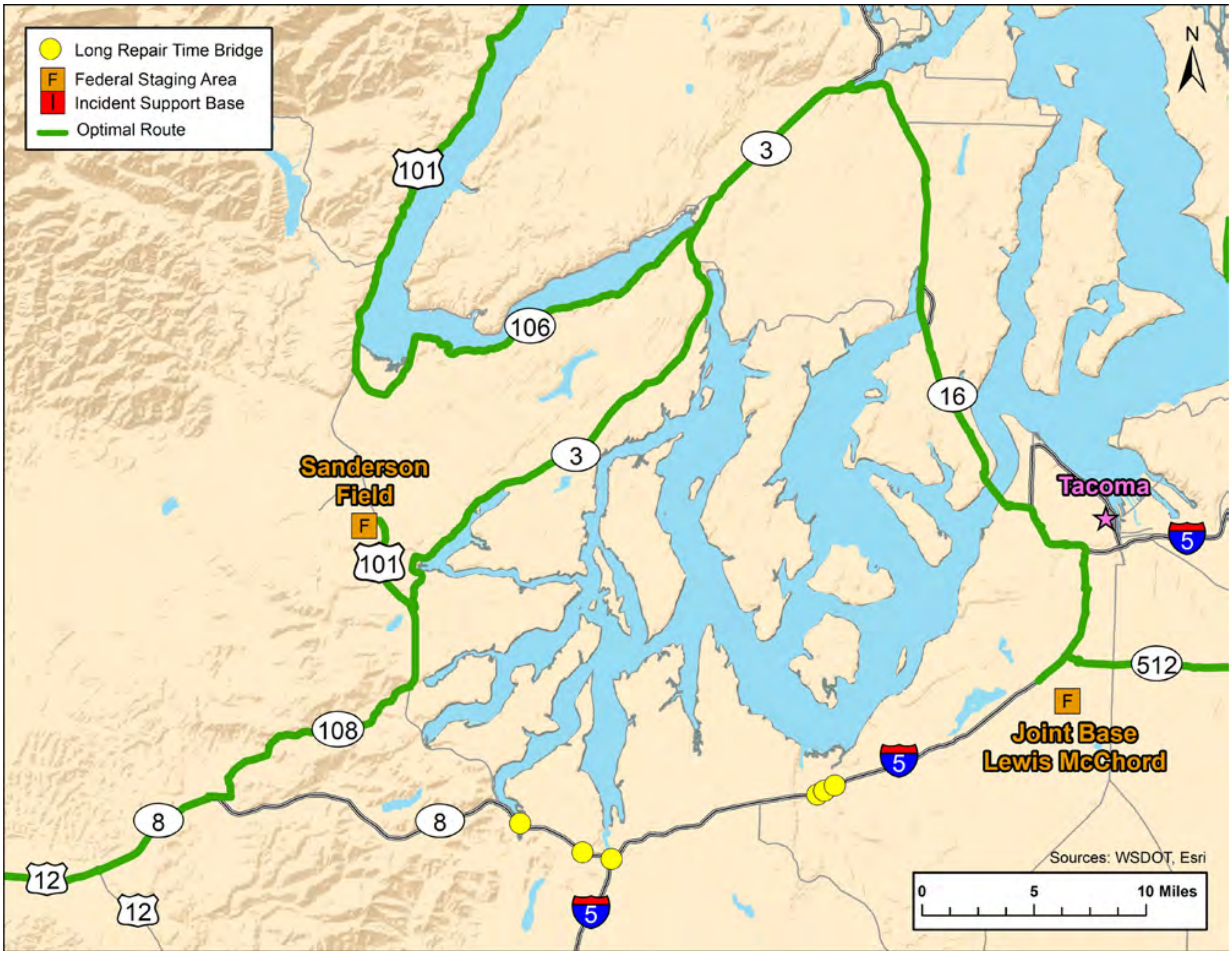

Figure 16: Interstate 5 and State Route 8 Bridges with High Repair and Reopening Times near Olympia, Wash.

Maritime Transportation Analysis

Maritime transportation offers the ability to move large volumes of goods to support post-disaster response and recovery activities. The RRAP core stakeholder group was interested in understanding better the extent of seismic impacts to the state's maritime transportation infrastructure, and the potential of that system to support CSZ earthquake response and recovery. To provide a baseline characterization of port seismic vulnerabilities, the RRAP research team first visited eight of the major commercial ports in Washington, shown in figure 17, to conduct facilitated discussions of seismic considerations with port personnel. The RRAP research team also engaged with WSF and USCG District 13. This RRAP study focuses on an analysis of the exposure of port infrastructure to seismic hazards, to serve as a common point of departure for future analysis and planning.

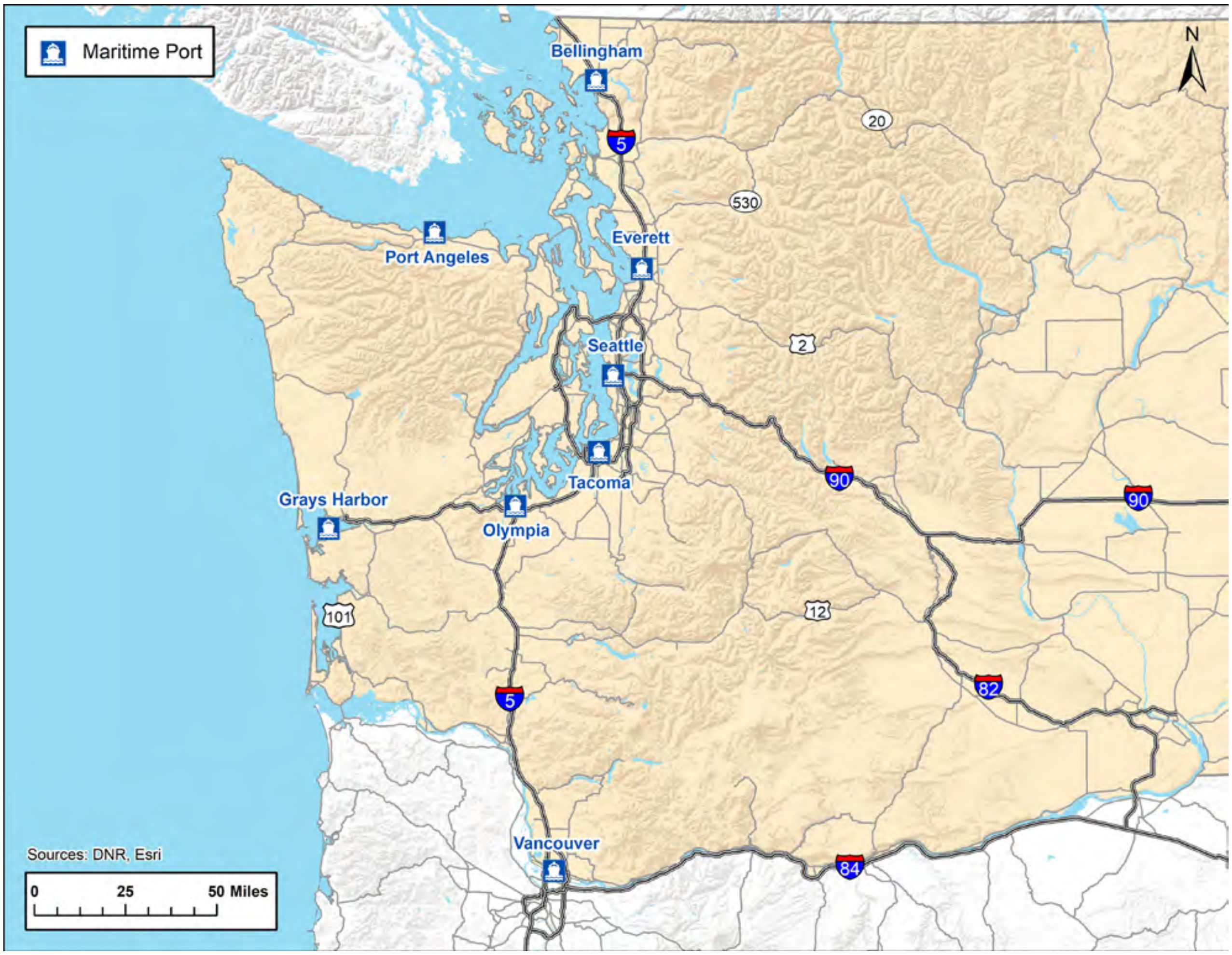

Figure 17: Western Washington State Port Locations Visited for RRAP

Port Tsunami Inundation and Soil Liquefaction Hazard Analysis

Port facilities are necessarily built in coastal environments and, in Washington State, they are most frequently located at the confluence of rivers with the Pacific Ocean or Puget Sound. These locations not only make ports vulnerable to inundation flooding and wave forces associated with a CSZ-induced tsunami, but also increase substantially the likelihood that they are built on liquefiable soils. In addition, several major ports in the region (e.g., the Ports of Seattle, Tacoma and Olympia) are built on imported fill materials that have been placed in previously open waterways or river deltas to expand buildable land. These fill materials are also frequently highly susceptible to liquefaction.

The RRAP research team mapped the approximate port facility boundaries for the eight major ports in western Washington, and overlaid those boundaries with datasets provided by DNR showing soil liquefaction susceptibility, and the flooding depths associated with the CSZ L1 tsunami scenario (DNR 2010, WGS 2017). Appendix A contains the full set of maps showing port facility exposure to liquefaction and tsunami hazards, which are summarized in table 4. All ports have significant exposure to liquefiable soils, and most are built upon soils with moderate-to-high and high liquefaction susceptibility. Additionally, six ports have significant tsunami exposure, although the depth and extent of projected impacts vary from up to 5 feet of inundation to between 10 and 20 feet across much of the ports' property.

Table 4: Summary of Liquefaction and Tsunami Hazard Exposure at Ports

Port	Liquefaction	Inundation depth
Port of Bellingham	High across most of the port property; some limited areas with Low and Low-to-Moderate	Up to 5 feet across most of the port property with major portions of the port up to 10 feet
Port of Everett	High across most of the port property; Moderate-to-High at the Mt. Baker Terminal	Limited inundation in areas adjacent to waterways up to 10 feet, but many commercial areas with no inundation. Some at 5-10 feet near southern portion of main commercial facility; more significant flooding in excess of 10 feet at Mt. Baker Terminal.
Port of Grays Harbor	Moderate-to-High across all port property	Up to 5 feet across most of the port property with major portions of the port up to 10 feet. In excess of 15 feet for portions of the Westport Marina, but all other areas up to 10 feet.
Port of Olympia	High across all port property	(No data in DNR L1 tsunami dataset)
Port of Port Angeles	Moderate-to-High and High across most of the port property; some areas with Very-Low-to-Low along the inland fringes of the port property	10-20 feet across most of the port property; some areas with 5-10 feet along inland fringes of the port property
Port of Seattle	High across all of the port property; some locations of Moderate-to-High along the Duwamish Waterway.	Most inundation located immediately adjacent to waterways, with some in excess of 10 feet; up to 10 feet in portions of the Duwamish Waterway
Port of Tacoma	High across all port property	5 feet across most of the port property, with some areas in excess of 10 feet immediately adjacent to the waterway.
Port of Vancouver	Moderate-to-High across all port property	(No data in DNR L1 tsunami dataset)

The liquefaction and tsunami hazards evaluated here identify the eight major commercial ports’ exposure to both tsunami inundation and soil liquefaction hazards in isolation. However, soil liquefaction could possibly exacerbate the impacts of tsunami inundation depths. As soils liquefy, they can flow down even gentle grades. This subsidence can lower the overall land elevation in these areas such that the *effective* depth of tsunami inundation is increased. Discussion with DNR indicated that the projections of inundation depths in the L1 scenario tsunami modeling accounted for *tectonic* subsidence (where rapid shifts in the underlying tectonic plates during an earthquake can cause ground elevations to change rapidly—dropping by as much as 2 meters along the coast), but that they did not account for the effects of soil liquefaction (DNR 2018). For these reasons, the inundation depths projected at the port facilities could occur in excess of those outlined in table 4 and shown in Appendix A. Additionally, DNR indicated that within Puget Sound, potential tsunamis related to other fault lines (e.g. a Seattle Fault tsunami) may pose a greater inundation threat to some ports.

