ANL/DIS-19/1

Washington State Highway Bridge Seismic Screening Tool (BSST)

Technical Report

Decision and Infrastructure Sciences Division

Acknowledgement

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Introduction

The Regional Resiliency Assessment Program (RRAP) is a cooperative assessment of specific critical infrastructure within a designated geographic area and a regional analysis of the surrounding infrastructure that addresses a range of infrastructure resilience issues that could have regionally and nationally significant consequences. In 2017, the U.S. Department of Homeland Security's Cybersecurity and Infrastructure Security Agency (CISA) sponsored the Washington State Transportation Systems RRAP project in coordination with the Washington Emergency Management Division (EMD), Washington State Department of Transportation (WSDOT), and other regional stakeholders. This project is focused on assessing the impacts of a Cascadia Subduction Zone (CSZ) earthquake on state transportation systems and, in particular, how those impacts may affect the ability of emergency response efforts to move supplies into the region. The intended outcome of this analysis is the prioritization of transportation routes and modes for additional planning, investment, hardening, or other activities to enhance their resilience—and therefore, to enhance their ability to support response and recovery efforts following a CSZ earthquake.

An important part of this transportation system-level assessment has been to assess the seismic vulnerability of the state highway system. In doing so, the RRAP project team developed a Bridge Seismic Screening Tool (BSST) to assess, at a system-level, the potential impacts that a CSZ earthquake could have on state highway bridges.[1] The first step in the BSST is to assess the seismic vulnerability of highway bridge infrastructure in Washington State following a CSZ earthquake to determine a projected or potential damage state. Damage states are then used to determine approximate reopening times for bridge crossings.[2] This document provides details on the methodological development of the BSST, the implementation of that tool to analyze the projected damage incurred in a CSZ earthquake scenario, and the determination of corresponding reopening times of interstate and state highway bridges following such an event. The BSST was implemented programmatically using a Microsoft Excel macro-enabled workbook; instructions on use of this tool are provided in the accompanying report, *Washington State Highway Bridge Seismic Screening Tool (BSST)—User Manual*.

Regional Stakeholder Engagement

Collaboration with state and regional experts was fundamental to the development of the BSST. The Washington State Department of Natural Resources (DNR), EMD, and WSDOT provided significant hazard-related data and information, including earthquake shakemap datasets, tsunami inundation datasets, and soil liquefaction datasets. Experts from the WSDOT Bridge & Structures Office, Bridge Preservation Program, and State Materials Laboratory provided significant technical input and review throughout the development of the BSST. In particular, the Bridge & Structures Office reviewed and offered methodological input on numerous early iterations of the BSST framework during development. That office also reviewed initial and final results of the BSST analysis. The RRAP research team presented the initial bridge analysis results to the WEMD, U.S. Coast Guard, and various WSDOT Offices in mid-August 2017. Updated interim bridge analysis results were also presented during subsequent follow-up stakeholder engagement meetings in November 2017, February 2018, and June 2018, with the final results presented to this stakeholder group in June 2018. During all interactions, input

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[1] This tool does not conduct a detailed, asset-level engineering analysis of individual structures; it is not intended to predict or provide a detailed or specific assessment of direct seismic and seismic-related impacts on individual bridges from a CSZ event, but rather to inform a system- or network-level vulnerability analysis.

[2] Reopening time refers to the amount of time required to repair a bridge crossing to a state of repair sufficient to support the movement of emergency response vehicles; it is different from restoration time in that it does not refer to complete restoration to a pre-event state of repair.

from state and regional stakeholders on the analysis and results was agreed upon and integrated into the final analytical tool and outcomes.

Identifying Relevant Hazards

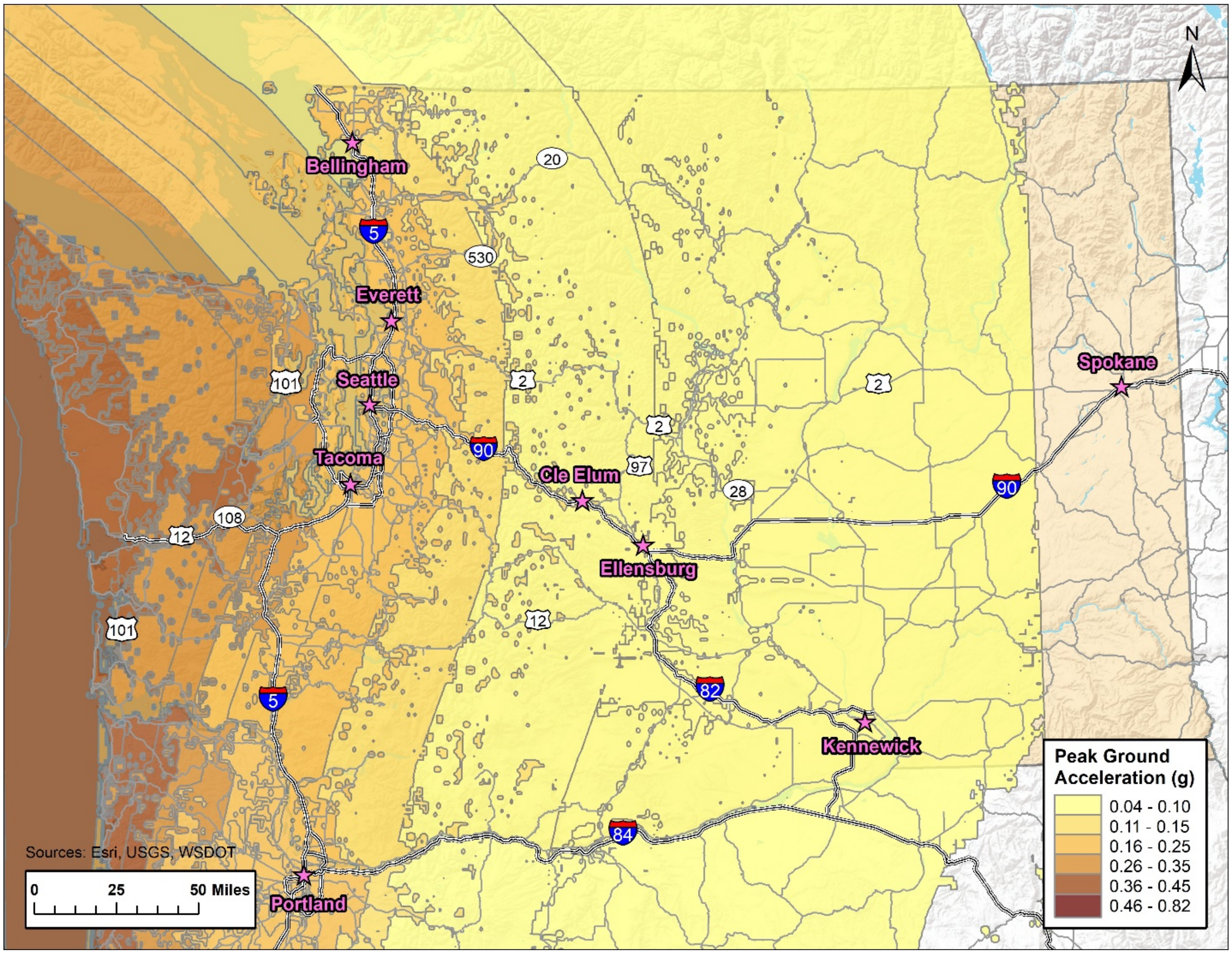
The goal of this analysis was to assess the projected damage to, and reopening time of, interstate and highway bridges within Washington following a CSZ earthquake. This assessment examined both the direct earthquake impacts (i.e., forces from seismic acceleration) and the impact of secondary earthquake-induced hazards on projected bridge damage and reopening times. Secondary earthquake-induced hazards assessed in this analysis include tsunamis and soil liquefaction.

Several secondary earthquake-induced hazards—including slope instability (i.e., landslides), rock falls, and avalanches—were initially considered for inclusion in this analysis, but they were ultimately excluded because of inconsistent or unavailable data. Aftershocks were also considered for evaluation; however, methods for estimating the degraded seismic capacity of already seismically damaged bridges to resist aftershocks is an area of ongoing research and is plagued by extremely high uncertainty. Furthermore, while aftershocks are characteristic of subduction zone earthquakes, their timing and magnitudes are extremely uncertain, and as such, this current analysis excluded them (CREW 2013). The subsequent sections provide greater detail on the direct and secondary earthquake-induced hazards included in the current bridge analysis, and a brief discussion of other earthquake-induced hazards not assessed in this analysis.

CSZ Earthquake Ground Motion

The CSZ is a subduction fault zone, where three regional tectonic plates (Explorer, Juan de Fuca, and Gorda) located just off the Pacific coast are subducting, or moving inland and sliding underneath the North American plate (CREW 2013). Across the globe, subduction faults have historically produced earthquakes of comparatively larger magnitude and longer duration than other, shallower fault types. The CSZ spans more than 1,000 kilometers from Northern California to Southern British Columbia and has the potential of producing a magnitude 9.0 (M9.0) or larger earthquake during a full-length fault rupture (USGS undated[a], PNSN undated). The recurrence frequency of such a full-length rupture of the CSZ fault is uncertain, with estimated recurrence rates between 350 and 600 years; however, some occurrences of such earthquakes have historically been separated by as few as 200 or as many as 1,000 years (CREW 2013). The date of the last known CSZ full-length fault rupture earthquake was in January 1700 (PNSN undated). Historical recurrence rates may suggest an increased risk of such an earthquake occurring in the near future. The Cascadia Region Earthquake Workgroup (CREW) estimates a 10 percent probability of a full-length fault rupture occurring in the next 50 years (CREW 2013).

The development of the BSST used gridded shaking intensity values (peak ground acceleration [PGA]) that the U.S. Geological Survey (USGS) developed and published to determine projected PGA values for all highway bridges in Washington State (USGS 2017). The specific USGS scenario used in this analysis was the “M9.0 Scenario Earthquake – Cascadia M9.0 Scenario (mean value).” This scenario was agreed upon with regional stakeholders, and was selected to be consistent with CSZ earthquake scenarios used in previous research and planning activities conducted in Washington. Figure 1 shows the PGA values throughout Washington State from the USGS scenario used in this analysis.



