Critical Energy Infrastructure Hub:

Seismic Hazard Mitigation Study of Fuel Facilities

Final Report to Oregon Military Department

December 2021

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EXECUTIVE SUMMARY

Hazard mitigation study was conducted on the Critical Energy Infrastructure (CEI) Hub to evaluate the risks posed by the stored liquid petroleum products from the CEI Hub and potential spillage into the Willamette and Columbia Rivers immediately following a major earthquake. While past studies have mainly qualitatively identified the general risks and associated hazards, the approach taken by this study was for more quantitative assessment. This assessment incorporated state of the art understanding of earthquake shaking resulting from full rupture of the Cascadia Subduction Zone (CSZ), which is the most likely seismic hazard at the Hub and one with the largest regional impact. Geologic and local soil conditions had been of concern for some time, and so data were researched from numerous sources and conditions modelled along three representative sections. These were in turn analyzed with representative shaking scenarios to estimate the ground deformations of the existing conditions, especially as related to liquefaction.

The results of the analyses focused on post-earthquake vertical settlement and lateral spread. While vertical settlement can pose issues for facilities at the Hub, the largest identified threat was liquefaction induced lateral spread. The lateral ground deformations were estimated of upward of 7m (23 ft) for certain scenarios, but were also found to significantly vary depending on the location. The deformations are largest near the free face closer to the river and significantly reduce in more inland areas suggesting that while some storage facilities will result in catastrophic damage, the entirety of the CEI hub and the products stored within will not be completely inundated. Since a significant number of tanks is located more inland, the fundamental data generated by this study can be used to further analyze in more detail the types of fuel and their potential survivability and spillage impacts. Additionally, the results of the analyses suggest that functions and facilities within 300 m (1000 ft) of the river will be highly impacted. These include the main supply pipelines and port transfer terminals that are needed for unloading and reloading of the stored products.

Mitigation options to address the largest issue of lateral spread are limited given the types of soil and the geographic spread of the facilities along the river. Cement deep soil mixing was determined to be the most likely mitigation approach. Using proof-of-concept analyses along the considered sections, the lateral spread was significantly reduced to deformations of less than

0.5 m (1.6 ft) in the worst affected areas and could be implemented to significantly minimize catastrophic failures of the storage tanks. Since the application of this mitigation is anticipated to be near the secondary containment surrounding the tanks, it is not anticipated to improve the situation for pipelines or port transfer terminals that are located closer to the river. As part of the recommendations going forward, those in charge of a large-scale mitigation pilot project should consider taking advantage of other (public or other) resilience resources that could benefit the hub. For example implementing a pilot mitigation project on a portion of the hub would be able to refine information on soil behavior, demonstrate the practicality of implementing the mitigation among the existing on-site infrastructure and establish realistic costs. These efforts could potentially take advantage of federal funds such as the new FEMA Building Infrastructure Communities mitigation grant or other resilience-related funding opportunities that may come out of new federal infrastructure legislation.

The quantitative assessment was also applied to map out in detail the petroleum-based products stored at the Hub. Most recent facility response plans were studied to obtain a realistic and up to date evaluation of the types of product, the location and the type of secondary containment. The secondary containment areas were found to be sized for varied volumes depending on location as compared to the cumulative tank storage they house. Nonetheless, these containments are expected to be rendered ineffective given the estimated ground deformations that were computed. Catastrophic failure of any tank is therefore likely to result in product spill into the river. The difficulty of the cleanup of the spill is compounded by reliance on a single provider for all of the different facilities in the hub. Mitigation of this risk needs to involve considerations of the amount of equipment and the strategic storage location necessary for a timely response to a spill involving more than a single facility. Estimates for cleanup costs were found to be wide ranging, nonetheless the costs of clean up and associated fines had been shown to rapidly approach several billion dollars.

