Washington State Highway Seismic Screening Tool (HSST)

Technical Report

Decision and Infrastructure Sciences Division

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Estimate of the Permanent Ground Deformation and Repair Times for Highways and Railways

Introduction

The U.S. Department of Homeland Security's Regional Resiliency Assessment Program (RRAP) undertook the Washington State Transportation Systems RRAP project in 2017 to assess the seismic vulnerabilities of that state's transportation system to a Cascadia Subduction Zone (CSZ) earthquake. The specific goal of that project was to assess the vulnerability of, and prioritize, transportation infrastructure for moving goods and supplies from Incident Support Bases to Federal Staging Areas within Washington State following a CSZ earthquake. As part of this analysis, Argonne National Laboratory (Argonne), with input and support from the Washington State Department of Transportation (WSDOT) maintenance and pavements offices and state geotechnical engineer, developed the Highway Seismic Screening Tool (HSST) to inform a system-level analysis of highway recovery and reopening times. This report provides a full discussion of the HSST's development, implementation, and results for the CSZ scenario earthquake.

The primary outcome of the HSST is to determine the approximate reopening times of highway segments or bridges damaged by a CSZ magnitude 9.0 seismic event. This is done by calculating the permanent ground deformation (PGD) caused by soil liquefaction along state highways, which can cause significant damage or displacement of highway pavement structures. The term "reopening time" is different from "restoration time" and is intended to represent the approximate amount of time that would be needed to return highways to a minimum state of repair sufficient to support the limited movement of emergency and response vehicles. Additionally, the HSST is referred to as a "screening tool," as it uses network- or system-level asset management information that WSDOT provided to assess seismic-related hazards and vulnerabilities of highways; it does not conduct an asset-level engineering analysis of seismic-related vulnerabilities. Accordingly, the results of the HSST analysis should only be used for system- or corridor-level planning and investment, and not for engineering or management decisions at the asset level.

The HSST is also applied to assess the exposure of statewide rail systems to soil liquefaction and PGD hazards. However, little information is available about the sensitivity or vulnerability of railways and rail yards to such hazards, and therefore researchers were unable to determine approximate reopening times for the state's rail system following a CSZ earthquake.

Geological Hazards in Washington State

During a CSZ earthquake, the surface transportation routes in Washington State will be subjected to deformation due to the propagation of waves of energy. Linear infrastructure, such as highways and railroads, may be subject to ground deformations resulting in partial to complete disruption of their function. A major source of these deformations associated with a CSZ event is the liquefaction of the soils underlying highways and rail lines. The routes are frequently located in valleys with alluvial soils and man-made fills which are subject to liquefaction under earthquake loadings.

Alluvial valley soils are often composed of saturated loose sands and silts that behave much like a liquid when subjected to shaking during an earthquake. The waves of energy released during a seismic event cause pore pressures in the sediments to increase, resulting in a decrease in the normal pressure that provides the friction between soil grains that gives the sediments their shear strength. When the grain-to-grain contact is lost, the sediments lose their strength and behave like a liquid, a phenomenon known as liquefaction. Liquefaction can result in the loss of support for surface structures such as buildings and bridges, soil flows on even very gentle slopes, large differential settlements, and—if the liquefaction

occurs at depth—sand boils erupting at the surface. The settlements and down-slope soil flows can trigger major damage to buildings, roads, rail lines, and pipelines (USGS 2006a). Three factors are needed for liquefaction to occur (USGS 2006b):

- loose, granular soils,
- groundwater saturation of the sediment, and
- strong ground motion.

In Washington State, all of these factors would be present during a CSZ earthquake. The liquefiable soils are located in the alluvial valleys in the Cascade mountain range and the Olympic peninsula, and in low-lying areas around Puget Sound. Figure 1 shows the distribution of the soils across Washington State that are susceptible to liquefaction. The soils that have moderate to high liquefaction susceptibility (and greater) located in the valleys descending from the Cascade Range topographic divide are primarily classified as Quaternary alluvium. The liquefiable soils in the valleys and shoreline areas of Puget Sound consist of Quaternary alluvium, Pleistocene glacial deposits, and Holocene soils, including man-made fills. The groundwater surfaces in the alluvial valleys and shoreline areas are commonly near the surface, leading to a nearly completely saturated soils column. As shown in figure 2, the reference earthquake for the CSZ used in this study is a magnitude 9.0 scenario event defined by the U.S. Geological Survey (USGS), which will result in strong, prolonged shaking as far east as Cle Elum, Wash.