Synthesis of Facilitated Discussions with Port Stakeholders

Members of the RRAP research team visited the eight major commercial ports in Washington State to engage with port security, emergency management, operations, and engineering personnel. The intention of these discussions was twofold:

1. To discover any prior or planned efforts undertaken by the ports to plan for, or understand their vulnerabilities to, a CSZ earthquake; and
2. To solicit the expert opinion of port facility personnel on the impacts to their ports from a projected CSZ earthquake.

Port CSZ Earthquake Planning or Vulnerability Studies

The most significant outcome of these eight facilitated discussions with ports was that although all ports have a general awareness of their physical vulnerabilities to a CSZ earthquake, none of the ports have undertaken studies to better assess or characterize the seismic vulnerabilities of their specific infrastructure to a CSZ earthquake. Furthermore, none of the ports have developed any formal plans for how they will respond to, and recover from, such an earthquake beyond more generalized continuity of operations plans. Several ports noted that this is due, in part, to the challenges associated with funding such studies alongside competing operational and planning priorities, and in the absence of broader CSZ-focused maritime transportation system studies to better justify their own focused port-level studies.

This lack of study by major ports of their respective CSZ earthquake vulnerabilities, and of planning to mitigate or recover from seismic impacts, are a significant blind spot for maritime transportation with respect to CSZ response planning. Furthermore, these gaps prevent state, federal, or other regional partners from more fully integrating the commercial maritime transportation system into the broader CSZ post-disaster supply chain with any level of certainty about that system's ability to support such activities.

Port Impacts from a CSZ Earthquake

Most ports were aware that their facilities are constructed on liquefiable soils and that the impacts of liquefaction-related ground failure could significantly disrupt their infrastructure and operations. Much of the port infrastructure in Washington State was built prior to the advent of seismic design, and therefore the seismic performance of that infrastructure is uncertain. Furthermore, the majority of dock and waterfront structures are constructed on wood piles that are subject to deterioration, thereby reducing their seismic resilience. The Port of Vancouver noted that deterioration in some of the wood piles supporting a concrete deck structure could fail, causing that dock to collapse due to strong ground motion (Port of Vancouver 2017). Other ports have undertaken more recent construction projects that may enhance the seismic resilience of portions of their ports. For example, the Port of Port Angeles recently undertook a pile replacement project at one of its terminals (Terminal 1), installing approximately 240 steel and steel-jacketed piles in 2016 (Port of Port Angeles 2017). Similarly, construction of the Port of Everett's Mt. Baker Terminal was completed relatively recently in 2006 and incorporated seismic design, and the Port of Tacoma noted that two of its terminals are built to current seismic standards (Port of Tacoma 2017). The Port of Everett also indicated that the majority of piles upon which its commercial port is built extend through the liquefiable soil layers to the underlying glacial till soil (Port of Everett 2017). This could reduce the impacts of soil liquefaction in the overlying soil layers, but additional study is required to better assess the extent to which this may be true.

All of the ports indicated their awareness of the threats posed by tsunamis; however, relatively few ports have strong visibility of the extent of tsunami hazard exposure to their facilities. The Port of Grays Harbor, for example, has had some interaction with the Grays Harbor County Division of Emergency Management (both prior to and during this RRAP project) to better understand local tsunami impacts to their facilities (Port of Grays Harbor 2018). None of the ports visited had undertaken studies to assess or quantify the impacts of tsunami inundation to their facilities.

Many ports, as well as USCG District 13, expressed concern that a CSZ earthquake could disrupt waterways, particularly those immediately adjacent to port facilities. The USCG indicated that with an average depth of 450 feet, Puget Sound would be unlikely to suffer major disruptions due to liquefaction or submarine landslides, but that areas near to docks and other shore structures (within approximately 250 feet of land) could be partially or fully infilled. This waterway infill could be exacerbated should port or other waterfront seawalls and earth retention structures fail, allowing liquefiable soils or port fill materials to spill into the waterway. Additionally, strong tsunami currents could carry and deposit sediments in waterways. In such cases, waterways would require dredging and surveying prior to reopening fully, but could possibly be operable for vessels with shallow drafts prior to dredging (USCG 2017). Additional study of port infrastructure, soil classification, and waterways are required to better characterize these potential impacts.

Several ports and other agencies noted concern about waterway impacts resulting from debris in the waterways. For example, the Port of Tacoma noted that the combined effects of ground motion and ground failure would likely result in the collapse of port cranes, which could block the waterway and require up to 6 months to remove (Port of Tacoma 2017). Additionally, DNR, USCG and several ports indicated that strong tsunami currents would likely dislodge and carry floating debris into waterways. That debris could damage port infrastructure and would have to be removed before waterways could be reopened (DNR 2018, USCG 2017).

Seismic Considerations for Ferries

WSF is a division of WSDOT that operates both automobile and passenger ferries in Puget Sound, with 10 routes that connect 20 ferry terminals in Washington and British Columbia (Canada). WSF's maritime transportation system is unique from commercial ports in Washington in that WSF owns, maintains, and operates all 20 maritime facilities that provide mobility throughout the Puget Sound region. The RRAP research team met with WSF personnel to discuss any prior or planned efforts undertaken by WSF for CSZ earthquake planning, and to better understand the impacts that a CSZ earthquake could have to WSF's infrastructure.

Over the past 10 years, WSF has engaged in numerous activities to analyze and retrofit their facilities for seismic impacts (HDR 2011, KPFF 2012, Kohut 2011, GeoEngineers 2013, Jumpawong 2015, Phan 2015). This program has focused on characterizing the seismic risks to ferry terminal structures from ground motion and ground failure impacts, which included geotechnical engineering studies of the liquefaction impacts at all 20 terminals. To date, WSF has not yet investigated the potential impacts from tsunami inundation or wave forces on their terminal structures.

WSF's efforts have focused on general seismic hazard risks throughout the Puget Sound region based on probabilistic earthquake events—for example, earthquakes with 100-year and 1,000-year return periods. While this probabilistic approach includes potential CSZ earthquake risks, it also accounts for earthquakes associated with other regional fault lines (e.g., Seattle Fault, Southern Whidbey Island Fault). In many cases, local ground motions experienced at ferry terminals from other regional fault earthquakes could exceed those projected for a CSZ earthquake at those same locations. To provide context for WSF's probabilistic based seismic analysis, the RRAP research team approximated ground motions at WSF terminal from a CSZ earthquake using the USGS Unified Hazard Tool (USGS Undated[c]). That approximation found that at most ferry terminals, the PGA projected for a 1,000-year seismic event exceeded the PGA projected for a CSZ earthquake at the same locations. The CSZ earthquake PGA values at WSF ferry terminals were, in most cases, closer to those associated with between a 100-year and 475-year seismic event.

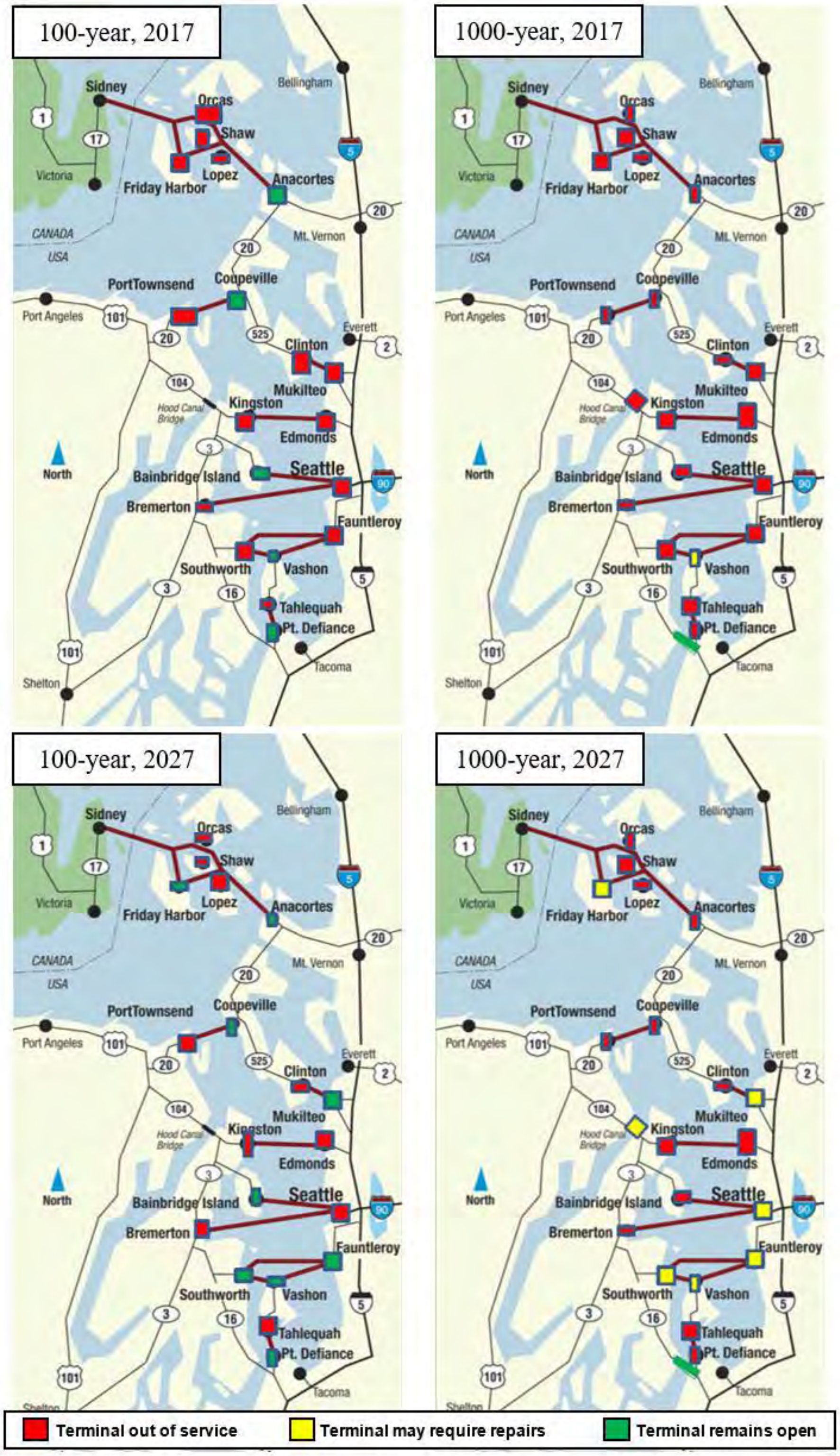

Figure 18: Ferry Terminal Seismic Performance for 100-year and 1,000-year Earthquakes, Given Present Day (2017) and Future Retrofit (2027) Designs (Bernstein 2017)

A 2017 presentation by WSF officials approximated the overall seismic performance and post-disaster operability of WSF terminals for a 100-year and 1,000-year earthquake event. These approximations were made given both present-day terminal designs and planned seismic upgrades at facilities that are expected to be completed by 2027 (Bernstein 2017). Figure 18 shows the projected seismic performance and post-disaster operability of WSF terminals. These figures reflect the current upgrade of the Vashon Island terminal to 1,000-year seismic design standards, as well as the new Mukilteo Ferry Terminal to be completed in 2019, and the planned seismic upgrades to the Seattle Terminal to be completed by 2022. These figures show that even a comparatively minor 100-year earthquake could cause extensive disruptions to WSF's terminals, but that numerous terminals will remain operable that could serve as vital connections between the Olympic Peninsula and the major metropolitan population centers along eastern Puget Sound.

WSF officials suggested that ferry terminals could potentially be used to receive non-ferry vessels such as shallow-draft barges or temporary harbor structures that are commonly used by the U.S. military (e.g., U.S. Transportation Command [USTRANSCOM], U.S. Northern Command [USNORTHCOM]). This RRAP project was unable to further assess the viability of such non-traditional uses of WSF terminal facilities; however, future studies should explore the possibility of such activities. Given the finding above that the main Puget Sound waterway will be minimally impacted by a CSZ earthquake, the timeline to remove floating debris and restore navigability may be shorter than some roadway reopening times, meaning that Puget Sound could serve as a vital transportation resource throughout the region.