The engineering data and associated analyses resulting from this study form a solid foundation for more realistic estimates of damage, spill and mitigation across the geographic spread of the CEI Hub. Concurrently to the quantitative analyses, interview-based assessment was conducted of subject matter experts and stakeholders on key topics of interest surrounding the seismic preparedness and mitigation concerns surrounding the CEI hub. Detailed outline of the methods is included as part of the appendix of this report. The main recommendations center around the need for collaborative approach in mitigating the hazards at the CEI hub though statewide response exercises. Broad review of emergency responder's human capital and infrastructure was also highlighted, including the potential revision of the state's urban search and rescue.

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1 OVERVIEW OF GEOTECHNICAL HAZARDS

1.1 Earthquake Induced Soil Failures

Strong earthquake shaking can cause large ground deformations and soil failures. This phenomenon can be the result of soil liquefaction, where soils build up water pressure and essentially behave like a liquid. Severe ground deformations can result from soil liquefaction in the form of either lateral spreading or building settlement (Figure 1-1). Lateral ground spreading or ground settlement can have severe impacts on lifeline infrastructure, such as pipe damage or rupture, structural failures at bridges and ports, or tilting of structures. Some examples of lifeline infrastructure damage due to soil earthquake liquefaction are shown in Figure 1-2.

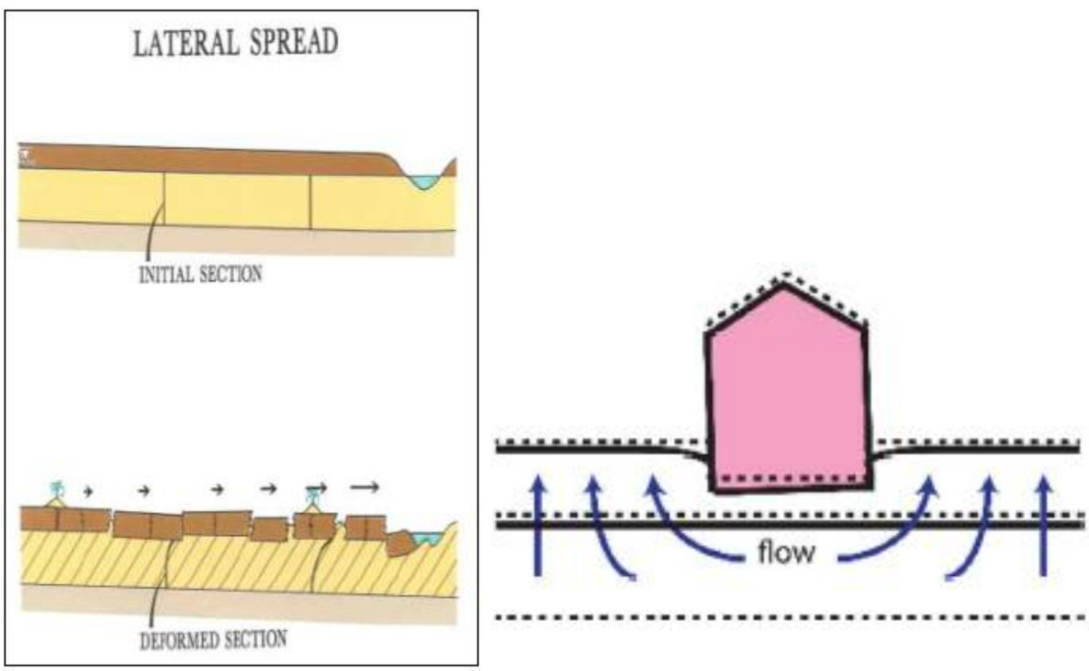


Figure 1-1. *Schematic figures showing lateral spreading (from USGS) and settlement due to post-liquefaction settlement (from Bray & Macedo 2017)*

Figure 1-2. *Examples of infrastructure damage at a port facility due to liquefaction (from Wang et al. 2013)*

A large subduction zone earthquake is anticipated in the Pacific Northwest of the United States. The Cascadia Subduction Zone (CSZ) is located off the Pacific Coast and is capable of producing up to a magnitude 9 earthquake (Atwater et al. 1995, Goldfinger et al 2012). Large ground deformations, including deformations due to soil liquefaction, are one of the hazards that should be considered from the CSZ event. Anticipation of a large earthquake event has led to increased efforts to understand the potential impacts of a CSZ event in Oregon. Based on the understanding of likely impacts, efforts are being undertaken to reduce earthquake risk and increase Oregon's seismic resilience.