Figure 1: Soil Liquefaction Susceptibility in Washington State

The construction of Washington State's surface transportation systems and urban development has occurred along the valleys through the Cascade Range and along the shores of Puget Sound. These areas are largely coincident with the locations of the liquefiable soils across the state, making the surface transportation system and the dependent emergency response functions significantly vulnerable to a major CSZ event (Youd 1995).

Figure 2: Projected Peak Ground Acceleration (PGA) for Washington State under the USGS M9.0 CSZ Scenario

Landslides and avalanches also hold potential for damaging or obstructing passage along the highway and railway systems after a CSZ event. Pavement segments at the locations of known landslide and avalanche areas represent a small percentage of the total pavement system. While WSDOT and several counties have developed maps of known or historic landslides, these efforts have a high degree of uncertainty and do not map *potential* or *new* landslides. In addition, avalanches are seasonal and highly specific to weather conditions and maintenance programs. As a result, this analysis did not incorporate damage, obstruction, or repair time associated with landslides or avalanches into the overall repair time analysis.

Highway Seismic Screening Tool: Damage and Repair Time Estimation

Argonne developed the HSST to assess the PGD and associated highway repair times in consultation with the WSDOT maintenance office, pavements office, and state geotechnical engineer. The major steps in the HSST process, as shown in figure 3, are as follows:

1. Developing a highway network;
2. Characterizing the segments (links) in the network;
3. Estimating a PGD for each segment on liquefiable soils;
4. Estimating a repair time for each segment;

The sections that follow provide additional detail on each of these steps.

Figure 3: Highway Seismic Screening Tool (HSST) Methodology

Step 1: Developing a Highway Network

Argonne developed a highway network for Washington State using the network analyst tool in ArcGIS. The input data for network development were WSDOT State Highway data, Open Street Map data, and Washington State Department of Natural Resources (DNR) Liquefaction Susceptibility and Landslide data. Researchers joined these data sets to generate a network of nodes and links that represent intersections and highway segments, including on-ramps and off-ramps, for additional characterization. The nodes included 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. Researchers further developed the network by adding bridges as nodes that, owing to their repair times, may influence corridor reopening times in addition to the pavement-based reopening times calculated here. The resulting Washington State highway network included a total of 21,356 segments (links) covering 9,425.2 miles (i.e. centerline miles of highways and adjacent on-/off-ramps).

Step 2: Characterizing the Segments in the Network

Argonne further characterized the highway network to support estimating PGD for those segments underlain by soils with moderate and high susceptibility to liquefaction. Within the network, 39 percent of the highway segments and 35 percent of the highway miles are located on liquefiable soils. For all segments in the network, researchers assigned a surface type using WSDOT's Washington State Pavement Management System (WSPMS) Surface Type data (WSDOT 2016). The flexible pavements (i.e., asphalt concrete) in the Washington State network constitute 87 percent of the total miles and the rigid pavements (i.e., Portland cement concrete) constitute 13 percent of the total miles. Table 1 shows the breakdown of rigid and flexible pavement segments and mileages across Washington State.

Table 1: Summary of Pavement Segments and Mileages by Surface Type

Pavement Surface Type	Total in Network		On Liquefiable Soils	
	Segments	Length	Segments	Length
Rigid Pavement (Portland Cement Concrete Pavement)	4,949	1,263.2	2,118	448.2
Flexible Pavement (Asphalt Cement Pavement, Bituminous Surface Treatment, Other)	16,407	8,161.9	6,316	2,545.1
TOTAL	21,356	9,425.1	8,434	2,993.3

The difference in pavement surface type impacts their repair times. Rigid pavements will likely require removal of the broken concrete surface course prior to backfilling displaced sections. In addition, compacted gravel or other temporary paving will need to be placed as a wearing surface for emergency traffic to traverse the disrupted section.

Step 3: Estimating a Peak PGD for Each Link on Liquefiable Soils

As described previously, the PGD associated with soil liquefaction can result in damage to the highway pavements that would be used to transport emergency equipment and supplies into the most heavily affected areas west of the Cascades. By estimating the PGD for highway segments, researchers can estimate the time required to bring the surface back to a condition that will allow emergency supply vehicles to transit the highway.