Sources: Esri, USGS, WSDOT

Figure 1: Projected Peak Ground Acceleration (PGA) for Washington State under the USGS M9.0 CSZ Scenario

Given the significant length of the CSZ fault, a full-length rupture of the CSZ will cause long-duration shaking lasting between 3 and 6 minutes (CREW 2013). While no formal definition exists for differentiating between long-duration and the more common short-duration shaking, the projected shaking duration following a full-length CSZ fault rupture is significantly longer than a typical earthquake used as a basis for seismic design. For example, earthquakes in California generally last for fewer than 30 seconds (Chandramohan 2016, Mohammed 2016). An increase in the duration of shaking similarly causes a significant increase in the number of high stress loading cycles that infrastructure assets and systems experience. When earthquake shaking causes inelastic deformation in an infrastructure asset, the increased number of inelastic loading cycles during a long-duration earthquake will cause significantly greater damage to the infrastructure asset than an earthquake of more typical, shorter duration with an equal level of ground motion (i.e., PGA, peak ground velocity [PGV], or permanent ground displacement). The BSST includes provisions to account for the impact of long-duration shaking; further details of such methods are provided in the Earthquake Duration section below.

Tsunamis

The sudden movement of tectonic plates beneath the ocean's surface during an earthquake has the potential to cause tsunamis. While the force of tsunami waves can damage bridge super- and substructures, other impacts can also occur. These include debris carried by tsunami waves accumulating against the bridge structure exerting significant lateral forces against the bridge piles and abutments, or water overtopping the bridge. Bridge overtopping can induce stresses into the bridge superstructure that can exceed its design strength and can potentially wash out the bridge deck.

Tsunamis can also cause rapid bridge scour, a condition where rapidly flowing water removes rocks, sediment, and other soils that support bridge foundations. When bridge scour removes significant quantities of sediment and rocks, bridge foundations can become exposed or potentially undermined, reducing the bearing capacity of the foundation. These conditions can significantly weaken vulnerable bridges and potentially cause partial or complete bridge collapse (WSDOT undated[a]).

Within the bridge analysis methodology, bridge vulnerability to tsunami damage was determined using tsunami inundation data that Washington State DNR provided. Figure 2 illustrates the tsunami inundation modeling extents in Washington. At the time of this study's bridge analysis, Washington State DNR had only published the 1A (500-year) Scenario dataset containing only tsunami inundation extents, not any inundation depth information. While additional tsunami modeling information (e.g., the L1 Scenario) was published during the overall RRAP project, it was not practical to re-run the BSST analysis with this new information given the project timeline. As such, this analysis considers only tsunami inundation data containing projected tsunami inundation areas from the 1A scenario, which were available when it was conducted.[3]

The most severe tsunami inundation in Washington State is projected to occur primarily along the Pacific coast. However, some areas of Puget Sound and the Columbia River may also experience tsunami inundation resulting from a CSZ earthquake. While most tsunami modeling on the Pacific coast is based on a CSZ earthquake, tsunami modeling conducted in Puget Sound has incorporated both CSZ and non-CSZ earthquakes (e.g., Seattle fault earthquake, South Whidbey Island fault earthquake). While non-CSZ-fault earthquakes pose a seismic and tsunami risk, they were excluded from this analysis given the overall RRAP project's focus on CSZ-related impacts. Based on input from Washington State DNR, this study selected the 1A Scenario, which projects tsunami inundation at various locations along the Pacific coast following a CSZ earthquake, as well as some impacts in the northern areas of Puget Sound. The 1A scenario was the most currently available tsunami dataset at the time the BSST analysis was conducted. Further details on the assessment of bridge vulnerability to tsunamis is provided in the Tsunami Damage section.

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[3] Tsunami modeling efforts in Washington State are ongoing, and the data used in the BSST study, as shown in figure 2, include all current tsunami-modeling outputs available for Washington State. Many coastal areas may be vulnerable to tsunami inundation; however, modeling of inundation for those areas has not yet occurred.

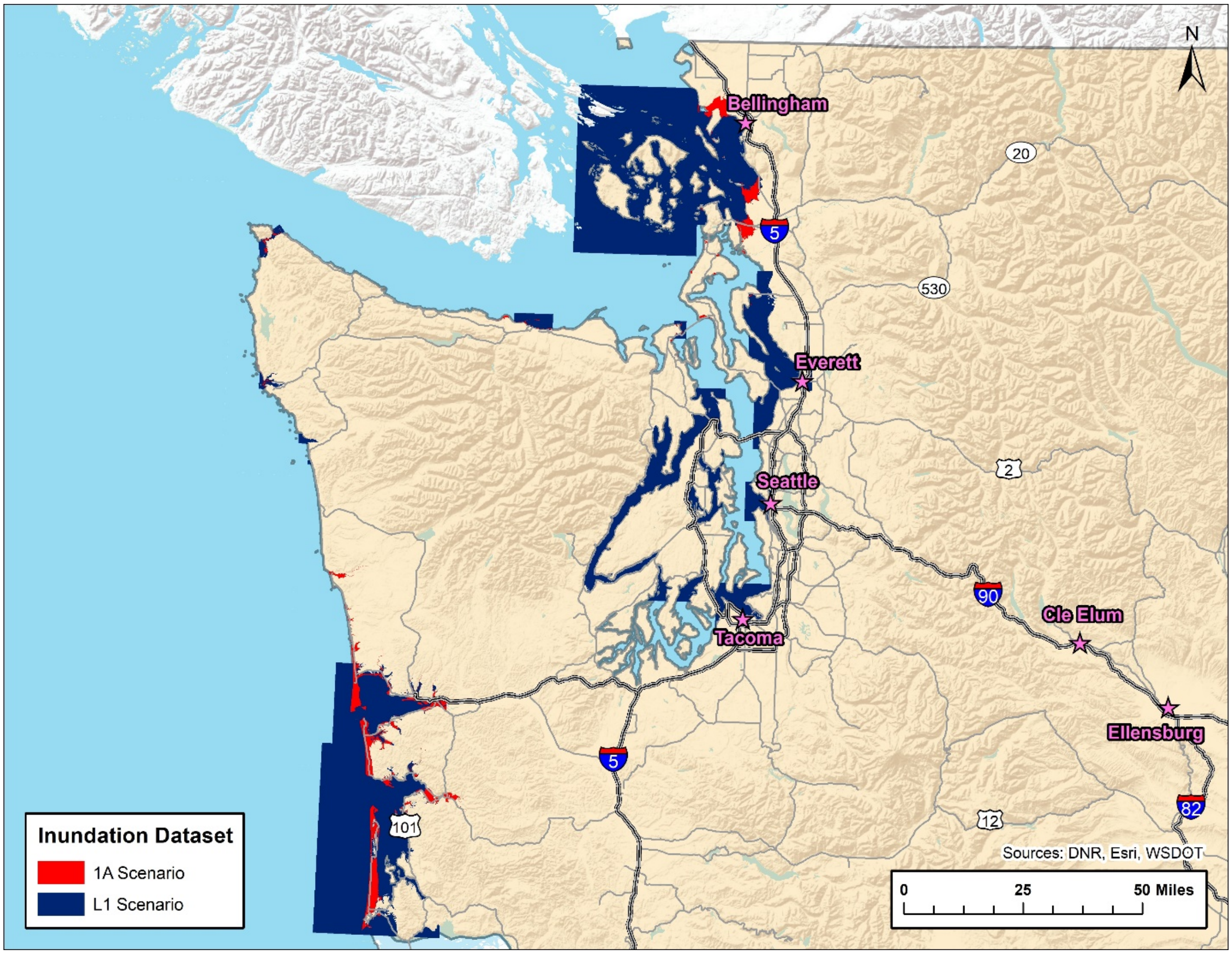

Figure 2: Washington State DNR Tsunami Inundation Datasets Coverage Comparison—the 1A Scenario was used in this Bridge Analysis

Soil Liquefaction

During earthquakes, rapid changes in soil stresses can cause fundamental changes in soil mechanical properties that adversely affect the soil's load-bearing performance. One such change can occur in saturated, relatively loose (i.e., high void ratio), cohesionless soil when rapidly changing stress levels cause mean pore pressure to exceed the stress existing in the soil, which in turn causes the soil to lose nearly all strength and stiffness and begin behaving as a liquid rather than a solid. This phenomenon, known as liquefaction, poses a significant threat to bridge structures built upon soils with comparatively higher liquefaction potential. Within the BSST, bridge vulnerability to soil liquefaction is determined using soil liquefaction potential data that Washington State DNR provided and which characterizes the soil liquefaction potential as detailed in the Soil Liquefaction Damage section. Figure 3 shows the soil liquefaction potential throughout Washington. Further details of how bridges were assessed for liquefaction damage are provided in the Soil Liquefaction Damage section.