There is particular concern about the impacts of strong earthquake shaking and soil liquefaction in the area of the Critical Energy Infrastructure (CEI) hub. The CEI hub is located in northwest Portland where 90% of Oregon's liquid fuel is handled and stored in above ground fuel tanks at the CEI hub (Wang et al. 2012). The CEI hub is underlain by soils that are characterized as liquefiable in strong earthquake shaking (GeoDesign 2016, Madin & Burns 2013, Bauer et al. 2012, Wang et al. 2013), with particular concern of shaking from a CSZ earthquake event. This is shown location of the CEI hub and estimates of soil susceptibility to liquefaction is shown in Figure 1-3.

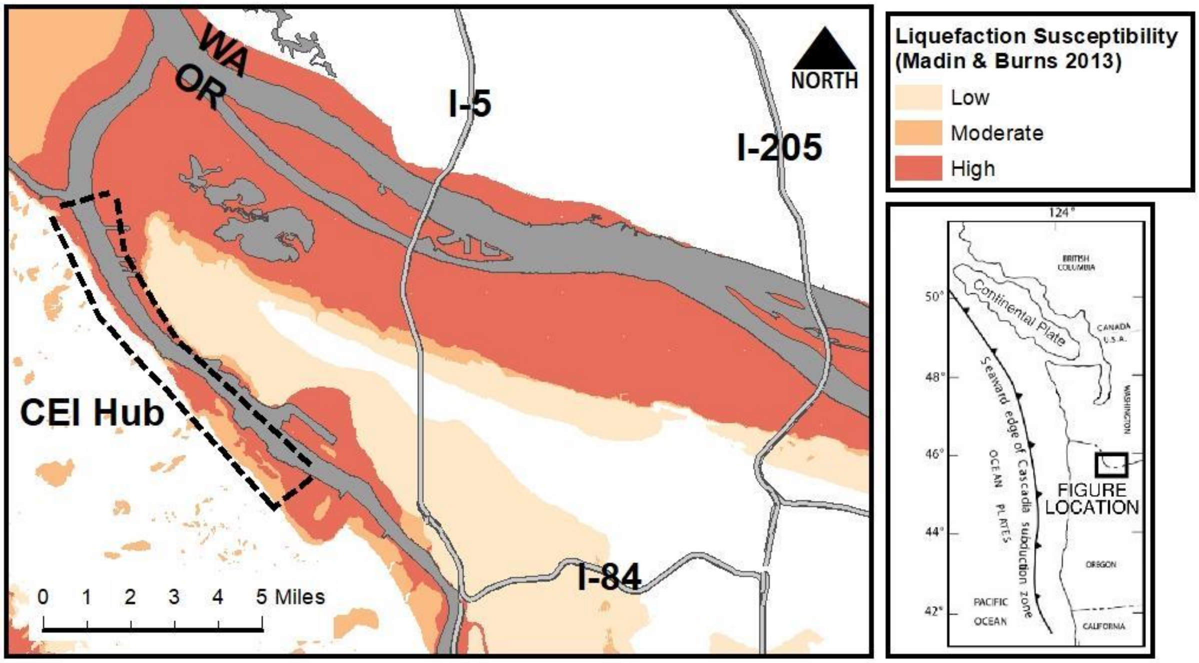


Figure 1-3. *Location of the CEI hub and liquefaction susceptibility estimated by Madin & Burns (2013).*

This chapter investigates possible CSZ earthquake induced lateral spreading and settlement in the CEI hub. The objectives of this chapter are to:

- Generalize ground and soil conditions that underlie the CEI hub.
- Estimate a range of potential lateral deformations and settlements in the CEI hub area from strong earthquake shaking. For this study, ground deformations for a magnitude 9 CSZ event was investigated.
- Explore potential approaches to reducing earthquake hazards in the CEI hub.