Technical Approach for PGD Estimation

The RRAP research team estimated PGD using the approach outlined by Bardet, Mace, and Tobita (1999). The empirically derived equation they developed reflects the relationship of the PGD to the magnitude of the earthquake, the distance to the epicenter, the ground slope, and the saturated thickness of the soil. PGD is calculated for each highway segment located on liquefiable soils using the following equation:

$$\text{Log}(DH + 0.01) = b_0 + b_1M + b_2\text{Log}(R) + b_3R + b_5\text{Log}(S) + b_6\text{Log}(T)$$

Where

DH (m) = Amplitude of ground deformation (PGD),

M = Earthquake moment magnitude,

R (km) = Closest distance to source,

S (%) = Ground slope, and

T (m) = Thickness of saturated soil.

Bardet, Mace, and Tobita performed two regression analyses for three use cases of the PGD equation: a slope only case, a free-face-only case, and a combined case for slope and free-face. Each use case resulted in a set of constants for use in the equation. The two regression analyses used close to the same set of constants for each of the three use cases. On the basis of the available data for the range of input parameters, the research team used the following values for the constants derived for the slope-only case for PGD estimation (Bardet, Mace, and Tobita 1999):

$$b_0 = -7.586$$

$$b_1 = 1.109$$

b2	= -0.233
b3	= -0.025
b5	= 0.477
b6	= 0.579

Researchers used the histograms for PGD in the study by Bardet, Mace, and Tobita (1999), and the range of typical void ratios for alluvial soils to limit the upper PGD value to 6 m or approximately 20 percent of the assumed saturated thickness. Researchers made these assumptions to generate a reasonable upper bound of potential for PGD. Owing to the uncertainties associated with the exact location of the CSZ event, the topography, and the saturated thickness of the soil, researchers made a series of assumptions, in consultation with WSDOT and in alignment with the broader, network-level approach of this Washington State Transportation Systems RRAP project, to allow a unified approach to calculating the PGD. The following assumptions were used in estimating the PGD:

- Magnitude = 9.0 as the reference earthquake for the CSZ;
- The epicenter of a CSZ earthquake will occur about 45 kilometers (km) east of the CSZ fault trace, on the basis of the USGS CSZ scenario earthquake whose epicenter is located at 45.733, -25.125;
- R is the minimum distance from a line 45 km east of and parallel to the trace of the CSZ as defined in WA DNR Seismogenic Features;
- Slope ranges from 0.1 to 50 percent, with the upper limit based on the angle of repose for alluvial sands;
- Saturated soil thickness is set at 30 m, on the basis of discussions with the WSDOT state geotechnical engineer; and
- Liquefaction susceptibilities driving the PGD estimate were selected as moderate or greater.

The research team used a minimum slope of 0.1 percent to account for the uncertainty in the slope dataset used. They selected the slope values at the midpoint of the individual segments as representative of the entire segment's slope. When a minimum value is selected for the slope areas where the slope data value is 0 percent, the equation provides an upper limit value for PGD for those segments. The results allowed an identification and quantification of impacts that included all segments on liquefiable soils. Because of the uncertainties and assumptions associated with the estimation of the PGD, the researchers view PGD values as upper limits and intend them to be used in aggregate along corridors rather than for resilience measure decisions at specific locations.

The research team used the following data sources to develop the parameters associated with estimating the PGD for highway segments:

- WA DNR Seismogenic Features (Bowman and Czajkowski 2016) – location of CSZ alignment to determine R, closest distance to source;
- WA DNR Ground Response to Earthquakes (DNR 2010) – location of liquefiable soils in relation to the highway network;
- USGS M9.0 Scenario Earthquake - Cascadia M9.0 Scenario (mean value) (USGS 2017); and
- Slope values derived from the USGS Digital Elevation Model (USGS undated).

Results of PGD Estimation for Highways

Using the equation and assumptions documented in the previous section, the research team estimated the PGD associated with each of the 8,434 segments underlain by liquefiable soils, as indicated in table 1. As shown in figure 4, the highest PGD estimates are concentrated from the Interstate 5 corridor west within about 300 km of the inferred fault trace of the CSZ. Highways on the Olympic Peninsula and in southwest

Washington State may experience the highest PGD, owing to their proximity to the CSZ. The highways from the I-5 corridor east to the topographic divide in the Cascade Mountain range have moderate PGD values associated with the colocation of the highway system with the valleys in the range. East of the topographic divide, PGD values are lower and associated with liquefaction of the alluvium in the river valleys flowing to the east. A closer view of the Puget Sound area in figure 5 shows the extensive potential highway surface displacement from liquefaction. The I-5/I-405 corridor and the east-west connections in the Seattle area have estimated PGDs that are frequently in the higher ranges.