Rail Transportation Analysis

Railroad transportation, like maritime transportation, has the ability to move large volumes of goods that could support post-disaster response and recovery activities. This RRAP study focused on assessing the system-level exposure of rail infrastructure to CSZ earthquake hazards.

The railway network in Washington State includes approximately 4,456 miles of rail that more than 20 different railroad companies own and operate (WSDOT Undated). The BNSF Railway Company (BNSF) and the Union Pacific Railroad (UP) own and operate the majority of railroads in Washington. BNSF owns or operates 1,454 route miles of rail across the state and is the primary major railroad operating in western Washington (BNSF 2018). UP owns or operates 532 miles of track primarily in the southern Puget Sound region and in eastern Washington (Union Pacific 2017). With the exception of the Palouse River and Coulee City Rail system, located in eastern Washington, all other short-line rail systems own or operate fewer than 100 miles each of rail lines in Washington State. The rail companies own and operate a total of 71 rail yards located in Washington State for intermodal and maritime freight, maintenance, switching, staging, or other rail operations activities (BTS 2018).

Discussions with Amtrak, Tacoma Rail, and WSDOT's Rail Office suggested that the two primary seismic vulnerabilities of concern to rail systems are the impacts of seismic shaking to rail bridges, and ground failure along rail lines, rail yards, and rail bridges.

Statewide Analysis of Hazard Exposure for Railways and Rail Yards

For rail lines and rail yards, the primary seismic hazard is ground failure due to soil liquefaction. This RRAP study applied the HSST methodology described earlier to assess PGD exposure along railways throughout the state; the accompanying report, *Washington State Highway Seismic Screening Tool—Technical Report*, describes in greater detail this application of the HSST to railways. This study estimated that 7,447 railway segments totaling approximately 1,766 track miles are built upon liquefiable soils, which were further evaluated for projected PGD exposure.

The PGD associated with each of the 7,447 railway segments built upon liquefiable soils are shown in figure 19. The highest PGD estimates for railways are concentrated along the Puget Sound & Pacific Railroad (PSAP) line (owned by Genesee & Wyoming Inc.) from Aberdeen, Wash., inland to both Chehalis and Shelton, Wash. Along these railways, some segments may experience PGD in excess of 8 feet of displacement. Some moderate to high PGDs are also projected along the BNSF-owned rail line between Chehalis, Wash., and Portland, Ore., where some segments may experience PGDs between 1 and 8 feet. These segments in southwest Washington State are projected to experience the highest PGD owing to their proximity to the CSZ. The railways from the east shore of Puget Sound to the topographic divide in the Cascade Mountain range have moderate

PGD values: mostly below 1 foot, with some isolated segments experiencing PGDs greater than 1 foot. East of the topographic divide, PGD values are lower— all below 12 inches—and associated with liquefaction of the alluvial soils in the river valleys flowing to the east.

The statewide distribution of PGD on the railway track mileage underlain by liquefiable soils is shown in table 5. More than 80 percent of the mileage of railway segments on liquefiable soils are estimated to experience 6 inches or less of displacement. Only 8.9 percent of the railway mileage on liquefiable soils is estimated to experience more than 24 inches of displacement, and are located primarily in southwestern Washington State.

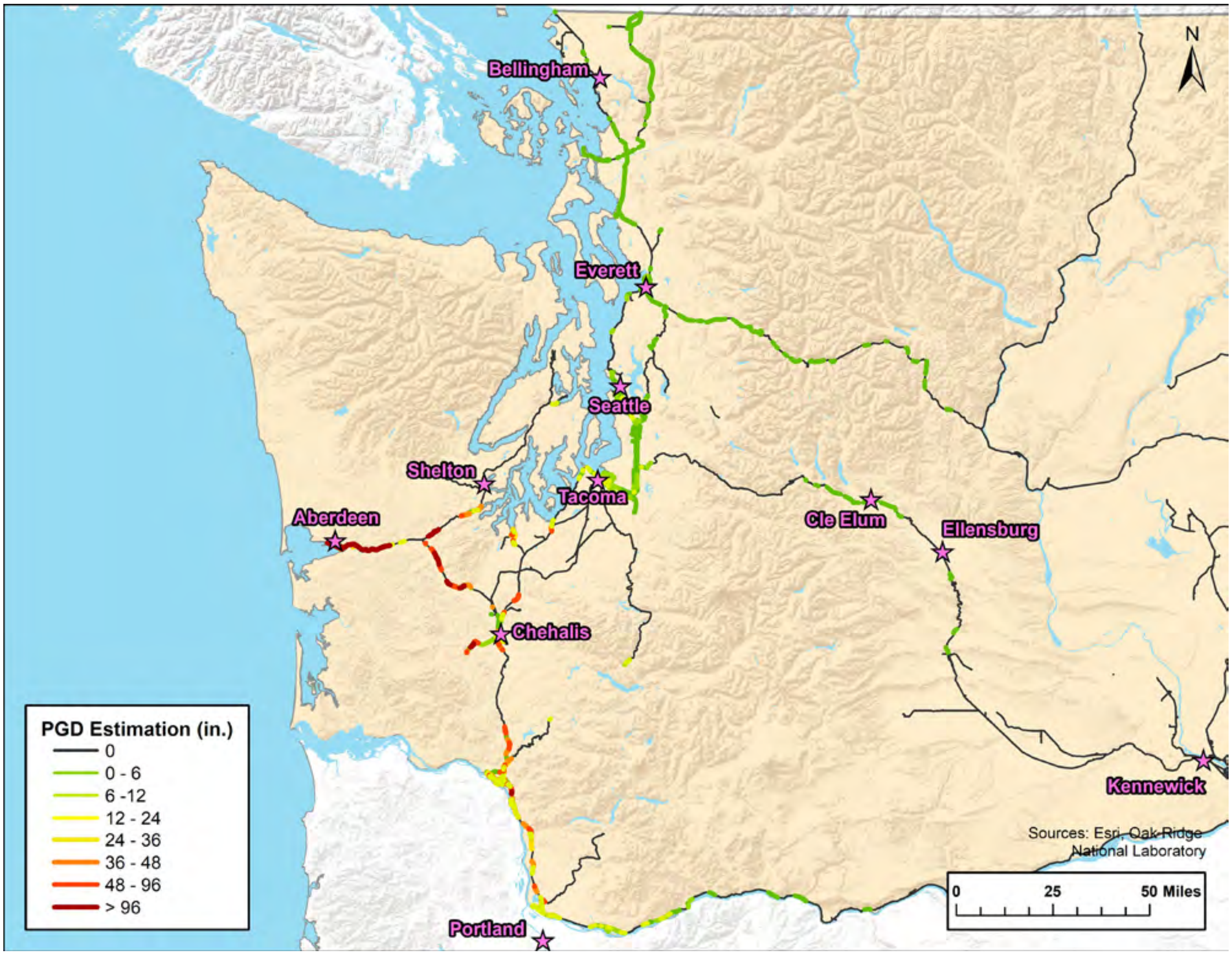

Figure 19: Statewide Distribution of Estimated Permanent Ground Deformation (PGD) of Railways on Liquefiable Soils

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Table 5: Mileage of Disrupted Railways on Liquefiable Soils by Permanent Ground Deformation (PGD)

Estimated PGD	Miles	% of Total
0 in	638.9	36.2%
0 to 6 in	784.9	44.5%
6 to 12 in	108.4	6.1%
12 to 24 in	75.3	4.3%
24 to 48 in	97.3	5.5%
48 to 96 in	24.8	1.4%
>96 in	35.8	2.0%
TOTAL	**1765.5**	

Of the 71 rail yards in Washington State, 54 located in central and western Washington were evaluated for PGD impacts, as shown in figure 20. Forty-two of these rail yards are underlain completely by liquefiable soils. Two additional yards, the Cascade and Columbia River Railroad Oroville rail yard and the BNSF Balmer rail yard, are 44 percent and 98 percent, underlain by liquefiable soils, respectively.

In general, PGD at rail yards statewide is relatively minor; 36 of the 44 the rail yards underlain by liquefiable soils are estimated to experience less than 6 inches of PGD. Among these rail yards evaluated, the PSAP Port of Grays Harbor rail yard is estimated to have the greatest PGD, in excess of 14 feet. The PSAP Hoquiam and Aberdeen rail yards and BNSF Rocky Point rail yard are estimated to have PGDs between 2 and 4 feet. The overall distribution of rail yards subject to PGD is shown in table 6. Only 9.1 percent (4 of 44) of the rail yards are estimated to experience more than 24 inches of PGD.

The configurations and construction details associated with waterfront rail yards, such as those located at port facilities, could significantly increase displacements there. Rail yards such as BNSF's Seattle Terminal and Intermodal Gateway, Tacoma Rail's Tacoma rail yard, and the BNSF Balmer rail yard, which are located on waterfronts, and in some cases built on fill placed in previously open water, may be subject to additional ground deformation. In addition, the structures retaining the fill upon which the rail yards are built may be subject to failure due to ground motion. These types of seawall failures could lead to large lateral and vertical displacements of the contained soils into the waterway, causing both significant landside PGDs and potential disruptions to waterway navigation. Even if the underlying liquefiable soils are contained, the bearing strength of the soils that support the yard structures and rail lines may be severely diminished, causing structure foundations to fail during the CSZ earthquake; however, additional details about rail and port infrastructure would be needed to better characterize these vulnerabilities.

Landslides also pose a potentially significant hazard to railways during a CSZ earthquake. During facilitated discussions, both DNR and Snohomish County indicated that landslides occur under normal conditions with some frequency along the railways connecting Seattle and Everett. DNR indicated that a risk report is under development for King County that may provide greater detail about potential ground failure hazards in areas along railways; however, such information is not broadly available throughout the state to support a further analysis of the entire state railway system's landslide exposure.

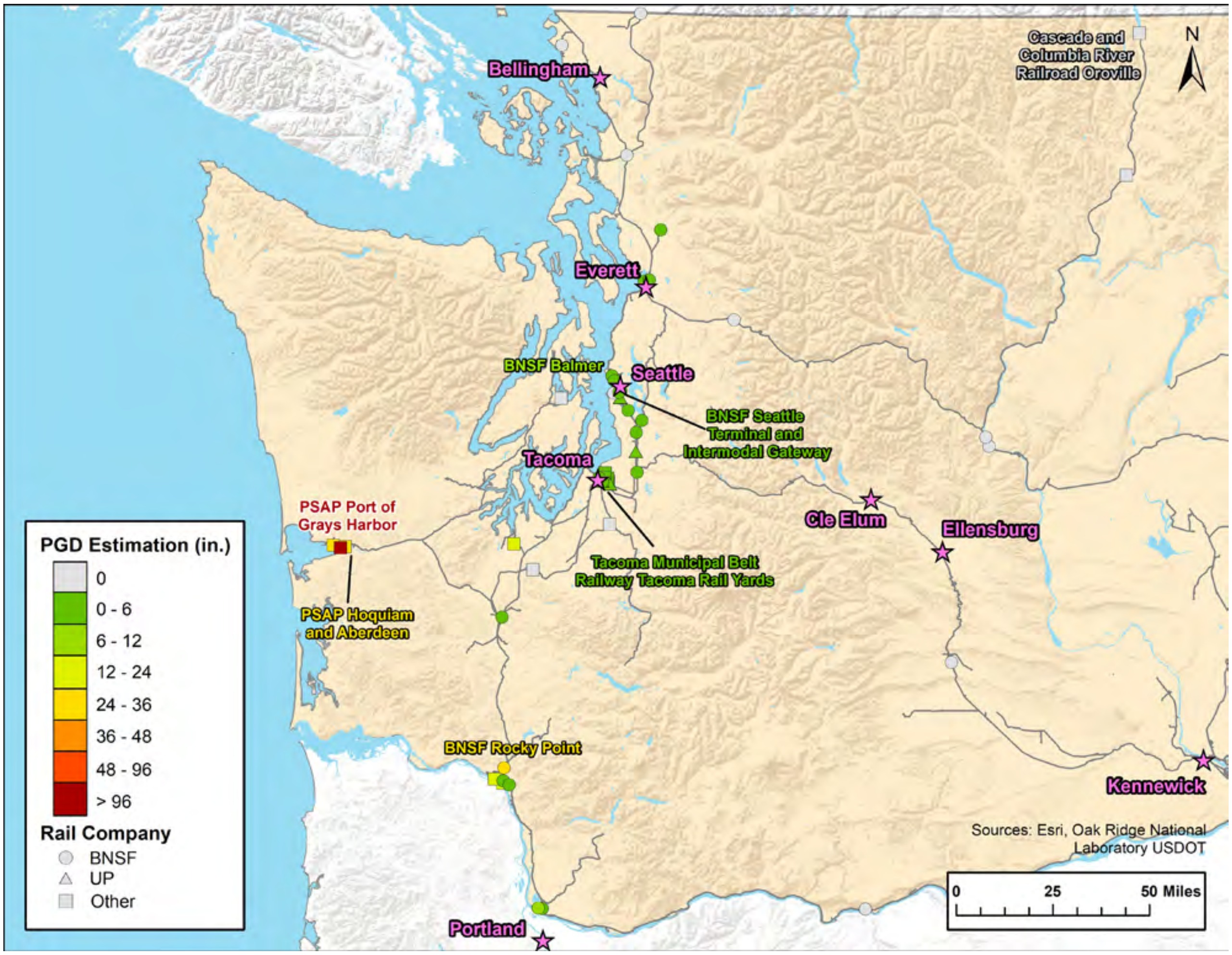


Figure 20: Statewide Location of Rail Yards with Projected Permanent Ground Deformation (PGD)