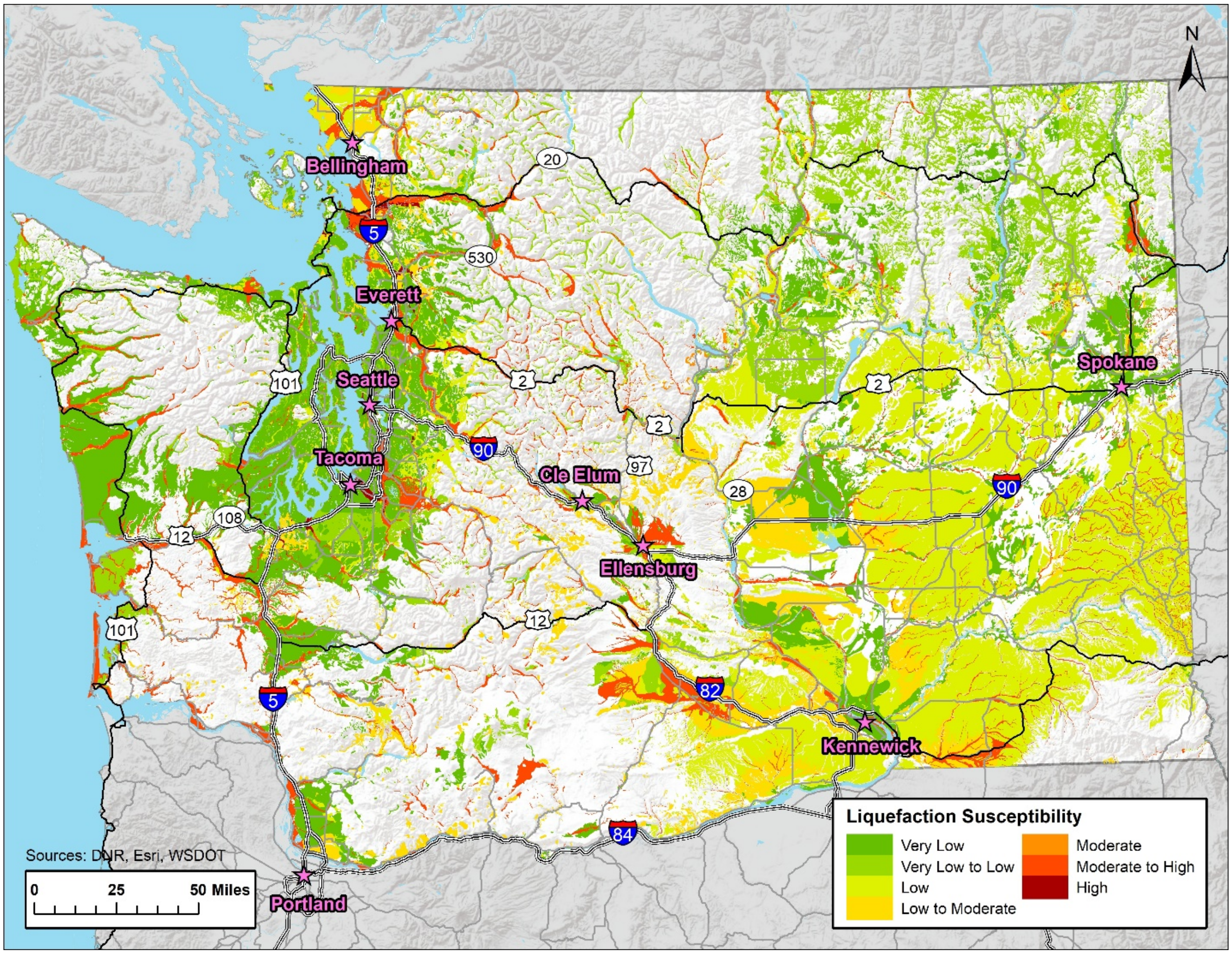

Figure 3: Soil Liquefaction Susceptibility in Washington State

BSST Assessment Methodology

The RRAP research team at Argonne National Laboratory (Argonne) developed the BSST methodology in coordination with WSDOT. In its final form, the BSST assesses bridges for numerous types of vulnerabilities associated with seismic and seismic-related hazards following a full-length CSZ fault rupture. In this respect, the methodology evaluates bridges against a range of potential vulnerabilities, in many cases beyond those associated with the primary failure mode. For example, if a bridge is initially determined to have an inadequate structural design to resist seismic forces, the BSST will still evaluate additional potential vulnerabilities to provide a more complete characterization of all possible failure modes. Conducting this additional analysis informs infrastructure resilience enhancement and investment decisions, and overall bridge repair or reopening times, all of which require identification of all bridge vulnerabilities. The developed methodology was implemented programmatically in Microsoft Excel using Visual Basic for Applications. The BSST also uses bridge asset data that WSDOT's Bridge & Structures Office provided during the development of the BSST methodology (see table 1).

Table 1: Bridge Data Provided by WSDOT

Dataset Name	Dataset Type	Description	Citation
Bridge Lines	Geographic Information System (GIS) shapefile	Polyline GIS data developed by WSDOT for some bridges in Washington State using linear referencing system (LRS) codes	(WSDOT 2017a)
BMS Elements	Spreadsheet	Bridge data is from WSDOT's Bridge Management Software database identifying the existence and quantity of various bridge systems and structural components	(WSDOT 2017b)
Inventory Data	Spreadsheet	Bridge data is from WSDOT's bridge inventory database containing various bridge design parameters and location information	(WSDOT 2017c)
Seismic Data	Spreadsheet	Bridge data created and maintained by WSDOT throughout the bridge seismic retrofit program containing information on the types and dates of seismic retrofits conducted on bridge superstructures and substructures, the expected 1,000-year earthquake PGA value for several bridges, information about the seismic retrofits needed/types based on WSDOT assessment	(WSDOT 2017d)

The BSST consists of three sections (figure 4). The first section of the methodology assesses the seismic design performance of a bridge by comparing the bridge's design capacity to the maximum PGA projected to occur at a bridge's location during a M9.0 full-length rupture of the CSZ (USGS 2017). The next section of the methodology evaluates potential bridge damage due to soil liquefaction and tsunami inundation. Finally, bridge reopening times are estimated on the basis of the projected extent and types of damage suffered by a bridge. The following sections provide greater details on each of these analytical components.

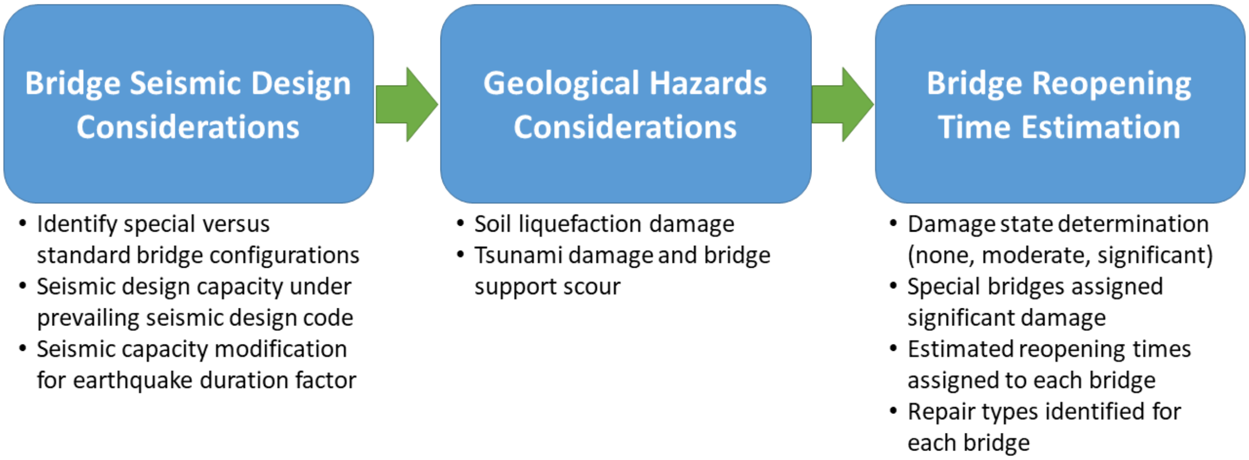

Figure 4: Bridge Seismic Screening Tool (BSST) Methodology

Step 1: Bridge Seismic Design and Damage Potential

The first step of the BSST analysis methodology focuses on bridge design to determine the type and extent of projected damage following a full-length rupture of the CSZ fault due to seismic loading. The primary types of damage include bridge failure due to bridge overloading (i.e., occurring when shaking during the CSZ full-length rupture exceeds a bridge's capability to withstand seismic shaking), soil liquefaction, and tsunami inundation damage.

The seismic design performance step begins by evaluating each bridge's design type, flagging it as either standard or special. The BSST methodology approximates damage on the basis of typical bridge performance for standard bridge designs. However, some bridges with non-standard designs (e.g., floating, suspension, moveable bridges) have unique vulnerabilities, and as such, the projected damage to these bridges is atypical. The following sections provide more details on the assessment of bridge damage types, starting with a discussion of how special bridge designs are treated.

Special Bridge Design Identification

The seismic performance of special bridges is highly complex, and thus it requires detailed dynamic seismic structural analysis of the projected earthquake time series to determine projected bridge performance. Although the BSST evaluation of special bridge designs does not include damage due to inadequate seismic design capacity, it does assess such bridges for other potential vulnerabilities, including liquefaction and tsunami-related overtopping or scour.

For the state highway bridge dataset that WSDOT provided, WSDOT's Bridge & Structures Office agreed upon five bridge types for classification as special bridges (35 bridges).[4] Table 2 provides the bridge types categorized as special bridges and the parameter values, from various files provided by WSDOT, used to identify each bridge type.

Within the BSST, reopening times for all special bridges are provided as an input; all special bridges were assumed to sustain significant damage and a reopening time of 2.5 years was assumed. Following the analysis, the reopening times for some of the special bridges were reduced after a discussion of bridges with experts in the WSDOT Bridge & Structures Office on an individual basis.

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[4] The bridge dataset provided by WSDOT excludes data from several counties in eastern Washington, as several previous studies have projected little to no impacts of a M9.0 CSZ earthquake in far eastern Washington owing to the low projected PGA values in these areas during the M9.0 CSZ earthquake.

Table 2: Bridge Types Classified as Special Bridges, and Sources Used for Identifying Each Bridge Type

Bridge Type	Number of Bridges	"alphabetic_span" Values [from the Inventory Data dataset provided by WSDOT]	"fed_main_design_code" Values [from the Inventory Data dataset provided by WSDOT]	"element_id" Values [from the BMS Elements dataset provided by WSDOT]
Floating	8	• CFP ("Concrete Floating Pontoon") • SFP ("Steel Floating Pontoon")		• 236 ("Concrete Floating Pontoon") • 238 ("Floating Bridge-Anchor Cable")
Movable	13	• BAS ("Bascule Lift Span") • SLS ("Steel Lift Span") • SSwS ("Steel Swing Span")	• 15 ("Movable-Lift") • 16 ("Movable-Bascule") • 17 ("Movable Swing")	• 367 ("Movable Bridge") • 501 ("Movable Bridge Steel Tower")
Cable Stayed	1	• CSS ("Cable Stayed Span")		• 149 ("Cable Stayed Bridge-Cable")
Steel Suspension	3	• SSuS ("Steel Suspension Span")		• 146 ("Suspension-Main Cable") • 147 ("Suspension-Suspender Cable")
Steel Tied Arch	10	• STA ("Steel Tied Arch")		• 143 ("Steel Suspender")

WSDOT bridge engineers also identified several bridges in the state that were constructed with hollow core concrete pile supports, which are highly vulnerable to earthquake damage and have very limited capability to withstand seismic forces. While these bridges may have a more standard design configuration, the unique seismic concerns associated with hollow-core piles nonetheless warrant special consideration, and they were therefore designated as special bridges in the BSST methodology. No feasible method for seismically retrofitting such piles has been identified. As such, bridges with hollow core concrete piles are assumed to suffer significant damage regardless of the PGA they experience during the M9.0 CSZ full-length rupture earthquake scenario. For the current Washington highway bridge analysis, the team first identified 22 bridges with hollow core piles in the data WSDOT provided. Bridges with hollow core concrete columns are still assessed in the BSST for other potential damage, such as soil liquefaction and tsunami damage, and the bridge's reopening time is assessed using the bridge analysis methodology.

Bridge Seismic Design Considerations

For all other bridges with standard design configurations (i.e., not special bridges), projecting bridge performance during an earthquake begins with determining each bridge's seismic design capacity. Without performing detailed dynamic seismic analysis, the exact seismic capacity of bridges cannot be determined. However, bridge seismic capacity can be approximated by considering the seismic design code that governed at the time when the bridge was designed.