Figure 4: Statewide Distribution of Estimated PGD for Highways Located on Liquefiable Soils

Figure 5: Distribution of Estimated PGD for Highways in the Puget Sound Area

The overall statewide distribution of highway mileage subject to the range of PGD values is shown in table 2. The majority of mileage of highway segments on liquefiable soils is estimated to experience 6 inches or less of displacement. Only 12.6 percent of the highway mileage on liquefiable soils is estimated to experience more than 24 inches of displacement.

Table 2: Summary of PGD Impacts by Mileage of Disrupted Highways

Estimated PGD	Miles	% of Total
0 in	1,280.9	42.8%
0 to 6 in	937.8	31.3%
6 to 12 in	225.0	7.5%
12 to 24 in	171.4	5.7%
24 to 36 in	123.9	4.1%
36 to 48 in	47.5	1.6%
48 to 60 in	24.4	0.8%
60 to 96 in	38.3	1.3%
>96 in	144.0	4.8%
TOTAL	2,993.3	

Step 4: Estimating a Repair Time for Each Segment

Basis for Estimating Repair Time

Repair time estimates are based on the magnitude of the PGD and the pavement surface type. For the purpose of this analysis, the repair is intended to establish a highway surface to facilitate the movement of emergency support and supply vehicles from eastern Washington into the most heavily impacted areas west of the Cascades. Other analytical tools and approaches, such as the Federal Emergency Management Agency's HAZUS model, focus on full restoration times to establish pre-event highway conditions. However, repair for the purpose of transporting emergency equipment and supplies requires only that the highway be at a reasonable grade and have a temporary surface layer that can withstand a limited number of vehicles per day associated with the emergency response needs. Thus, the associated repair steps included in this analysis centered on clearing damaged highway sections, re-establishing the highway elevation through the damaged section, and placing a temporary wearing surface of crushed rock or gravel fill.

Discussions with WSDOT research and maintenance staff resulted in the following guidelines for the estimation of repair times:

- One foot of replacement fill over a distance of one mile can be placed in one day.
- Clearing debris through damaged flexible pavement sections will not add to the time required to place new fill.
- Removal of a mile of rigid pavement debris will require one day.

The simplified result is that the repair time for a mile of flexible pavement in days is equal to the PGD in feet. For flexible pavements, researchers derived the repair time for a segment by dividing the estimated PGD in feet by the fill rate of 1 foot per mile per day and multiplying by the segment length. For rigid pavements, the repair time was the repair time for an equivalent flexible pavement segment, plus a day for each mile of pavement length to account for clearing damaged concrete pavement prior to backfilling. The research team applied the repair time estimation for all segments, including those where the PGD was less than 1 foot, resulting in repair times of partial days. The repair times estimated in this analysis assume a single lane of travel. If a highway segment originally consisted of multiple lanes and multiple lanes are required for emergency response purposes, the repair time increases in proportion to the number

of lanes repaired. The equations used for calculating repair times for flexible and rigid pavement segments are as follows:

$$\begin{aligned}
 & \textbf{Flexible Segment Repair Time (days/lane)} \\
 & = \frac{PGD(ft)}{\text{Fill Rate} \left(\frac{ft \text{ miles}}{day} \right)} \times \text{Segment Length (Miles)} \\
 & \textbf{Rigid Segment Repair Time (days/lane)} \\
 & = \frac{PGD(ft)}{\text{Fill Rate} \left(\frac{ft \text{ miles}}{day} \right)} \times \text{Segment Length (Miles)} + \frac{\text{Segment Length (miles)}}{\text{Concrete Clearing Rate} \left(\frac{miles}{day} \right)}
 \end{aligned}$$

In accordance with discussions with WSDOT, the fill rate is set at 1 foot-mile per day for both flexible and rigid pavements. For rigid pavements, the concrete clearing rate is set at 1 mile per day.