Table 6: Distribution of Permanent Ground Deformation (PGD) at Rail Yards by Number and Area

Estimated PGD	Number	% of Total	Area (Km²)	% of Total
0 in	6	13.6%	0.2	3.7%
0 to 6 in	30	68.2%	3.8	82.4%
6 to 12 in	1	2.3%	0.4	9.1%
12 to 24 in	3	6.8%	0.1	1.7%
24 to 48 in	3	6.8%	0.1	1.8%
48 to 96 in	0	0.0%	0.0	0%
>96 in	1	2.3%	0.1	1.3%
TOTAL	**44**		**4.6**	

Statewide Analysis of Hazard Exposure for Rail Bridges

The two primary hazards for rail bridges across the state are the seismic forces associated with ground motion and the liquefaction of the soils that support rail bridge foundations. The only data available publicly for rail bridges identifies their ownership and physical location. The RRAP team was unable to obtain more detailed information about rail bridges, such as their age, condition, design configuration, seismic design, or the prevailing design code at time of construction. Therefore, the analysis here is limited to a general exposure of statewide rail bridges to critical seismic design values and their exposure to liquefiable soils.

Similar to highway bridges, PGA is the primary design metric for rail bridge seismic design. The American Railway Engineering and Maintenance-of-Way Association (AREMA) publishes the national design standard, the *Manual for Railway Engineering* (AREMA 2010). This design document identifies three limit states, or PGA thresholds for rail bridges (serviceability, ultimate, and survivability), that drive a risk-based calculation in determining rail bridge designs. AREMA (2010) defines these limit states as follows:

- **Serviceability:** This limit state is associated with "only moderate damage that does not affect the safety of trains at restricted speeds…" and that structures "shall not suffer any permanent deformation due to deformations or liquefaction of the foundation soil." It is associated with PGA values projected for a 100-year seismic event.
- **Ultimate:** This limit state ensures that if structural damage occurs, it "should occur as intended in design and be readily detectable and accessible for repair. The structure shall not suffer any damage which threatens the overall integrity of the bridge due to deformations or liquefaction of the foundation soil." It is associated with PGA values projected for a 475-year seismic event.
- **Survivability:** This limit state allows for "extensive structural damage, short of bridge collapse…," and that "failures of the foundation soil shall not cause major changes in the geometry of the bridge. Depending on the importance and the replacement value of a bridge, an individual railroad may allow irreparable damage for the survivability limit state, and opt for new construction. It is associated with PGA values projected for a 2,400-year seismic event.

Using these PGA-based definitions of structural failure states, the RRAP team conducted an exposure analysis of 1,608 statewide railway bridges to the PGAs associated with a CSZ earthquake, to identify their controlling limit states. This is not a prediction of bridge failure, as no information about the design configurations of rail bridges were available, but a relative measure of the seismic risks to which each bridge could be exposed during a CSZ earthquake. Table 7 shows the results of this analysis. BNSF Railway, given its strong operational presence in western Washington, has the greatest number of bridges potentially impacted by strong CSZ ground motion. Over 58 percent of all rail bridges statewide fall within the Serviceability limit state, meaning that bridges designed to this limit state may remain operable following a CSZ earthquake. However, over 32 percent of statewide rail bridges could experience PGAs associated with the Survivability limit state, requiring either significant rebuilding or replacement before those bridge crossings are reopened.

Among railway companies operating in Washington, BNSF-owned infrastructure has the greatest exposure to PGA-based ground motion impacts. While nearly 55 percent of BNSF bridges fall within the Serviceability limit state, 34 percent of BNSF rail bridges could be exposed to ground motions that disrupt service (Ultimate limit state), and 11 percent of BNSF bridges fall within the Survivability limit state, meaning that they could require significant rebuilding or replacement to reopen even if built to this standard. The exposure of rail bridges owned by UP and other railway companies to critical ground motion limit states is not as severe, with the majority of bridges falling in the Serviceability limit state. However, nearly 40 percent of all other rail bridges in the state owned by other railways could sustain damage, and 5 percent could experience PGAs associated with the Survivability limit state, which could require significant rebuilding or replacement before reopening. These results suggest that additional studies are warranted that incorporate more detailed and specific information about individual rail bridges to more fully and accurately understand the statewide vulnerability of rail bridges to CSZ earthquake ground motion impacts, and the impacts to operations that could result.

In addition to the structural hazards associated with ground motion, the RRAP team also assessed the exposure of rail bridges across the state to liquefiable soils, using the liquefaction susceptibility data and categories that DNR provided. These results are also shown in table 7. Over 80 percent of rail bridges in Washington State are constructed on or near to soils with some level of liquefaction susceptibility, with fully half of those bridges owned by BNSF. The majority of bridges (54 percent) located on or near liquefiable soils, across all rail companies, are located on soils with moderate-to-high and high liquefaction susceptibility. This is consistent with the finding that 1,208 of the 1,608 rail bridges in the state (or 75 percent) cross rivers or other waterways, which are associated with the presence of liquefiable soils. Additional studies with more detailed rail bridge information are necessary to more fully and accurately understand statewide vulnerability of rail bridges to seismic-induced ground failure during a CSZ earthquake.

Table 7: Rail Bridge Peak Ground Acceleration (PGA) and Soil Liquefaction Exposure Results

Rail Bridges – Seismic Limit States	BNSF	UP	Other	Total
Seismic – Serviceability	447	62	433	942
Seismic – Ultimate	280	13	232	525
Seismic – Survivability	91	1	49	141
Rail Bridges – Liquefaction Susceptibility	**BNSF**	**UP**	**Other**	**Total**
Non-liquefiable soil	167	19	129	315
Liquefaction susceptibility (very low)	102	14	137	253
Liquefaction susceptibility (very low to low)	55	1	27	83
Liquefaction susceptibility (low)	90	14	52	156
Liquefaction susceptibility (low to moderate)	39	6	59	104
Liquefaction susceptibility (moderate)	0	0	0	0
Liquefaction susceptibility (moderate to high)	351	15	306	672
Liquefaction susceptibility (high)	14	7	4	25
Crossing rivers	720	63	425	1208

Key Findings

The remainder of this report focuses on documenting the Key Findings for the Washington State Transportation Systems RRAP project. The Key Findings are a result of the information-gathering and analytical activities for this assessment. Each of the Key Findings is supported by an explanation of the significance of the finding, Resilience Enhancement Options that could improve resilience in the focus area, and suggested organizations or agencies for implementing these options.

Key Finding: The surface transportation system in Washington State is vulnerable to CSZ earthquake-related impacts that have the potential to significantly disrupt the movement of emergency supplies and resources into the affected region.

Washington State's surface transportation system will be exposed to both direct seismic impacts from earthquake-related ground motion, as well as secondary impacts in some areas, including the potential for widespread soil liquefaction, tsunami inundation along Washington's coastlines, and landslides and avalanches. Together, these direct and secondary seismic impacts could significantly damage the surface transportation infrastructure system, requiring either partial or full restoration for resumed movement of goods into the region.

Extensive hazard and infrastructure data and information exists within the state to support an analysis of the surface transportation system's seismic vulnerability. However, persistent data gaps prevent a *general* understanding of some hazard-related vulnerabilities, such as the full exposure of Washington State's coastlines to tsunami impacts, or of its highways to potential landslides across the state. Furthermore, these data gaps also prevent a *deeper* understanding of more specific potential impacts; for example, although soil liquefaction data is available statewide, the thickness of liquefiable soil layers is not well-documented and therefore cannot be integrated into statewide ground failure analyses.

Resilience Enhancement Options

Washington EMD and Washington State DNR should improve upon tsunami modeling efforts conducted to date by better characterizing tsunami inundation and wave forces resulting from a CSZ earthquake in the entire Puget Sound region. This will better support vulnerability analyses at major ports, ferry terminals, and other maritime and coastal transportation infrastructure systems.

WSDOT and Washington State DNR should develop an expanded, statewide searchable database of historic subsurface boring and other subsurface exploration reports in a GIS database, and maintain that database with up-to-date records, to better enable the identification of liquefiable soil characteristics at specific locations across the state. This effort should prioritize the inclusion of data and reports for subsurface borings and explorations along the priority highway routes identified in this study, before expanding to other locations across the state.

Washington State DNR, USGS, and WSDOT should integrate *potential* landslide locations and unstable slopes (i.e., as may be affected by a seismic event) across the state into WSDOT's Unstable Slopes Program database, which is currently limited to only known, historic or chronic landslide and rock-fall locations adjacent to state highways. FEMA Region 10, DNR, and Washington State Department of Ecology have published county risk reports for Chelan, Okanogan, Pierce, and Whatcom counties that identify and locate potential deep and shallow landslide risks throughout those jurisdictions, which could serve as a model for statewide studies (FEMA 2017, Undated-a, b, Mickelson et al. 2017).

Key Finding: An analysis of highway infrastructure and systems within Washington State has identified priority response routes with potentially greater seismic resilience, which can be used to inform emergency response planning and future resilience investments.

To facilitate the movement of post-CSZ earthquake emergency supplies into western Washington, the highway transportation system does not necessarily need to be restored to a pre-disaster state of repair. Washington EMD and the core stakeholders have agreed that the priority is to reestablish connectivity among ISBs and FSAs within the surface transportation system by reopening highways to a condition sufficient to support the movement of emergency supplies and response vehicles. This study prioritized highway transportation infrastructure and corridors on the basis of those that compose routes connecting the primary ISB and FSAs with the shortest reopening timeline given the projected extent and magnitude of earthquake-related damage.

An analysis of statewide highway transportation infrastructure has identified several priority highway corridors that provide essential paths between the primary ISB and FSAs. This analysis finds that a series of routes comprising Interstates 90 across the Cascade Mountains, and Interstates 5 and 405; U.S. Routes 2, 97, 101; and numerous state routes will likely have post-earthquake reopening times that are lower than other highways in Washington State, and as a result may serve as critical routes for bringing life-saving and life-sustaining resources into western Washington as part of federal, state, and local response activities.

This analysis also evaluated highway bridges and highway pavements, finding that across all Washington State highways, bridge reopening times are the predominant factor in reestablishing highway connections.

In particular, those bridges that traverse rivers and other waterways have an outsized contribution to delays in highway reopening times given the general lack of alternate routes and the frequent presence of liquefiable soils along waterways. Efforts to strengthen or enhance the resilience of these types of crossings could have the greatest returns in buying down both bridge and route reopening times.

This analysis of highway bridges and highway pavements constitutes a worst-case scenario for highway reopening times. While many sources of uncertainty in the seismic screening analyses were addressed conservatively (e.g., long-duration shaking effects to bridge superstructure performance), others could not be addressed systematically in the analyses (e.g., the availability of response resources, identification and mitigation of *potential* ground failure), which could be partially mitigated through additional studies and research.