Bridge seismic design in Washington State began after 1983, using the 1983 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications for Seismic Design of Highway Bridges*, the first available comprehensive guidance of its kind published by a national organization. Bridges designed prior to the publication of the 1983 AASHTO guidance were not designed with considerations of seismic forces, although some may have some inherent capability to withstand seismic forces. Discussions with WSDOT bridge engineers suggested that historically, bridges in Washington State have suffered minor to no damage when subjected to a PGA less than 0.15 g.[5] As such, bridges built in 1983 or earlier were considered to have a seismic capacity of 0.15 g. Furthermore, a PGA of 0.15 g was also assumed to correspond to the maximum PGA causing elastic deformation; bridges experiencing PGA greater than 0.15 g were assumed to experience inelastic deformation (see Earthquake Duration section).

All bridges designed after the publication of the 1983 AASHTO guidance were seismically designed using the prevailing AASHTO highway bridge design codes. These bridge design codes specify the probabilistic minimum seismic shaking (in terms of PGA) that a bridge may experience over its lifetime on a location-specific basis. Prior to 2007, the PGA specified in AASHTO codes corresponded to the highest PGA a site would expect to experience using a 500-year recurrence rate. After 2007, WSDOT began designing bridges in Washington State using the highest PGA based on a 1,000-year recurrence rate.

For the current analysis of Washington State highway bridges using the BSST, the design year of a bridge is determined as the more recent date between (1) the year the bridge was constructed and (2) the year a superstructure seismic retrofit was completed, using data that WSDOT provided (WSDOT 2017d). WSDOT's seismic retrofit program has primarily focused on seismically retrofitting bridge superstructures, not bridge substructures. Table 3 provides the documents and/or methods used for determining bridge seismic design capacity on the basis of bridge design (or superstructure retrofit) year.

Table 3: Determination of Bridge Seismic Design Capacity Based on Bridge Design Year

Bridge Design Year	Document/Methodology for Determining Bridge Seismic Design Capacity
1983 or earlier	Based on historical observation of bridge performance during earthquakes; seismic design capacity of 0.15 g used for all bridges
1984–1998	The Argonne team digitized Figure 3 from the 1983 AASHTO *Guide Specifications for Seismic Design of Highway Bridges* (AASHTO 1983) in ArcGIS to determine PGA design values for each bridge in the WSDOT-provided Inventory Dataset (WSDOT 2017c) on the basis of its location.
1999–2007	The Argonne team digitized Figure 3.10.2-1 from the 1998 *AASHTO LRFD Bridge Design Specifications* (AASHTO 1998, 2004)[6] in ArcGIS to determine PGA design values for each bridge in the WSDOT-provided Inventory Dataset (WSDOT 2017c) on the basis of its location.
2008– 2014	Bridge seismic design capacities were provided by WSDOT in the "1000 YR PGA" column of the Seismic Data dataset (WSDOT 2017d). However, 148 bridges with design years between 2008 and 2014 did not have values in this file. For such bridges, the Argonne team extracted 1,000-year PGA design values[7] from the U.S. Seismic Design Maps tool using the 2009 AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (USGS undated[c], AASHTO 2009).
2015 or later	Bridge seismic design capacities were provided by WSDOT in the "2014 PGA" column of the Seismic Data dataset (WSDOT 2017d). However, 44 bridges with design years of 2015 or later did not have values in this file. For such bridges, the Argonne team extracted 1,000-year PGA design values from the U.S. Seismic Design Maps tool using the 2009 AASHTO *Guide Specifications for LRFD Seismic Bridge Design* (AASHTO 2009).

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

[6] This figure is the same as Figure 3.10.2-1 in the 2004 *AASHTO LRFD Bridge Design Specifications*.

[7] The 1,000-year PGA design value for a location represents the maximum PGA expected to occur at the site from all potential earthquake sources, which appears to be based on the *Guide Specifications for LRFD Seismic Bridge Design, 1st Edition, with 2010 Interim Revisions* (AASHTO 2009).

For bridges built between 1984 and 2007, seismic design capacities (in terms of PGA) were determined using the relevant AASHTO seismic bridge design codes and guidance documents as identified in table 3. Within the AASHTO seismic bridge design codes, maps displaying PGA contours provide the minimum seismic demand that bridges are designed to withstand. The Argonne team digitized the PGA contour maps using ESRI ArcGIS software and then assigned bridges the relevant PGA level on the basis of bridge location. If a bridge fell between contour lines, then the bridge was assigned the more conservative of the two contour values.

After determining a bridge's seismic design capacity, that design capacity is compared to the projected PGA at the bridge site during a full-length rupture of the CSZ fault for the M9.0 USGS scenario. However, the seismic design of bridges is based on the standard-duration earthquake. As previously mentioned, a M9.0 full-length rupture of the CSZ fault is projected to last between 3 and 6 minutes (CREW 2013). This requires some modification of the CSZ M9.0 scenario-based PGA values for the purposes of evaluating projected bridge performance and long-duration effects. As discussed in the next section, this effectively requires an adjustment factor that categorically reduces bridge seismic design capacities. In practice, this is implemented instead by slightly increasing projected PGA values.

The modified projected PGA values from the M9.0 CSZ scenario are compared with the bridge capacity values to determine projected bridge performance. If the modified projected PGA values from the M9.0 CSZ scenario exceed the bridge seismic capacity, the bridge is assumed to sustain significant damage. However, WSDOT bridge engineers noted that bridges with single spans (i.e., no columns) or bridges with pier walls tend to prove more resilient to seismic loading and sustain less damage than other bridge configurations when overloaded. As such, bridges with single-span or pier wall support designs that are projected to experience a modified PGA exceeding the bridge seismic design capacity were considered to be moderately damaged because of excessive seismic loading. These bridges were then assessed for other types of damage (e.g., liquefaction or tsunami), which may cause significant damage to the bridge.

In addition to checking for seismic forces in excess of bridge design capacity, the modified PGA values are also compared to a minimal PGA as a threshold for bridge damage. From discussions with WSDOT bridge engineers based on prior experience with regional earthquakes, it was determined that a PGA below 0.15 g is unlikely to cause significant bridge damage. Thus, bridges with seismic design capacities exceeding the modified projected PGA values from the CSZ scenario earthquake were also evaluated for this minimal PGA. If the modified projected PGA exceeds 0.15 g, the bridge is considered to experience moderate damage, but not significant damage, given the comparatively lower PGA.

Earthquake Duration Adjustment Factor

As mentioned earlier, ground motion during a full-length rupture of the CSZ fault is projected to last for 3-6 minutes, significantly longer than the typical earthquake duration for which design codes have primarily been developed. Quantifying the impact of longer-duration shaking on projected bridge performance is uncertain and a currently active, ongoing area of research. A recent study by Mohammed (2016) assessed the impact of earthquake duration on a standard reinforced-concrete column bridge design's capacity using both analytical and experimental methods. That study estimated that long-duration earthquakes can reduce bridge seismic displacement capacity by 25 percent and can reduce a bridge's ability to withstand spectral accelerations by 21–29 percent compared to its capability during a short-duration earthquake.

On the basis of this work, the BSST methodology applies a 25 percent reduction of bridge seismic design capacities to all WSDOT bridges in order to account for duration effects during the full-length CSZ fault rupture for the current bridge analysis. However, in practice, this accounting was accomplished instead by increasing the projected seismic demand by 33 percent to enable the future analysis of aftershocks (should such an expansion of the analysis be undertaken), which would more likely be of a standard duration.

This modified PGA is then used to determine the projected damage (and corresponding repair types and reopening times) for damage caused by projected modified PGAs exceeding bridge design capacities, liquefaction, and tsunamis.

As long-duration earthquakes cause greater numbers of loading cycles, when the level of earthquake shaking is low enough to cause only elastic deformation, the increased number of cyclic loads is unlikely to cause significantly greater damage as compared with a regular-duration earthquake with an equivalent level of shaking (i.e., PGA or PGV). Conversely, when shaking is strong enough to cause inelastic deformation, the increased number of loading cycles during a long-duration earthquake will increase the level of damage compared to a regular-duration earthquake causing an equivalent level of shaking (in terms of PGA or PGV). On the basis of discussions with WSDOT bridge engineers, the 0.15-g PGA level was used as a threshold for plastic/inelastic deformation. Bridges experiencing unmodified PGAs below this value were determined to experience only elastic deformation, and thus the long-duration effect in the bridge analysis methodology was not applied to those bridges.

Step 2: Geological Hazard Considerations

In addition to evaluating the damage caused by direct seismic forces exceeding bridge design capacities, the BSST assesses damage caused by two other seismic-related geological hazards: (1) soil liquefaction and (2) tsunami-related inundation and bridge scour hazards.

Soil Liquefaction Damage

Discussions with experts in the WSDOT State Materials Laboratory led to the identification of PGA between 0.1 g and 0.15 g as sufficient to cause liquefaction in saturated, cohesionless soils with high void ratios (e.g., loose soils, generally sand or compacted fill). Soil liquefaction potential data that Washington State DNR provided, identifies 12 categories to classify liquefaction potentials in the top-most layer of soil, as shown in table 4. These 12 categories were simplified into four broader categories for potential liquefaction by the Argonne team to better align with the critical PGA values identified in collaboration with WSDOT and mapped in ESRI ArcGIS software.

In accordance with the location-specific liquefaction potential of soils, the PGA threshold for liquefaction is determined for each bridge and compared to the modified PGA (accounting for long-duration effects) projected at each bridge site. If the modified PGA exceeds the liquefaction PGA threshold, soil liquefaction is assumed to occur at the site and the bridge is assumed to suffer significant damage because of soil liquefaction at the bridge location. If the modified PGA is less than the liquefaction PGA threshold, no liquefaction is assumed to occur at the bridge site, and the bridge is assumed undamaged due to soil liquefaction hazard.