The research team used these guidelines and equations with the estimated segment PGD to provide an estimate of repair times for each highway segment in the identified network subject to liquefaction.

Assumptions in Estimating Repair Times

In addition to the guidelines established with WSDOT, the research team made the following assumptions when estimating and aggregating repair times:

- **Availability of sufficient fill materials:** WSDOT has identified multiple potential sources for fill materials, and this study assumed that the quantity and availability of these materials were sufficient for highway repairs, and could be supplied immediately.
- **One-way access to the disrupted pavement:** For the purpose of estimating aggregate repair times, this study assumed access to the segments to be unidirectional. That is, in the period immediately after the event, highway access is likely only available from one direction, allowing only sequential segment repairs. As the repairs proceed, more segments may be able to be accessed from both directions, reducing repair times significantly.
- **Availability of sufficient manpower and equipment:** Major highway construction in Washington State is generally conducted by private contractors retained by WSDOT. The amount of equipment and manpower from across the country that would become available through response and recovery efforts is unknown. As a result, this study did not consider those factors as constraints in this analysis.

Because of the uncertainties and assumptions associated with the estimation of the segment repair times, this study views repair time values as upper limits and intend them to be used in aggregate along corridors rather than to support maintenance or improvement decisions at specific locations.

Results of Repair Time Estimates

Based on these inputs, the research team estimated the repair time associated with each of the 8,434 segments underlain by liquefiable soils. As shown in figure 6, the highest average per-mile repair times coincide with high PGD values and are projected to occur from the I-5 corridor to the west. Average per-mile repair times from the I-5 corridor to the topographic divide in the Cascade range are comparatively lower, with a few higher values occurring in the alluvial valleys and fills along the major east-west routes. Figure 7 shows the average repair times per 1-mile segment in the Puget Sound area, where I-5 and I-405 exhibit significant repair times per mile.

Figure 6: Statewide Average Per-mile Repair and Reopening Time Based on PGD Disruptions

Figure 7: Puget Sound Area Average Per-mile Repair and Reopening Time Based on PGD Disruptions

The overall statewide distribution of highway mileage for the range of average per-mile repair times is shown in table 3. The majority of highway segments have an average per-mile repair time of 0.5 day. Only 13 percent of the highway mileage on liquefiable soils is estimated to require more than 2 days per mile to repair.

Table 3: Summary of Average Repair Days per Mile by Mileage of Disrupted System

Repair 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 LIQUEFIABLE MILES	2,993.3		

Even with the increased time to clear away rigid pavement debris before placing fill, rigid pavements have similar average repair times per mile to flexible pavements. The similarity of average per-mile repair times between flexible- and rigid-surfaced pavements occurs in large because hundreds of miles of rigid pavements occur further east in the state, where the ground shaking is less intense, and the flexible pavements include hundreds of miles on the Olympic peninsula and in southwestern Washington State, nearer to the CSZ.

Table 4: Repair Days by Pavement Type

Pavement Type	Liquefaction Miles	Total Repair Days	Avg. Repair Days/Mile
Flexible	2,545.1	3,564.3	1.4
Rigid	448.2	400.1	0.9
Overall	2,993.3	3,964.4	1.3

Step 5: Using the Highway Repair Time Estimate Results

Repair time results illustrate the relative repair times associated with PGD damage to pavement systems. The repair time estimates are best used in aggregating the time to restoration for emergency vehicle passage. The RRAP study used the results of the pavement repair time analysis in identifying the optimal routes for moving emergency response supplies and resources from eastern Washington into the most heavily affected area west of the Cascades. The pavement repair times are combined with the bridge repair times (see report ANL/DIS-19/1, *Washington State Highway Bridge Seismic Screening Tool (BSST) – Technical Report*) to understand the optimal routing options. Individual repair times should not be used to identify specific pavement sections that require improvement.