Resilience Enhancement Options

WSDOT should evaluate and enhance the resilience of bridges along priority highway routes, with particular attention to bridges that span water, those that may be located on soil with an increased potential for liquefaction, and those that cause significant local or regional detouring (e.g., the Interstate 90 bridges near Ellensburg). The goal is to reduce post-CSZ earthquake priority route reopening times. Resilience actions could include identifying viable alternative local routes with less vulnerability or shorter reopening times, bridge retrofitting actions (in addition to those undertaken through WSDOT's current Bridge Seismic Retrofit Program), bridge replacement, subsurface soil improvement, or targeted response plans for such structures, among other options.

WSDOT and Washington EMD should investigate actions that could accelerate response and reopening for vulnerable bridges along priority routes. Such options could include temporary structures, accelerated or pre-staged bridge construction, or relocation of construction resource and supply storage to identified locations along the priority routes, among other options.

WSDOT should investigate actions that could accelerate response, repaving, and reopening of roadway segments along priority routes. Such options could include prestaging or relocation of construction equipment and materials to existing maintenance facilities, construction of new maintenance facilities along priority routes; identification of, and response planning for, priority rock quarries along priority routes to provide materials for temporary wearing surfaces; and enhanced avalanche and landslide mitigation activities along priority routes.

WSDOT should work with local and county departments of transportation, departments of public works, or similar agencies with jurisdiction over transportation systems to investigate the seismic vulnerability of county and local roadways that may be used as part of the priority routes, and to identify and prioritize local or regional lifeline routes, such as those between FSAs and pre-identified local post-disaster community points of distribution. These coordination efforts should also include the development of interagency agreements for alternate routing onto local roadways, consistent with Recommendation 6 in *Resilient Washington State: A Framework for Minimizing Loss and Improving Statewide Recovery after an Earthquake* (Resilient Washington State Subcommittee 2012), particularly along the priority routes identified in this study.

WSDOT and Washington State DNR should continue to support research efforts in critical areas that can reduce uncertainty in vulnerability analyses. Such areas of research could include the effects of long-duration shaking on bridge structural performance, and seismic design options to mitigate such effects; and strategies to mitigate landslide and other ground failure hazards to seismic impacts.

Key Finding: Maritime transportation infrastructure within Puget Sound has the potential to support the movement of emergency supplies and resources; however, additional planning and analysis are necessary to better incorporate this capability.

The ability of the maritime transportation system to move bulk emergency relief supplies into western Washington could prove critical to post-disaster response and recovery efforts, particularly given the significant reopening times projected for highway surface transportation routes. However, the vulnerabilities of commercial maritime ports to the impacts of a CSZ earthquake are not well-characterized. None of the eight major commercial ports in western Washington surveyed in this study have undertaken comprehensive studies to assess the vulnerability of their facilities and operations to direct seismic forces, liquefaction, tsunami-related inundation and wave forces, or damage caused by floating debris or vessels located at or near ports resulting from a CSZ earthquake and tsunami.

Given its depth, Puget Sound's main navigation channels are unlikely to be affected by CSZ earthquake impacts and obstructions, with the exception of floating debris. Water-side impacts will likely be limited to coastal and submarine landslides, as well as soil liquefaction, all occurring at shoreline locations. This relatively minor level of impact to the waterway could enable Puget Sound, the Strait of Juan de Fuca, and the Pacific Ocean to serve as a conduit for emergency supplies and resources via maritime transportation. However, although the waterway may remain in serviceable condition, the state of shore-side maritime transportation infrastructure, maritime vessels, and intermodal connections will be affected by both direct and indirect seismic impacts. The state of these systems will affect the degree to which maritime transportation can serve as an effective conduit for moving supplies and resources to support response operations.

WSF has undertaken an extensive effort to characterize the vulnerability of state-owned and -operated ferry terminals to seismic impacts related to ground motion and ground failure. However, WSF has not yet evaluated the effects of tsunami-related inundation and wave forces on those terminals, nor the secondary impacts to vessels and operations. Given the large uncertainty surrounding the viability of commercial ports, the flexibility of roll-on-roll-off capabilities at WSF terminals, and WSF's efforts to characterize and mitigate seismic impacts, the ferry system could serve an important role in maritime transportation disaster response.

Resilience Enhancement Options

Washington ports and port authorities, in cooperation with Washington EMD and the USCG, should conduct seismic vulnerability assessments of their maritime facilities. These efforts should start with those ports that may have an increased likelihood of survivability as well as those that are near FSAs, major population centers, or communities that will become isolated due to impacts to land surface transportation. For example, the Ports of Everett and Olympia are expected to sustain lower levels of tsunami-related inundation and both are situated nearer to planned FSA locations; they could therefore be prioritized for further seismic vulnerability assessment before other ports.

WSDOT and WSF should continue and expand efforts to characterize the seismic vulnerabilities of ferry terminals to tsunami-related impacts, and to identify formal response strategies that enable ferry terminals to receive goods from military or commercial vessels such as barges.

WSDOT and WSF should investigate and plan for impacts to both vessels, operations, and emergency operations; these actions could include planning for impacts to operations such as vessel fuel supplies, personnel considerations, and restoration of priority ferry terminals to enable either the berthing of ferries, or to receive non-ferry supply vessels.

The Washington Military Department should facilitate the coordination among maritime infrastructure owners (e.g., WSF, commercial ports), waterway managers (e.g., U.S. Army Corps of Engineers, USCG), and relevant U.S. military commands (e.g., USNORTHCOM, USTRANSCOM) to investigate the potential to use U.S. Department of Defense Joint Logistics Over-the-Shore capabilities or other types of temporary harbors at ferry terminals and commercial port facilities. Such actions could either enable/expand the ability of those facilities to receive emergency supplies, or accelerate their restoration to a state of repair that is able to receive supplies.

Key Finding: The emergency management community lacks an awareness and understanding of private sector rail's infrastructure seismic vulnerabilities, and the ability of the rail industry to support the movement of emergency response supplies into western Washington.

Private sector freight rail systems operate throughout Washington State and could serve an important role in CSZ earthquake response and recovery efforts, given their ability to move large volumes of goods efficiently on dedicated infrastructure. However, much of that system is exposed to similar seismic hazards as the state's highway system, including strong ground motion, ground failure, and potential tsunami inundation. Despite these potential exposures, state transportation and emergency management officials are largely unaware of the rail system's vulnerability to a CSZ earthquake, or of any studies and planning efforts that rail operators may have undertaken to address such vulnerabilities.

Many of the seismic screening tools and methodologies developed in this RRAP project to assess highway transportation systems have been applied to assess the relative seismic hazard exposure of the state's rail network. With further participation of private sector rail in future studies, those methodologies could be better adapted, through collaboration with the state, to conduct network-level vulnerability assessments of the rail system. These vulnerability assessments could ultimately inform railway corridor prioritization analyses that inform both state emergency response planning as well as rail infrastructure asset management.

Resilience Enhancement Options

Washington EMD and WSDOT should work with BNSF, UP, and Class III/short-line railways operating in western Washington to better characterize rail system seismic vulnerabilities and collaboratively develop plans that outline the role that rail systems could play in the movement of emergency goods and resources into the affected area. These actions could include the identification of priority rail lines, using analysis similar to that undertaken in this study for highway prioritization, or leveraging analyses that have been conducted by private sector railways.

WSDOT and the Washington State Department of Commerce should consider supporting actions that enhance or increase the resilience of priority rail lines in the state; these actions could include direct investment in improving rail infrastructure, or including rail companies in proactive emergency response planning efforts.

Rail companies should share infrastructure seismic vulnerability information, response plans, anticipated repair time planning factors, and their expectations/needs for post-disaster support with WSDOT and Washington EMD (with the appropriate data and information protections from the state) to enable better coordination of rail response planning with the state and federal response planning efforts.

Conclusion and Next Steps

Conclusion and Next Steps

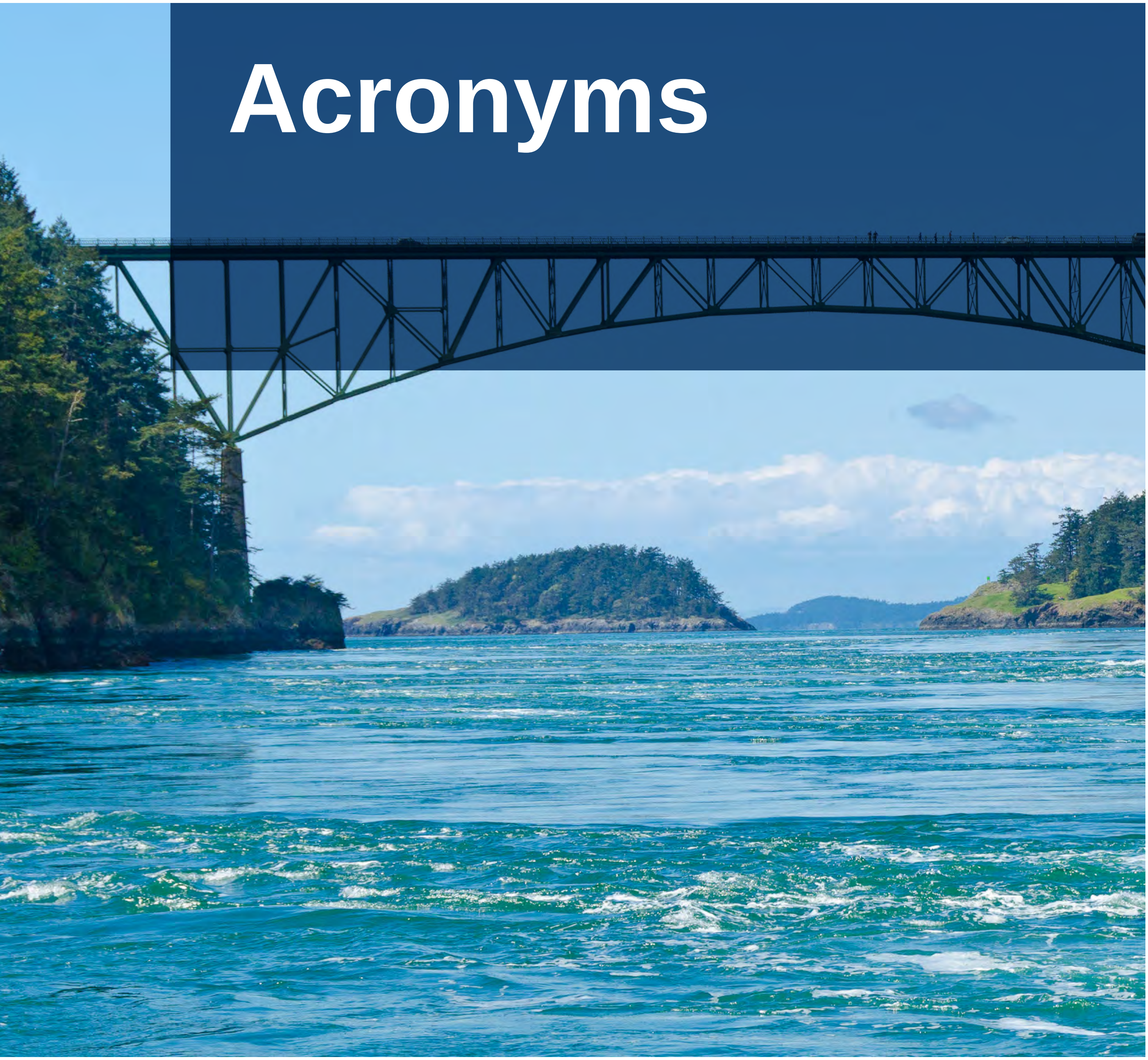
The Washington State Transportation Systems RRAP project integrated the expertise and knowledge of participants in the region to assess the vulnerabilities of statewide surface transportation infrastructure systems to the anticipated impacts of a CSZ earthquake, including ground motion, ground failure, and tsunamis. The primary analytical outcome of this RRAP project is a detailed finding that prioritizes state highway routes for response and recovery efforts, which could receive additional investment from the state to enhance their seismic resilience to a CSZ earthquake. Additionally, this RRAP project assessed the hazard exposure of maritime and rail transportation systems to serve as a common point of departure for future studies and planning efforts.