Table 4: Determination of Bridge Seismic Design Capacity Based on Bridge Design Year

Categories of Liquefaction Potential in DNR Datasets	Simplified Categories of Liquefaction Potential	PGA Causing Each Level of Liquefaction
N/A (bedrock)	Not Vulnerable	N/A
N/A (peat)	Not Vulnerable	N/A
N/A (water)	Not Vulnerable	N/A
Very Low	Not Vulnerable	N/A
Very Low to Low	Not Vulnerable	N/A
Low	Low	0.15 g
Low to Moderate	Moderate	0.15 g
Moderate	Moderate	0.15 g
Moderate to High	High	0.1 g
High	High	0.1 g
High to Very High	High	0.1 g
Very High	High	0.1 g

Tsunami Damage

Bridges are next assessed in the BSST for damage caused by tsunami impacts, which can include bridge scour or overtopping of bridge decks leading to excessive lateral loads on the bridge structure. Bridges are assessed for both of these tsunami damage types within the bridge analysis methodology. As previously mentioned, tsunami inundation maps were provided to Argonne by Washington State DNR. However, tsunami modeling efforts in Washington State are ongoing, and the data used in the present study include all tsunami modeling outputs available for Washington State at the time the bridge analysis was conducted; however, they do not provide complete coverage of all statewide coastlines. Many coastal areas may be vulnerable to tsunami inundation, but tsunami modeling for those areas is not yet available.

Bridge vulnerability to tsunamis is determined by comparing bridge geolocation to all tsunami inundation maps. If a bridge lies within one of the mapped tsunami inundation zones, the bridge is considered vulnerable to tsunami inundation in the bridge assessment methodology. At the time of this study, available tsunami inundation data (i.e., the 1A Scenario dataset) did not include inundation depth information. As such, bridge overtopping during a tsunami could not be directly assessed. Instead, the waterway adequacy code in the WSDOT bridge database is used as a proxy for bridge vulnerability to overtopping. The waterway adequacy code is based on the historical frequency of bridge overtopping due to flooding. Any bridge located in a tsunami inundation area with a waterway adequacy code identifying "Occasional overtopping of bridge deck and roadway approaches with significant traffic delays," or more severe or frequent overtopping, is considered to sustain significant damage due to tsunami overtopping.

Next, bridges are assessed for scour damage potential using the bridge scour rating in the WSDOT bridge database. Bridges located in the tsunami inundation zone that are listed as scour critical were assumed to be vulnerable to scour damage during a tsunami, and assessed to sustain significant scour damage during a CSZ-related tsunami.

Step 3: Bridge Reopening Times

All bridge vulnerability and potential-damage analysis is ultimately used to inform the determination of an approximate bridge reopening time for each structure following a full-length rupture of the CSZ fault.

Bridge *reopening time* is different from bridge *repair time* or restoration time; reopening time refers to the amount of time required to repair a bridge crossing to a minimum functional state of repair sufficient to support the movement of emergency response vehicles. It does not necessarily refer to complete restoration to a pre-event state of repair. The estimated reopening times include the time necessary to perform a bridge damage inspection, bridge rehabilitation or bridge replacement, or to construct a temporary road to bypass the bridge. Bridge reopening times (see table 5) were determined in collaboration with the WSDOT bridge engineers on the basis of damage criteria, bridge length, and repair type, as discussed in the following sections.

- **No Bridge Damage -** Bridges identified as suffering neither significant nor moderate damage are assumed to sustain no structural damage during the CSZ earthquake scenario and thus assumed to not require any repairs prior to reopening. These bridges may suffer minor surface cracking.

- **Moderate Bridge Damage -** Bridges identified as suffering *moderate* damage of at least one damage type and not identified as suffering significant damage of any of the potential damage types are assumed to be moderately damaged following the CSZ earthquake scenario and related geological hazards. For such bridges, it is assumed that a bridge damage inspection would be necessary prior to reopening, but that limited or no bridge repairs would be required. Furthermore, it is assumed that the bridge inspection and any necessary repairs would require 2 weeks to complete, after which time the bridge would be reopened.

- **Significant Bridge Damage -** Bridges identified as suffering *significant* damage are evaluated within the BSST to determine the amount of time required to either repair or replace the bridge, or to build a temporary road that bypasses the bridge, if possible. Bridges suffering significant damage are considered damaged to such an extent that major bridge rehabilitation, partial rebuild, or complete rebuild would be necessary. Given the extensive time required for such work, the construction of temporary roadways to replace bridges when possible was deemed preferential in the BSST methodology. If it was determined that a temporary roadway could not be constructed, the bridge rehabilitation or replacement time was determined as a function of bridge length and considerations of any subsurface strengthening necessary to improve liquefied soils at the bridge location.

Table 5: Bridge Reopening Times and Repair Types Based on Damage and Bridge Length

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[8]	> 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	

Temporary Road Considerations

Temporary bypass roads are considered to be a viable option for damaged bridges that do not cross waterways and where the underlying topography is relatively flat; that is, the bridge does not traverse a deep ravine or other impassable topographic feature. The waterway adequacy code in the WSDOT bridge database was used to determine whether a bridge crosses a waterway. A national digital elevation model (DEM) published by USGS through The National Map (USGS undated[b]) database is used to identify large variations in ground elevation below a bridge structure.[9] This is done by determining the maximum and minimum ground elevations that occur beneath the entire length of each bridge and computing the total change. If the difference between the maximum and minimum ground elevations below a bridge is calculated to exceed 30 ft, it is assumed that variations in land topography are too great to feasibly construct a temporary surface roadway to bypass the bridge. If the difference between the maximum and minimum ground elevations is less than or equal to 30 ft, it is assumed that a temporary surface roadway is a viable bypass option.

Two methods were used to calculate the maximum and minimum ground elevations below bridges—the first using a GIS polyline bridge dataset and the second using a GIS point bridge dataset, both provided by WSDOT. Within the polyline dataset, bridges are represented by line features in ArcGIS, providing location information along the entire centerline of the bridge. The maximum and minimum ground elevations underneath each bridge are calculated in ArcGIS by examining ground surface elevations for an area defined as half roadway width on each side of the bridge line, over the entire length of that line.

Within the line dataset, there were some cases where bridges were associated with multiple routes, which were designated within that dataset using WSDOT's roadway linear referencing system (LRS). For example, a bridge may carry entrance/exit ramps in addition to the primary route; each of these would have a different LRS identifier and thus be represented by a different line in the line dataset. In these cases, it was assumed that the bridge from the bridge line dataset with a length closest to the length of the

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[8] See Temporary Road Considerations section for definition of impassable topography.

[9] The DEM provides ground elevation throughout the nation; a 1/3 arc-second DEM resolution was used in this analysis.

bridge structure carrying the route provided in the point bridge database best represented the topography that a temporary road would be built upon to bypass the significantly damaged bridge structure. Then, the maximum and minimum elevation under this bridge line is calculated as before.

The line bridge dataset provides the greatest amount of detailed locational information for highway bridges; however, the dataset is incomplete, accounting for only 92 percent of all highway bridges in Washington State. For those bridges that were not included in the line dataset (213 bridges), maximum and minimum elevations below the bridges were determined using the bridge point database. While the point-based dataset does not provide as much information about the location and orientation of the complete bridge structure, it does contain all highway bridges in Washington. For those bridges not contained in the line dataset, ground elevation data were calculated using similar methods to those described above, but using a circular buffer around the bridge point location with a radius of half the bridge length.

When it is determined that a temporary road can be built to bypass a significantly damaged bridge, the time necessary to construct the temporary road is computed as a function of bridge length. For bridges up to 50 ft in length, a value of 2 weeks is used to approximate bypass road construction time. For bridges over 50 ft in length, a value of 2 weeks per 50 ft of bridge length is used. These construction estimates are based on conversations with WSDOT personnel. It is important to note that these roadway construction time estimates are based on the construction of roads with a temporary wearing surface (e.g., compacted gravel) to enable the passage of emergency response and recovery vehicles. These temporary roadways are not intended for public use, would not be as durable as roadways with more permanent wearing surfaces, and would likely require ongoing maintenance given heavy use by emergency response and recovery vehicles and environmental conditions.

Bridge Rehabilitation or Replacement

When the construction of a temporary road is not feasible, bridge rehabilitation or replacement is necessary. On the basis of discussions with WSDOT bridge engineers, bridge length and the potential need for soil liquefaction mitigation improvements were identified as the primary metrics influencing bridge repair or replacement time. The bridge replacement times are provided in table 5, above. Generally, bridges that are greater in length and requiring soil liquefaction mitigation require longer reopening times than those with shorter spans or no soil liquefaction.

Discussion of Analytical Uncertainty

Argonne National Laboratory developed the BSST analytical methodology in close collaboration with WSDOT bridge engineers, with agreement that this analysis likely represents a “worst case scenario” for bridge damage due to an M9.0 CSZ earthquake scenario. Several assumptions that affect the uncertainty in the bridge analysis have been described throughout this report. However, several additional overarching sources of uncertainty in the bridge analysis are important to note, yet are difficult to quantify and account for systematically in the BSST. For this reason, here we discuss broadly several additional sources of uncertainty that could influence the outcomes of the BSST analysis.

Bridge Data Uncertainty

Several datasets were identified and used for the bridge analysis, including the following:

- WSDOT Bridge Inventory Database (GIS point feature data)
- WSDOT Bridge Inventory Database (GIS polyline feature data)
- WSDOT Bridge Management System Database
- WSDOT Bridge Seismic Retrofit Program Database
- Washington State DNR Soil Liquefaction Potential Maps (GIS polygon feature data)

- USGS The National Map Ground Level Digital Elevation Model
- Washington State DNR Tsunami Inundation Area Maps (GIS polygon feature data)

Many of these datasets were highly structured and standardized; however, as with any dataset, it is possible that errors are present or that data are incomplete. For the current analysis, it was assumed that all datasets were accurate to the extent possible. The researchers identified some errors during the course of the analysis, which they strove to address. However, it is possible that some errors remain in the source data that could contribute to uncertainty or error in the overall analysis.

Bridge Performance Uncertainty

It is impossible to predict with certainty how a given bridge will perform. Even a full dynamic structural analysis, which requires significant labor and costs beyond the scope of this project, can only seek to minimize uncertainty. The assumptions listed below were made regarding the influence of various bridge properties on the projected bridge vulnerability and performance.

Seismic Design Capacity

Determining bridge seismic design capacities is a two-stage process: The first stage determines the bridge design year and the second estimates the bridge seismic design level based on bridge design year.

Bridge seismic design capacities were determined based on the design year of bridge *superstructures* (either initial construction or retrofit), which assumes that the *superstructure* design year controls the seismic design capacity of a bridge structure. WSDOT indicates that the majority of highway bridge seismic retrofits have focused on bridge superstructures, with very few *substructure* retrofits. WSDOT also indicates that historically, bridge superstructures have been more seismically vulnerable than bridge substructures. Given these factors, this analysis assumes that few bridges are likely to have seismic capacity greater than that determined using the superstructure design year, and thus uses superstructure design year as a proxy for overall bridge design year.