Railway and Rail Yard Damage Estimation Process

Highways and railways are similar in that they are both linear transportation assets with similar PGD concerns. For this study, the research team also applied the HSST process and seismic parameters to assess the permanent ground deformation for railways and rail yards to provide some insight into their seismic hazard and impact exposure. Researchers did not perform repair time estimates because of a lack of information on rail infrastructure assets, as well as the activities necessary to bring railways and rail

yards back into service after major ground displacements. Thus, the major steps in the rail damage estimation follow a process similar to that for highway damage estimation:

1. Developing a railway and rail yard network
2. Estimating a PGD for each segment or rail yard on liquefiable soils.
3. Using the railway and rail yard PGD results

Step 1: Developing a Railway and Rail Yard network

The railway network was developed from the WSDOT Washington State Rail System data (WSDOT undated). The railway system in Washington State includes approximately 4,456 miles owned by more than 20 different organizations. The railway network was divided into 13,155 distinct segments on the basis of intersections, landslide areas, and liquefiable areas in the state. Burlington Northern/Santa Fe (BNSF), with 7,200 segments and 2,285 miles, is the major rail owner/operator in Washington State. Union Pacific (148 miles) and Palouse River and Coulee City (147 miles) are the only other owners/operators with more than 100 miles of right-of-way. For the rail yards, the research team buffered the outside rail lines of the yards in Washington State to generate a polygon for 54 rail yards located in western and central Washington (BTS 2018).

Step 2: Estimating a PGD for Railway Segments and Yards on Liquefiable Soil

A total of 7,447 railway segments totaling 1,766.3 miles are underlain by liquefiable soils. For each segment, researchers measured a distance to the CSZ and estimated a slope using the USGS Digital Elevation Model. For each of the 54 rail yards, researchers measured a distance from the CSZ to the centroid of the polygon and estimated a slope at the centroid of the yard from available USGS Digital Elevation Models. Researchers estimated the area of the rail yard from the polygon and intersected the area with WA DNR data on liquefaction to identify those rail yards subject to PGD and the associated area that may experience the ground failure. The research team used the same equation and range of parameters used for the highway system in calculating the PGD associated with railways and rail yards.

Results of PGD Estimation for Railways

This study estimated the PGD associated with each of the 7,447 railway segments underlain by liquefiable soils using the equation and assumptions documented in the previous highway section. Figure 8 shows the statewide distribution of PGD along railways. As shown in figure 8, the highest PGD estimates for railways are concentrated along the Puget Sound & Pacific Railroad (PSAP) line south and west of Bangor, Wash. As with the highways, railways on the Olympic Peninsula and in southwestern Washington State may 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. East of the topographic divide, PGD values are lower and associated with liquefaction of the alluvium in the river valleys flowing to the east.

Figure 8: Statewide Distribution of Estimated PGD for Railways Located on Liquefiable Soils

The overall statewide distribution of PGD on the railway 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.

Table 5: Summary of Statewide Mileage of Disrupted Railways on Liquefiable Soils by 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	

Results of PGD Estimation for Rail Yards

Of the 54 rail yards in Washington State shown in figure 9, 42 yards are underlain completely by liquefiable soils. Two additional yards, the Cascade and Columbia River Railroad's Oroville and BNSF's Balmer yards, are 44 percent and 98 percent underlain by liquefiable soils, respectively.

Figure 9: Statewide Distribution of Estimated PGD at Rail Yards

The estimated PGD at each of the rail yards is shown in figure 9. The PSAP's Port of Grays Harbor rail yard is estimated to have the greatest PGD, in excess of 14 feet. The PSAP's Hoquiam and Aberdeen rail yards and BNSF's Rocky Point rail yard are estimated to have PGDs between 2-4 feet. The overall distribution of rail yards subject to PGD is shown in table 6. More than 80 percent (36 of 44) of the rail yards are estimated to experience less than 6 inches of PGD. Only 9.1 percent (4 of 44) of the rail yards are estimated to experience more than 24 inches of PGD. More than 86 percent of the overall rail yard area is estimated to experience less than 6 inches of PGD, with only 3.1 percent of the total area estimated to experience more than 24 inches of PGD.

Table 6: Distribution of PGD at Rail Yards by Number and Area

Estimated PGD	Number	% of Total	Area (Km ²)	% 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	

Step 3: Using the Railway and Rail Yard PGD Results

The railway and rail yard PGD values are estimated to enhance understanding of potential impacts on the Washington State rail network at a system-level; they are not intended to provide information about the performance of specific rail segments or yards, which would require a site-level engineering analysis. Nonetheless, they provide a valuable overview of the relative exposure of the state's rail system to earthquake-induced seismic impacts related to PGD and soil liquefaction-related ground failure. These results may be useful to WSDOT, Washington Emergency Management Division, and other State officials in engaging with private sector rail to better understand the seismic vulnerabilities of rail and of that system's capability to support post-CSZ earthquake response and recovery efforts.