The project revealed opportunities for public and private sector entities to enhance the resilience of the state's surface transportation infrastructure in order to better support CSZ earthquake response and recovery efforts. Potential options for enhancing the resilience of those systems include enhanced efforts to catalog more completely and accessibly numerous geologic hazards associated with a CSZ earthquake; increased investment in priority highway corridors throughout the state to further minimize the amount of time required to reopen impacted highway routes; collaborative assessments of commercial maritime ports throughout the state, and expanded seismic assessment of the state’s ferry system, to better understand their potential to support post-disaster response and recovery efforts; and enhanced engagement with private sector rail companies throughout the state to better integrate rail’s capabilities to aid in response and recovery efforts.

DHS CISA, State of Washington departments and agencies, and other public and private partners involved in this RRAP project intend for this Resiliency Assessment, and all associated documents and data, to provide valuable considerations for addressing the surface transportation needs of public and private sector entities as they engage emergency response planning, infrastructure investment, or other efforts that will enable greater regional preparedness for a CSZ earthquake.

For more information, please contact CISA Region 10 Operations at IPRegion10Ops@hq.dhs.gov.

Acronyms



Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AREMA	American Railway Engineering and Maintenance-of-Way Association
BNSF	BNSF Railway Company
BSST	Bridge Seismic Screening Tool
CISA	Cybersecurity and Infrastructure Security Agency
CSZ	Cascadia Subduction Zone
DHS	U.S. Department of Homeland Security
DNR	Washington State Department of Natural Resources
EMD	Washington Emergency Management Division
FEMA	Federal Emergency Management Agency
FSA	Federal Staging Area
GIS	Geospatial Information System
HSST	Highway Seismic Screening Tool
ISB	Incident Support Base
IT	Information Technology
M	Magnitude
MMS	Moment Magnitude Scale
NISAC	National Infrastructure Simulation and Analysis Center
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PSAP	Puget Sound & Pacific Railroad
RRAP	Regional Resiliency Assessment Program
UP	Union Pacific Railroad
USCG	U.S. Coast Guard
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
USNORTHCOM	U.S. Northern Command
USTRANSCOM	U.S. Transportation Command
WGS	Washington Geological Survey
WSDOT	Washington State Department of Transportation
WSF	Washington State Ferries

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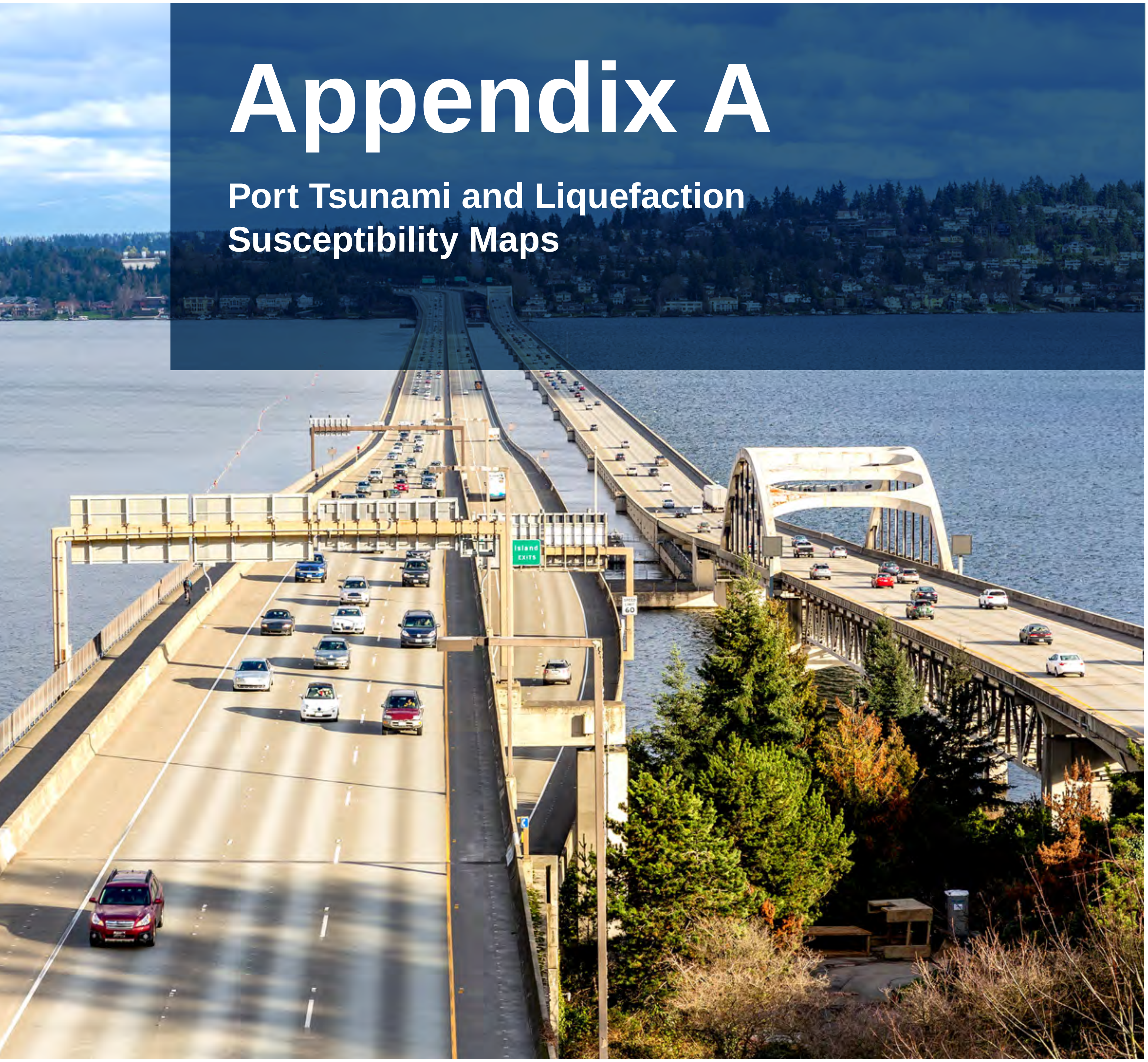

Appendix A

Port Tsunami and Liquefaction Susceptibility Maps

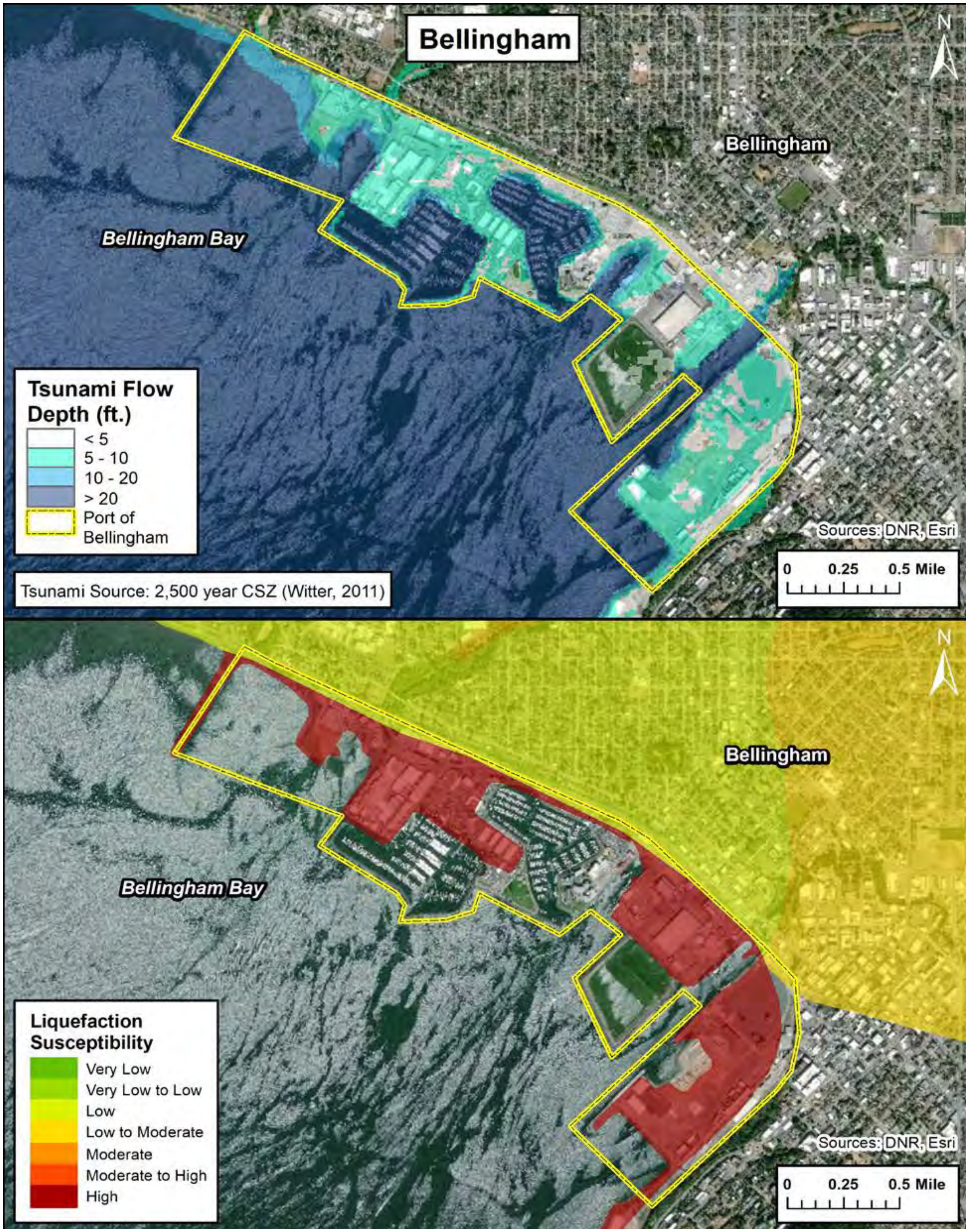

Figure A-1: Port of Bellingham – Tsunami Inundation and Liquefaction Susceptibility