Uncertainties also exist in estimating the bridge seismic design capacity on the basis of the bridge seismic design year and design values provided from several sources, or assumed values for bridges built prior to the first seismic design codes in 1983 (USGS undated[c], WSDOT undated[b], AASHTO 1983, 1998).

AASHTO seismic bridge design codes were used to determine seismic design capacities for bridges with design years between 1984 and 2007, by evaluating PGA maps within the codes and choosing the lesser of the two bounding PGA map contours. This method assigns a conservative seismic design value where seismic capacity is less than the projected PGA for the design, and assumes that bridges are designed only to withstand the minimum PGA as required by code. It is possible that some bridges were designed to a seismic capacity greater than that mandated in the prevailing AASHTO code. Both of these factors potentially underestimate seismic design capacity for bridges with design year between 1984 and 2007.

Bridges designed at the time of, or before, the publication of seismic bridge design codes in 1983 are not seismically designed, and are assumed to have a seismic design capacity of 0.15 g, on the basis of historical seismic performance and discussions with WSDOT engineers.

Seismic design capacities for most bridges designed after 2007 were provided by WSDOT; however, some bridge records were incomplete. In these cases, bridge seismic design capacities were extracted using the USGS U.S. Seismic Design Maps tool, although it is unclear which AASHTO design code corresponded to the AASHTO design level used in the tool (USGS undated[c]).

Projected Seismic Damage

Within the BSST methodology, a bridge is assumed to suffer significant damage when the effective PGA from the CSZ scenario earthquake exceeds the bridge seismic design capacity. In reality, it is likely that some bridges will remain undamaged when experiencing a PGA exceeding the design, while other bridges will suffer damage at PGAs below the design level.

Shaking Duration Impact

The assumed seismic design capacity of 0.15 g for bridges that are not seismically designed is considered as a minimum PGA that may cause moderate or significant bridge damage. This value was selected, in consultation with WSDOT, under the assumption that this PGA is the maximum PGA at which a bridge would still experience elastic deformation, and that PGA greater than 0.15 g would cause inelastic (i.e., permanent) deformation. As discussed earlier, it is assumed that an increased number of loading cycles during a long-duration earthquake would have an amplifying effect on the damage caused to bridges undergoing inelastic deformation. As such, an effective PGA was computed by amplifying the PGA by 33 percent, which corresponds to a 25 percent reduction in a bridge's seismic capacity to account for this effect of long-duration shaking.

Bridge Skew

The BSST methodology does not account for bridge skew, which is the angle between the bridge roadway centerline and the centerline of the bridge supports (i.e., pier or abutment). Bridges with significant skew angles perform differently from bridges with small or no skew angles, and the AASHTO seismic bridge design codes did not account for bridge skew effects until 2007 (Fu and Chun 2013). Nearly 44 percent of the highway bridges within Washington are skewed bridges.

Pier Wall and Single Span

The BSST methodology assumes that bridges are damaged if the PGA experienced exceeds their capacity level. However, WSDOT bridge engineers indicated that bridges with either a single span (no columns) or pier wall supports may perform better than expected. Owing to inconsistencies between the WSDOT seismic retrofit database and WSDOT BMS database, it is difficult to identify bridges with pier walls. For this analysis, only bridges identified in *both* datasets as having pier walls were considered to have pier walls.

Bridge and Span Length

The effects of total bridge structure length and maximum span length on projected bridge damage were not considered; however, total bridge length was a primary driver of projected bridge reopening time.

Fracture Critical Bridges

Some bridges have fracture-critical members, where lack of redundancies in the primary structural members could cause partial or complete bridge collapse or a significant degradation in a bridge's structural capacity (FHWA 2012). Discussions with WSDOT bridge engineers suggested that fracture-critical bridges may not be any more vulnerable to seismic damage than non-fracture-critical bridges, and so no special consideration was made for such bridges (approximately 6 percent of highway bridges in Washington) in the BSST.

Hazard Uncertainties

Several hazards were considered in the bridge analysis methodology, but some additional hazards were excluded from the bridge analysis methodology owing to excessive uncertainties, complexities in modeling such hazards, or minimal projected impact to bridges. The following sections detail the various assumptions and sources of uncertainties in the hazards considered in or excluded from this analysis.

Scenario Earthquake

The USGS M9.0 full-length CSZ rupture earthquake scenario was selected for this analysis to remain consistent with the Federal Emergency Management Agency, WEMD, and WSDOT planning efforts to date. The projected ground motion values are a function of several complex phenomena and properties including ground attenuation, fault location and geometry, faulting and stress release along the fault, and location of earthquake initiation along the fault. These characteristics are used to estimate a fault's theoretical maximum earthquake and also to estimate the probability of occurrence of earthquakes of various intensities, communicated as a rate of recurrence. Given uncertainty in these estimations, the frequency of a full-length rupture of the CSZ fault is uncertain, with estimated recurrence rates between 350 and 600 years; however, occurrences of such earthquakes have historically been separated by 200 to 1,000 years (CREW 2013).

USGS has published several CSZ scenario earthquakes based on different assumptions in model parameters. As stated previously, the M9.0 full-length CSZ rupture earthquake scenario was used in this analysis to be consistent with prior research and planning efforts in Washington.

Soil Liquefaction

Liquefaction is a highly uncertain phenomenon that is a function of soil void space, water saturation (which can be seasonally dependent), and other factors. Soil liquefaction potential data provided by Washington State DNR only characterize the top layers of soil using a scale ranging from none to very high. Critical PGA thresholds were assumed and then assigned to the liquefaction potential categories within this dataset on the basis of conversations with the WSDOT State Material Laboratory and the State Geotechnical Engineer.

Tsunami Uncertainty

Significant uncertainties exist in the projected extent of bridge damage due to tsunamis caused by a full-length rupture of the CSZ fault: in the projected extent of inundation, the severity and depth of inundation, and the level of damaged caused.

All tsunami inundation maps that Washington State DNR provided were assumed to correspond to tsunamis triggered following the CSZ scenario earthquake, giving greater coverage of tsunami-vulnerable coastlines in Washington State—particularly in Puget Sound where comparatively fewer CSZ tsunami modeling results were available at the time of this analysis. At the time of analysis, these included Puget Sound tsunamis that were based on Seattle and South Whidbey Fault scenarios. Accordingly, this likely overestimates the extent of CSZ tsunami inundation in areas where only non-CSZ tsunami inundation information was available at the time of analysis.

Additionally, tsunami inundation studies have only been conducted for select locations within Washington, and have generally concentrated around major population centers. It is highly likely that areas outside of these areas would suffer tsunami inundation following a CSZ earthquake, but any such impacts to bridges outside of modeled tsunami impact extents were excluded from this analysis given the lack of supporting data.

At the time of this analysis, the tsunami information did not contain information on the projected inundation depth. Incorporating that information into this study in the future could affect the outcomes for bridges in coastal locations related to overtopping and increased scour potential.

One of the primary ways in which bridges are damaged during a tsunami is from bridge overtopping. As inundation depth information was not available at the time of analysis, the BSST methodology uses the National Bridge Inventory waterway adequacy code as a proxy for bridge vulnerability to tsunami overtopping based on historical rates of bridge overtopping (FHWA 2018).

Tsunami waves can also cause new, or exacerbate existing, bridge scour. Predicting the likelihood and severity of scour caused by tsunamis with greater certainty would require a bridge-by-bridge analysis, which is outside the scope of this study. Only 9 percent of highway bridges within Washington are scour-critical bridges, and only five of these bridges are located within a tsunami inundation area.

The collection of debris carried by tsunami waves against bridge abutments and piers can contribute significantly to bridge damage; however, this is an extremely uncertain and difficult-to-model phenomenon that is affected by numerous external factors. In the BSST, the risk of debris damming was not explicitly considered, but the use of the bridge waterway adequacy code as correlating with an increased risk of tsunami damage may offer some indirect consideration of debris accumulation impacts.

Excluded Geologic Hazards

Several geological hazards were excluded from the bridge analysis methodology, including landslides, rock slides, avalanches, ground faulting and lateral spread, and aftershocks. The analysis did not include these hazards because of uncertainties such as lack of available data, lack of available models, or complexity of models which precluded their use in the bridge analysis methodology; uncertainties in bridge vulnerability to these hazards; or uncertainty in the dependency and correlation between these hazards and hazards considered in the bridge analysis methodology. Inclusion of these hazards would likely increase the projected bridge damage and reopening times projected by the bridge analysis methodology; however, it is unclear to what extent this inclusion would impact the results.

Utilities Carried by or Located Near Bridge

Utilities are often collocated on bridges, and can affect both bridge vulnerability and reopening time, as damage sustained by the utilities themselves can affect the bridge structure. WSDOT specifies that all pipes transporting hazardous (flammable, corrosive, etc.) or pressurized material should be encased in a pipeline sleeve and designed such that pipeline rupture will not result in damage to the bridge (WSDOT 2014). There remains the potential for damage to these systems to cause damage to bridges, however this analysis did not include such considerations.

Dam Failure

Dam failure as the result of an earthquake could create flood waves or inundation areas that could damage bridges located within the proximate risk area. Dam vulnerability to failure during an earthquake was outside of the scope of this analysis, and therefore the BSST methodology did not consider flooding or flood wave impacts on bridges as a result of local dam failures.

Fire Following Earthquake

Earthquakes have the potential to cause fires, such as when the earthquake damages pipelines or power conduits. However, owing to data limitations and uncertainty in the factors that influence fire propagation, this analysis did not include such impacts.

Repair Type and Reopening Time

Bridge repair types and reopening times are determined using the projected levels and types of damage determined by the BSST methodology. The repair types and reopening timelines are assumed on the basis of discussions with WSDOT bridge engineers; however, uncertainty exists in these assumptions, as outlined in the following:

Temporary Roadways

Bridges projected by the BSST to sustain significant damage are evaluated for the viability of a new, temporary bypass roadway (e.g., around a collapsed overpass). It is assumed that significantly damaged bridges over waterways or large elevation changes, such as ravines or canyons, cannot be replaced by a temporary bypass, but that all others could be temporarily bypassed. Large elevation changes prohibiting bypasses were assumed to be those in excess of 30 ft.

Route Service Restoration Time Uncertainty

Assumed bridge repair and replacement, bridge structural inspection, and temporary roadway construction times were informed by discussions with WSDOT bridge engineers. The estimated times were based on several assumptions about the availability of repair crews, construction materials, and equipment, as well as the ability of these to access a bridge site, as discussed in the following.

The assumed bridge repair and replacement, bridge structural inspection, and temporary roadway construction times were based on the assumption of an unconstrained workforce and excluding potential funding or permitting delays.