Assumptions in Estimating Rail System Impacts

These estimated PGD values use the slope-only formula for PGD. The construction details associated with waterfront rail yards may significantly increase the displacements at those rail yards. Rail yards such as BNSF's Seattle Terminal and Intermodal Gateway, Tacoma Rail's Tacoma rail yard, and BNSF's Balmer rail yard, which are located on the waterfront and in some cases built on fill placed in previously open water, may be subject to additional ground deformation. The structures retaining the fill upon which the rail yards were built may be subject to failure owing to ground motions leading to large lateral and vertical displacements of the contained soils into the water. Even if the underlying liquefiable soils are contained, the bearing strength that supports such yards' structures and rail lines may be severely diminished, causing the structures to fail during the CSZ event. Additional details regarding the construction of rail yards located along the waterfront would be needed to derive a more complete understanding of the potential failure modes and associated displacements and damage.

Conclusions

The Highway Seismic Screening Tool (HSST) was developed to assess the potential impacts of a CSZ earthquake to highway pavements and to inform a system-level analysis of repair and reopening times as part of the Washington State Transportation Systems RRAP project. Given similarities in the configuration of highways and rail systems as linear infrastructure systems, this study also uses the HSST to examine the exposure of rail infrastructure to PGD.

The results project that statewide, the majority of highways will experience relatively low PGD—74.1 percent of highway miles will experience less than six inches of PGD, with approximately 31 percent of those experiencing none at all. The study projects that the most significant PGD will occur in southwestern Washington and on the Olympic Peninsula, with some comparatively larger PGD occurring throughout the Puget Sound area. Moderate to minor PGD is projected to occur along highways leading into the Cascade Mountains, but east of the Cascades PGD is projected to occur at minor or insignificant levels.

The repair times for highway pavements largely mirror the results of projected PGD magnitudes; however, given the varying types and thicknesses of highway pavement structures, there is some minor variability in per-mile repair times. The study 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 damaged pavement and debris removal prior to repaving with a temporary wearing surface.

The study also projects PGD exposure for the statewide rail system. As with the HSST results for highways, the largest PGDs for rail systems are projected to occur on rail lines located in southwestern Washington and on the Olympic Peninsula, with the Puget Sound and Pacific Railroad projected to experience the greatest system-wide PGDs. Nonetheless, rail lines statewide will experience relatively minor PGD exposure with over 80 percent of rail miles experiencing six inches of displacement or less. Similarly, 80 percent of rail yards in Washington are projected to experience less than six inches of PGD, with only four of the 44 rail yards studies projected to experience PGD in excess of 24 inches. This study was unable to approximate rail line and yard reopening times given the projected PGD exposure of those systems. Engagement with rail industry professionals could provide better context for the rail system vulnerabilities—and therefore, restoration and reopening timelines—given the PGD impacts projected in this study.

This HSST is primarily intended to inform regional highway prioritization for emergency response activities conducted as part of the larger RRAP project. However, the HSST could also be useful in evaluating seismic-induced liquefaction impacts to other roadway systems, including county or local roadways. Evaluating the seismic impacts to pavements of these regional or local systems could complement the statewide analysis outlined in this study and provide a more complete characterization of statewide roadway impacts. Furthermore, applying the HSST to county and local roadway systems could also inform the identification and evaluation of feasible alternate or detour routes around state highways and bridges that experience significant seismic-related disruptions.

The HSST uses currently available seismic and geotechnical information. This study incorporates several analytical assumptions, particularly with respect to statewide subsurface conditions. As new or more complete seismic and geotechnical information becomes available, planners or engineers should integrate that information into the current HSST methodology to provide an updated analysis of seismic-induced impacts to state highways.

Acronyms

BNSF	BNSF Railway Company
CSZ	Cascadia Subduction Zone
DNR	Washington State Department of Natural Resources
EMD	Washington Emergency Management Division
HSST	Highway Seismic Screening Tool
I	Interstate
km	kilometers
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PSAP	Puget Sound & Pacific Railroad
RRAP	Regional Resiliency Assessment Program
UP	Union Pacific Railroad
USGS	U.S. Geological Survey
WSDOT	Washington State Department of Transportation
WSPMS	Washington State Pavement Management System

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