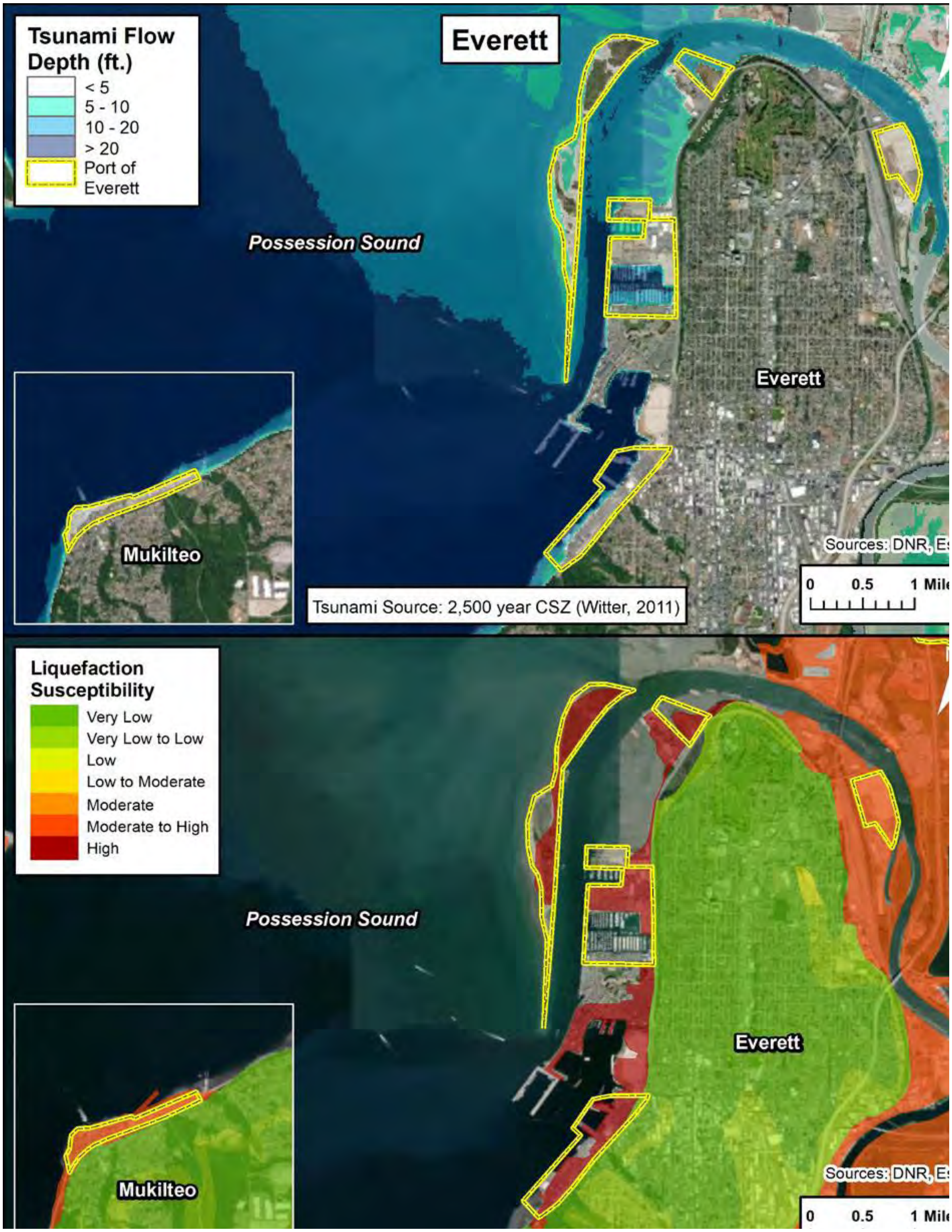

Figure A-2: Port of Everett – Tsunami Inundation and Liquefaction Susceptibility

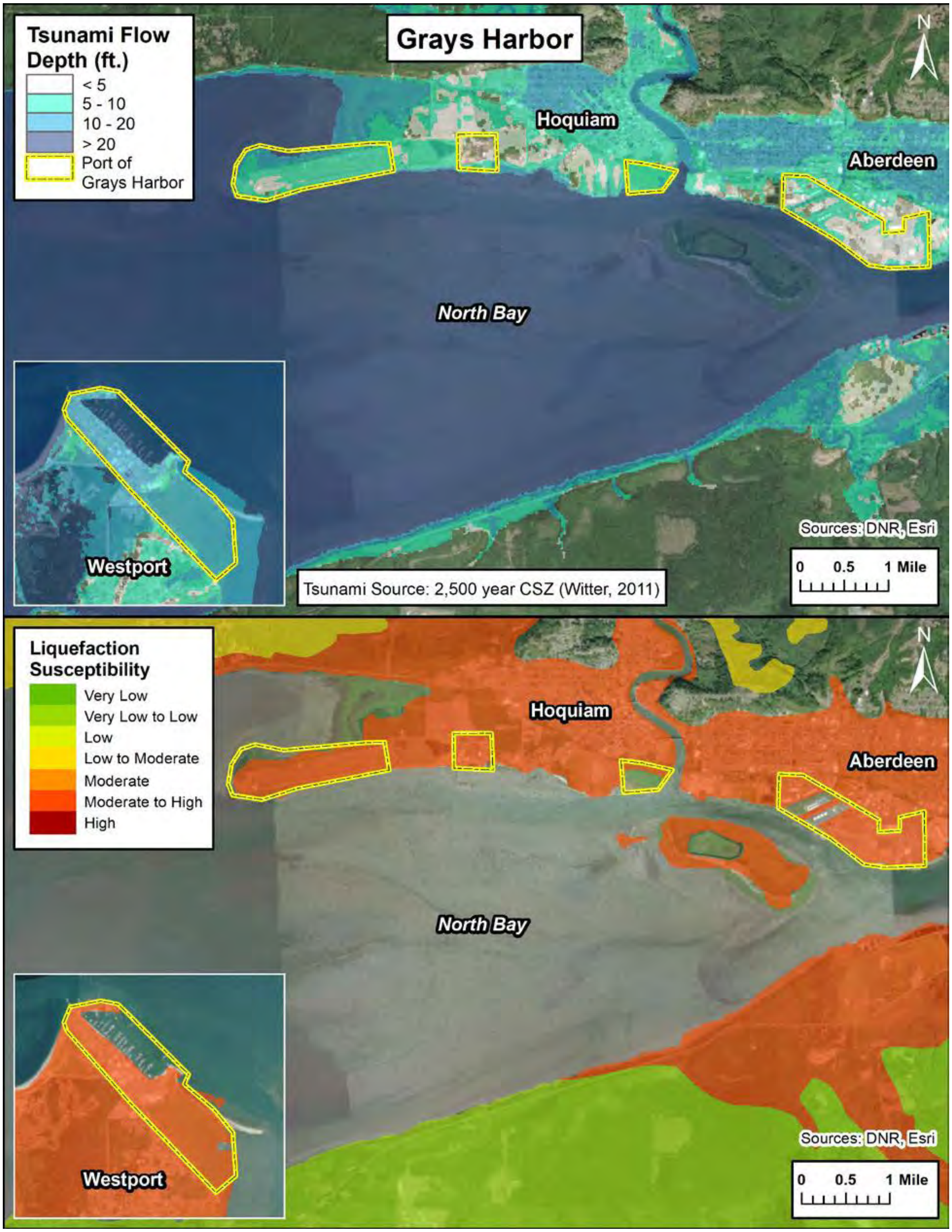

Figure A-3: Port of Grays Harbor – Tsunami Inundation and Liquefaction Susceptibility

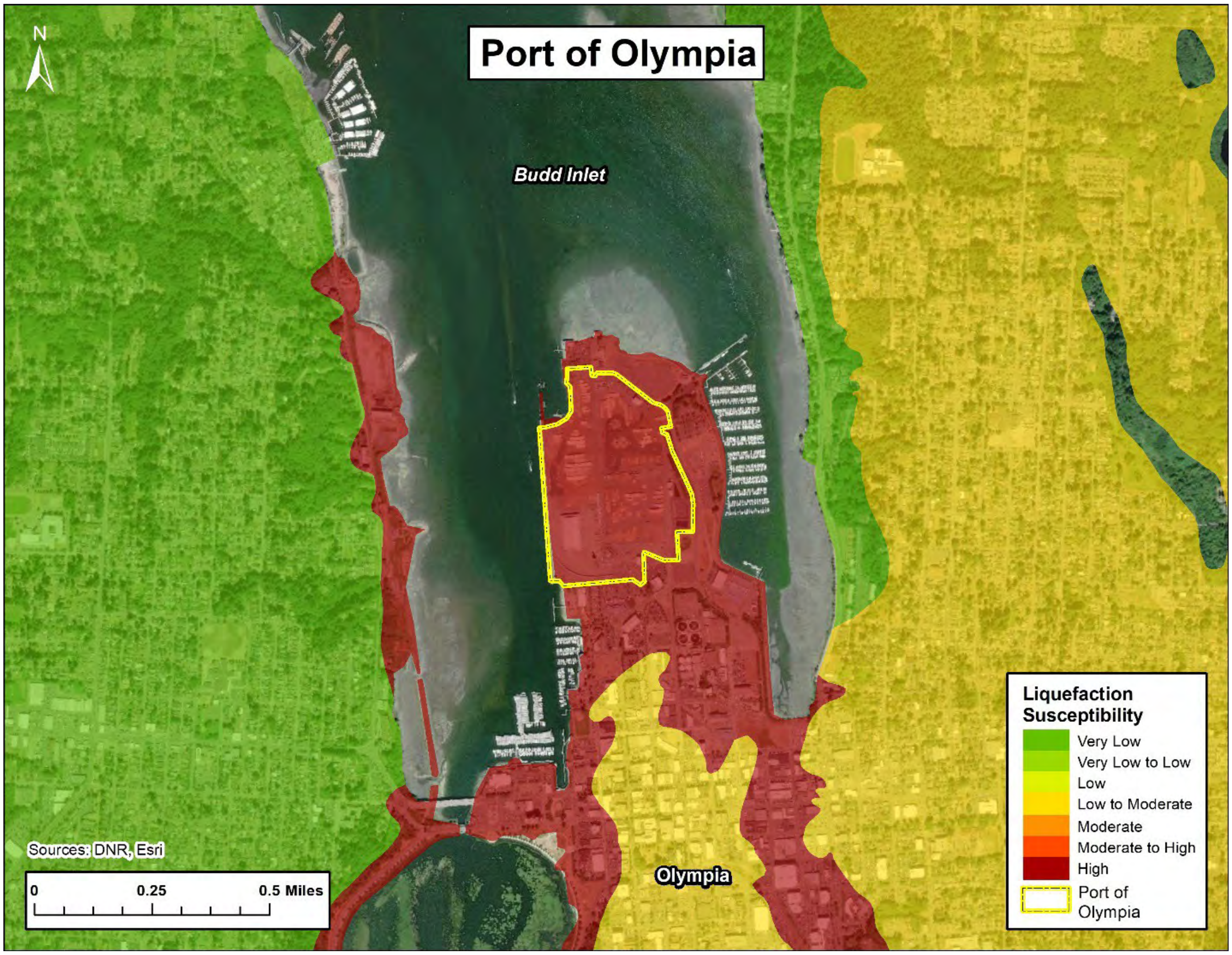

Figure A-4: Port of Olympia – Liquefaction Susceptibility[6]

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[6] *The Washington DNR L1 and 1A tsunami datasets do not currently contain tsunami data for the Port of Olympia*

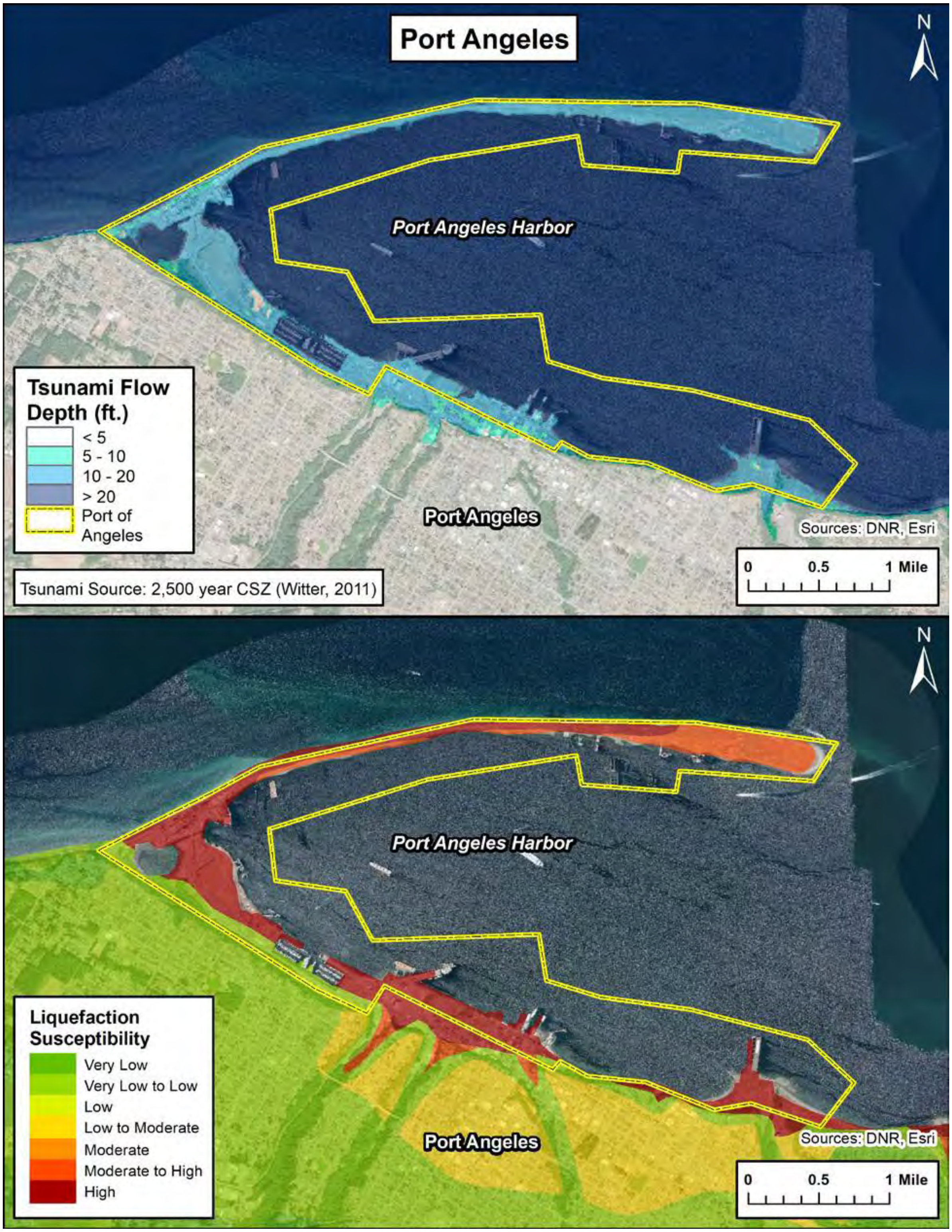

Figure A-5: Port of Port Angeles – Tsunami Inundation and Liquefaction Susceptibility