Within the bridge analysis methodology, the ability to access a site was not considered. Thus, the projected bridge reopening times are independent of any potential delays in accessing a bridge location to commence repair work.

The reopening-time assumptions in the bridge analysis methodology assume the general and unconstrained availability of construction materials and equipment through a coordinated national emergency response effort.

Bridge Seismic Screening Results

The 2,717 highway bridges incorporated into this study from the WSDOT bridge inventory database were assessed using the BSST analysis methodology detailed previously in this report. Results consist of three types of outcomes: Bridge Damage Levels and Types, Bridge Repair Types, and Bridge Reopening Times.

Bridge Damage Levels and Types

Bridge damage types are projected on the basis of both damage level (None, Moderate, Significant), whether a bridge is a special bridge type, and also the types of damage that the bridge will experience (including both direct seismic and secondary earthquake-induced impacts); these results for the CSZ scenario earthquake are summarized in table 6. 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, 32.5 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). An additional 31.5 percent of the bridges projected to experience significant damage will do so as a combined result of inadequate seismic design and the potential liquefaction of soils supporting the bridge’s substructure. In fact, soil liquefaction at the bridge location is a potential controlling or contributing factor for nearly 40 percent of the bridges projected to experience significant damage as a result of the CSZ scenario earthquake.

It is encouraging that no bridges evaluated in this analysis (i.e., falling within the available tsunami model inundation extents) are projected to suffer damage due to tsunami overtopping following the CSZ scenario earthquake. However, limitations of the methodology used for assessing bridge vulnerability to overtopping during tsunamis may underestimate tsunami risks, and these should be tested further when tsunami inundation depth data with more comprehensive coverage of Washington coastlines becomes available. Additionally, the results project that only five bridges could suffer significant scour damage during post-earthquake tsunamis.

Table 6: Projected Bridge Damage Types and Levels from CSZ Scenario Earthquake

Damage Level	Damage Type	Number of Bridges
None	None	621
Moderate	Seismic demand exceeds minimum PGA, which can damage bridges but is less than bridge's seismic design capacity.	84
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge has pier walls.	43
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge is single-span.	183
Significant	Bridge damaged owing to hollow core piles.	11
	Bridge damaged owing to hollow core piles, and soil liquefaction occurs at bridge location.	11
	Soil liquefaction occurs at bridge location.	124
	Seismic demand exceeds minimum PGA, which can damage bridges but is less than bridge's seismic design capacity, and soil liquefaction occurs at bridge location.	56
	Seismic demand exceeds bridge’s seismic design capacity.	670
	Seismic demand exceeds bridge’s seismic design capacity and soil liquefaction occurs at bridge location.	650
	Seismic demand exceeds bridge’s seismic design capacity, soil liquefaction occurs at bridge location, and bridge is damaged by significant bridge scour occurring during tsunami following CSZ earthquake.	1
	Seismic demand exceeds bridge’s seismic design capacity and bridge is damaged by significant bridge scour occurring during tsunami following CSZ earthquake.	1
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge has pier walls, and soil liquefaction occurs at bridge location.	45
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge has pier walls, and bridge is damaged by significant bridge scour occurring during tsunami following CSZ earthquake.	1
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge is single-span, and soil liquefaction occurs at bridge location.	180
	Seismic demand exceeds bridge’s seismic design capacity, but bridge damage is lessened because bridge is single-span, soil liquefaction occurs at bridge location, and bridge is damaged by significant bridge scour occurring during tsunami following CSZ earthquake.	1
Special	Seismic performance of special bridges not assessed.	20
	Seismic performance of special bridges not assessed and soil liquefaction occurs at bridge location.	14
	Seismic performance of special bridges not assessed, soil liquefaction occurs at bridge location, and bridge is damaged by significant bridge scour occurring during tsunami following CSZ earthquake.	1

Figure 5 shows the geographical distribution of highway bridges throughout Washington State with their projected damage types. In western Washington and the Puget Sound region there appear to be 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). Moving eastward into the primary routes crossing the Cascade Mountains, potential soil liquefaction becomes the predominant projected damage type; this is particularly evident on Interstate 90, State Route 2 and State Route 20, which are largely built in river valleys, where liquefiable soils are more prevalent. East of the Cascades, a significantly greater number of bridges are projected to experience no damage. Many of those bridges located east of the Cascades that are projected to experience some damage will only experience moderate damage; although their seismic design capacities are not exceeded, PGAs could still cause moderate damage that would require repair before reopening.

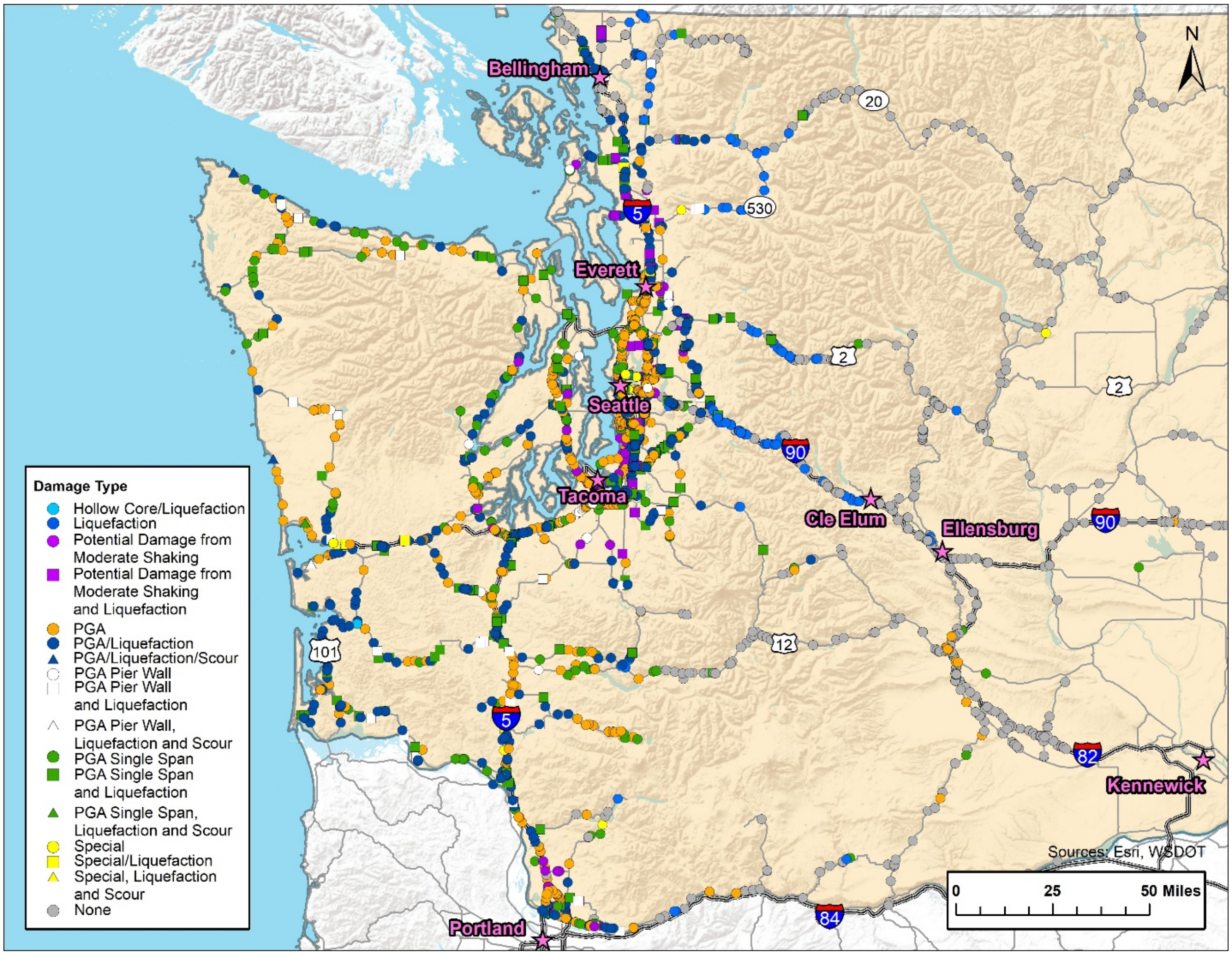

Figure 5: Bridge Seismic Screening Tool (BSST) Projected Damage Types for Highway Bridges in Washington from the CSZ Scenario Earthquake

Bridge Damage Repair Types & Reopening Times

The projected repair types and reopening times necessary to bring bridges back to a minimum level of functionality that enables their use for emergency response were computed using the methodology specified in the Bridge Reopening Times section. Table 7 provides a summary of the projected repair types. A large number of bridges (951, or 35 percent) can be reopened by implementing a temporary roadway that bypasses the bridge. An example of this would be a collapsed highway overpass, where a temporary roadway is constructed with a surface intersection between the mainline and intersecting roadways. However, of the brides 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; 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.

Table 7: Projected Bridge Repair Types after CSZ Scenario Earthquake

Repair Type	Number of Bridges
None	621
Bridge Inspection with Potential Minor Repairs	310
Temporary Road to Bypass Bridge	951
New Bridge over Water	175
New Bridge over Impassable Topography	3
New Bridge over Water with Subsurface Strengthening	622
New Special Bridge	35

Table 8 provides the projected reopening times that would be necessary to either constructing a temporary bypass road, conducting bridge rehabilitation repairs, or build a replacement bridge. 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 some structures, which could cause minor delays in reopening. Nonetheless, 13 percent (or 363) bridges could be reopened within the first month after the earthquake occurs after inspections and minor repairs are made. 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.

Table 8: Projected Bridge Reopening Times after 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

Figure 6 shows the geographical distribution of bridges in Washington State according to their repair types. Notably, the predominant repair type along the Interstate 5 corridor is the construction of temporary bypass roadways. However, a substantial number of bridges along that same corridor are also projected to require a new bridge to be constructed over water, in many cases with soil improvements. The dominant repair type projected for bridges located on the major routes crossing the Cascade Mountains is also a new bridge over water, in most cases with soil improvement. This is consistent with the Damage Type results discussed above, as many of these routes follow river valleys leading into the mountains from western Washington. On the Olympic Peninsula, and along much of southwestern Washington, where bridges frequently cross rivers and other water features, new bridges over water is the repair type projected for the majority of bridges. Particularly in southwestern Washington, many of these bridge repairs may also require subsurface strengthening or improvement given the presence of liquefiable soils.