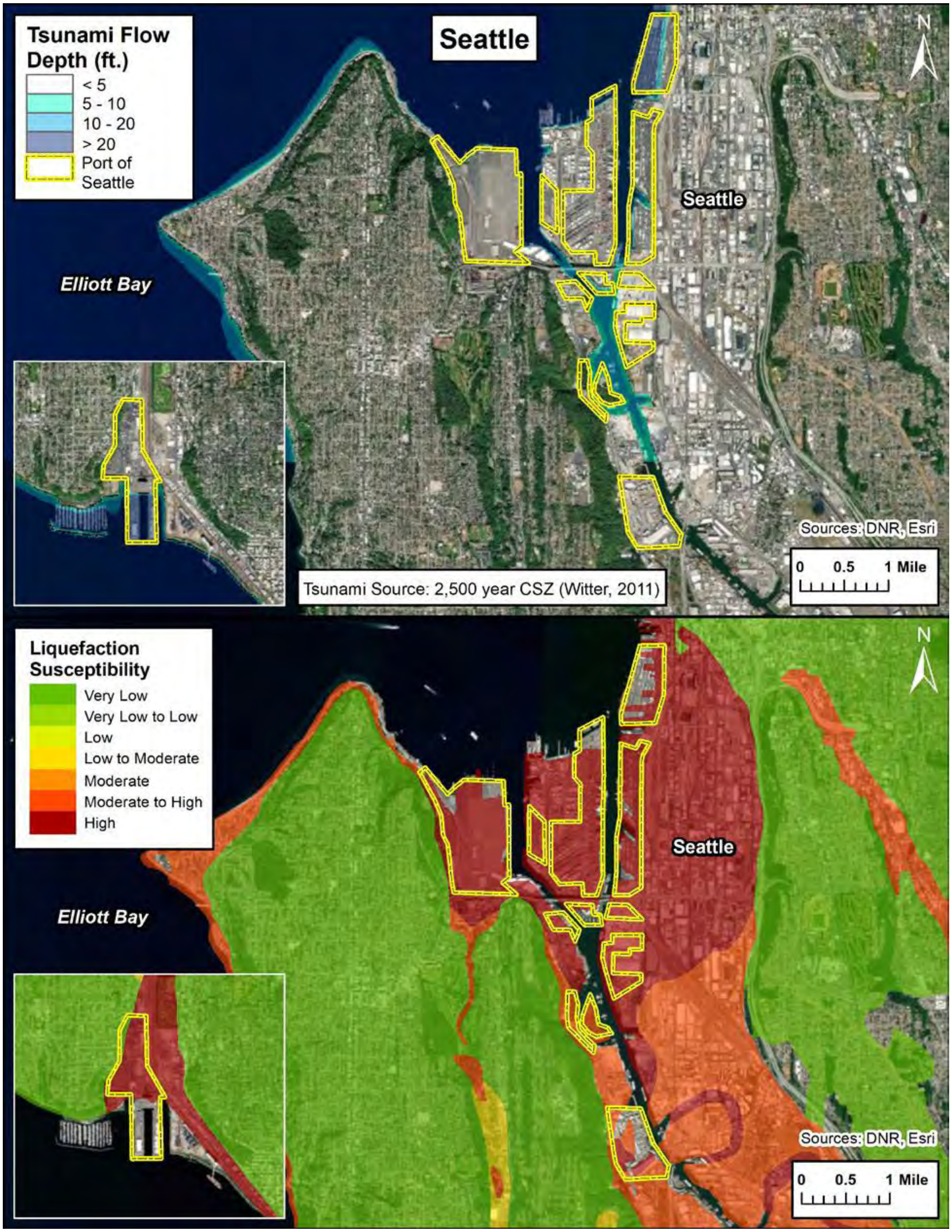

Figure A-6: Port of Seattle – Tsunami Inundation and Liquefaction Susceptibility

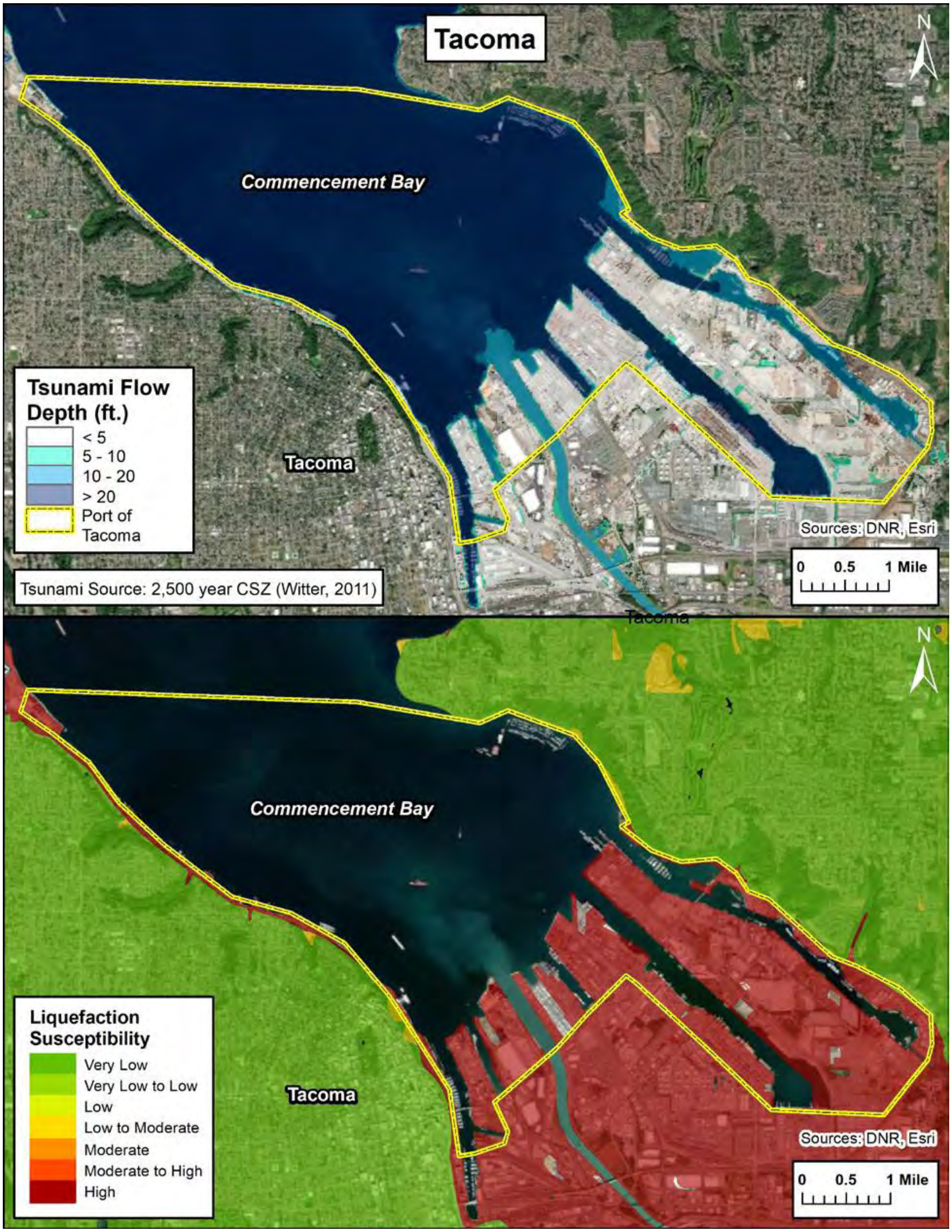

Figure A-7: Port of Tacoma – Tsunami Inundation and Liquefaction Susceptibility

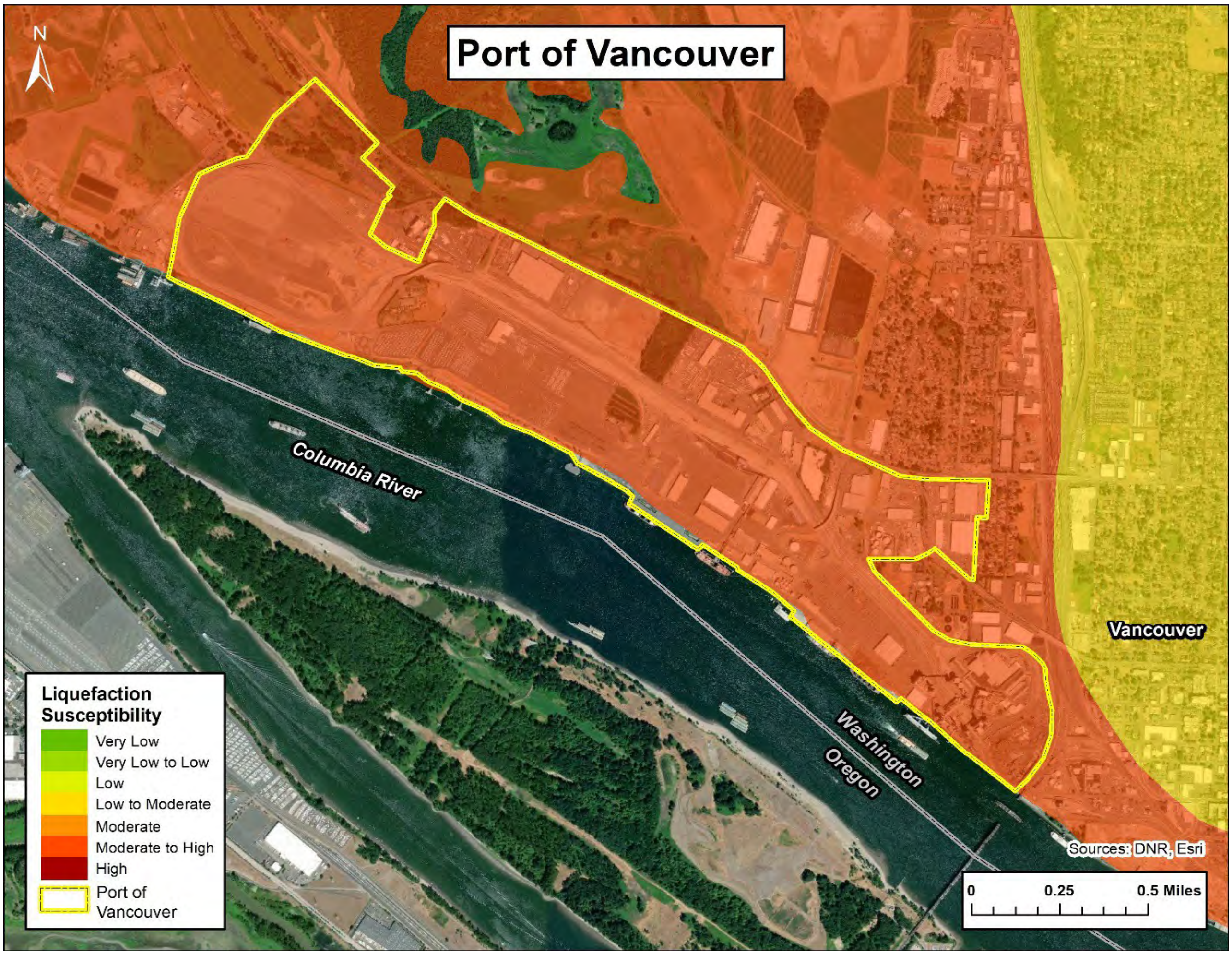

Figure A-8: Port of Vancouver – Liquefaction Susceptibility[7]

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[7] *The Washington DNR L1 and 1A tsunami datasets do not currently contain tsunami data for the Port of Vancouver*

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