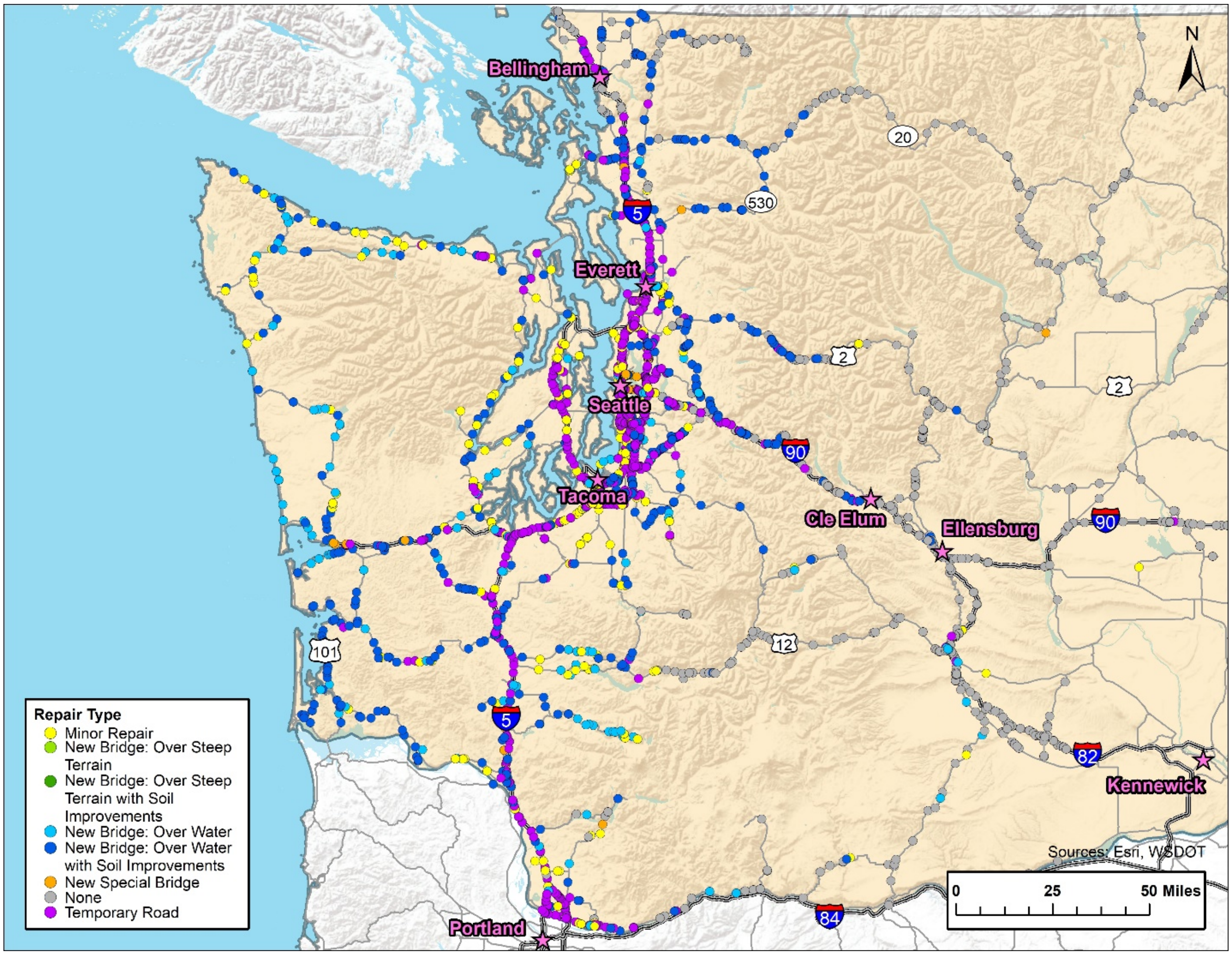

Figure 6: Bridge seismic Screening Tool (BSST) Projected Reopening Repair Types for Highway Bridges in Washington after the CSZ Scenario Earthquake

Figure 7 shows the geographical distribution of bridges in Washington State according to their reopening times. Reopening times are greatest in the Puget Sound region, southwestern Washington, and on the Olympic Peninsula. In those latter regions in particular, this is consistent with the repair types requiring the construction of new bridges over water, and frequently with soil improvements.

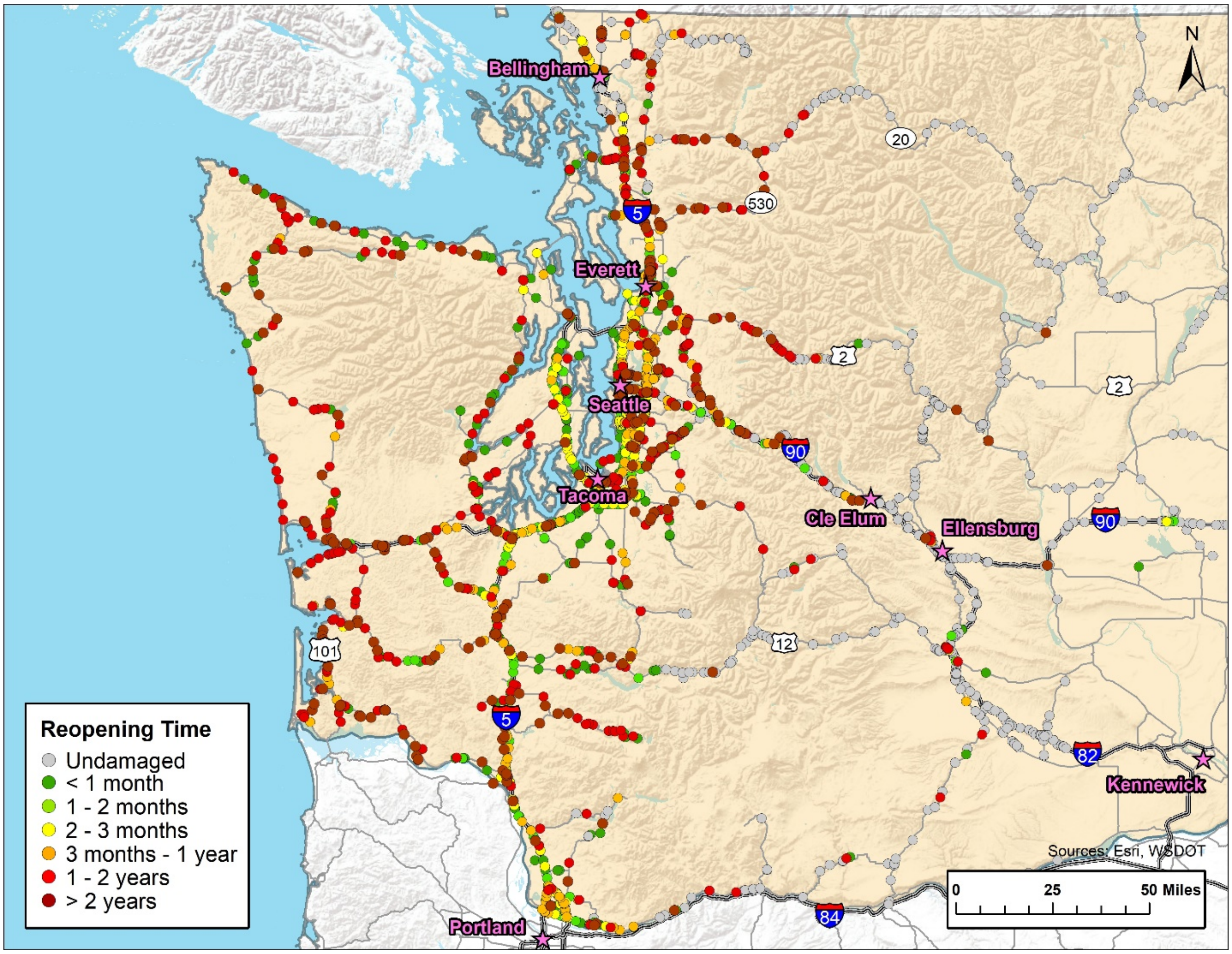

Figure 7: Bridge Seismic Screening Tool (BSST) Projected Reopening Times of Highway Bridges in Washington after the CSZ Scenario Earthquake

Conclusions and Future Use

The BSST was developed to assess the potential impacts of a CSZ earthquake to highway bridges in Washington State at a system-level as part of the Washington State Transportation Systems RRAP project. The results provided identify the Damage Levels, Damage Types, Repair Types and Reopening Times associated with 2,717 bridges located in Western and Central Washington that were evaluated for this RRAP project. Understanding that this analysis likely constitutes a “worst-case scenario” with respect to bridge damage, the results nonetheless project that the majority of bridges in Washington State will experience moderate to significant damage resulting from a CSZ earthquake. While the majority of bridges that experience damage could be reopened within one year of the earthquake, a substantial number of those bridges (28.7 percent) are projected to take more than a year to reopen—in many cases 2 or more years. The results also project that while many bridges may be reopened after either minor repairs/inspections or the construction of a temporary bypass road, a substantial number of more significantly damaged bridges (797 structures) span bodies of water and will require complete replacement prior to reopening. This suggests that significant gains in roadway *corridor* reopening times could be gained by focusing on retrofits or upgrades to these more vulnerable bridges that span rivers and other bodies of water.

This tool is primarily intended to inform regional highway prioritization for emergency response activities; however, the BSST provides a useful evaluation methodology that could be applied to other regional emergency preparedness and infrastructure assessment studies. This could include studies of bridge infrastructure to other potential seismic events within the region, or at varying jurisdictional levels (i.e., county, local). The BSST also uses currently available seismic, seismically-induced secondary hazard and infrastructure information. As new seismic information becomes available, or as secondary-hazards (e.g., landslides, avalanches) become characterized more comprehensively, such information could be integrated into the current BSST methodology. Similarly, as seismic retrofit activities or other infrastructure improvement projects continue throughout Washington State, or as new infrastructure are built, it will be important that the infrastructure data integrated in the BSST also be updated periodically. Doing so will ensure that planners and infrastructure managers maintain the most current and complete understanding of the network-level seismic risks of a CSZ event to Washington State highways.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
BSST	Bridge Seismic Screening Tool
CREW	Cascadia Region Earthquake Workgroup
CSZ	Cascadia Subduction Zone
DEM	Digital Elevation Model
DNR	Washington State Department of Natural Resources
GIS	Geographic Information System
LRS	linear referencing system
PGA	peak ground acceleration
PGV	peak ground velocity
RRAP	Regional Resiliency Assessment Program
USGS	U.S. Geological Survey
WEMD	Washington Emergency Management Division
WSDOT	Washington State Department of Transportation

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