This report first summarizes the primary geologic units in the CEI hub and the geotechnical properties. Then, an overview of the geotechnical analysis is provided. Next, estimates of potential lateral ground deformations and settlement are presented based on the geotechnical ground deformation analysis. Finally, potential hazard reduction from ground improvement is explored with numerical simulations.

1.2 Data Sources

The analysis and information presented in this chapter are based on data from the following sources:

- State of Oregon Department of Geology and Mineral Industries (DOGAMI) lidar data for ground surface elevations (https://gis.dogami.oregon.gov/maps/lidarviewer/).
- Bathymetry data of the Willamette River from Dr. Scott Wells at Portland State University (personal communication).
- Geotechnical and geologic data provided in DOGAMI Open-File report O-13-12 (Roe et al. 2013). This database includes shear wave velocity data for common geologic units in the Portland area, GIS layers with locations of geotechnical explorations, characterization of geologic units in the explorations, and references to public geotechnical reports.
- Geotechnical site investigation reports referenced in O-13-12 and provided by the City of Portland.
- Geotechnical data collected by Portland State University researchers from June to September 2019 and published in Moug et al. (2020) and Sorenson et al. (2022). These data were collected at a site managed by Portland General Electric on NW Marina Way, slightly north of the CEI Hub.
- Synthetic ground motions developed for the M9 Project (Frankel et al. 2018).
- Geotechnical laboratory test reports from two sites on the Willamette River (Dickenson et al. forthcoming). The laboratory testing includes monotonic undrained direct simple shear tests to characterize undrained shear strength, and cyclic undrained direct simple shear tests to characterize cyclic strength.

1.3 Limitations

The data and analyses in this chapter are presented to the best of the authors' knowledge. There is inherent uncertainty in geotechnical data and estimations of ground conditions over a large area. The estimates provided herein are meant to provide guidance over the region of the CEI hub and should not be used in place of site-specific site investigation.

2 SUBSURFACE CONDITIONS AT THE CEI HUB

This study used existing geologic information and geotechnical data for the CEI hub to generalize stratigraphy, generalize groundwater conditions, and approximate geotechnical properties for major geologic units.

2.1 Geologic units in the CEI hub

The CEI hub is underlain by dredged fill soils and alluvial deposits from the Willamette River (Madin et al. 2008). Generally, there are four geologic units: Columbia River basalt (CRB), weathered Columbia River Basalt (WCRB), quaternary alluvium (QAL) and engineered fill (FIL). The depth to bedrock (CRB, WCRB) is generally largest near the Willamette River and then decreases with distance from the river. This reflects the location of the Tualatin mountains which border the CEI hub to the southeast and are aligned with the Willamette River for the length of the CEI hub. The ground water table at the CEI hub is influenced by Willamette River levels and seasonal drainage from the nearby Tualatin Mountains. Site-to-site variations throughout the CEI hub are expected due to varying depth to bedrock, historic depositional patterns of the Willamette River, variations in FIL thickness including locations that were historically lakes and subsequently filled in.

Liquefaction susceptibility is considered high to very high for recently deposited river channel deposits and uncompacted fill (Idriss & Boulanger 2008). Therefore, the primary units of concern for large deformations during earthquake shaking are QAL and FIL. These units are the focus of the investigation into earthquake-induced ground deformations.

Alluvium is a general term for soils deposited by flowing rivers, such as the soils deposited by the Willamette River. Geotechnical data from the CEI hub indicates that there is a range of soil types that occur within the QAL unit, from fine-grained soils (clays and silts) to coarse-grained soils (sands). This variation of soil types and grain sizes can affect the soil’s susceptibility to earthquake-induced ground deformations. Based on information and geotechnical data described in the following sections, the QAL unit was assessed for liquefaction susceptibility in the case of fine-grained QAL (FG-QAL) predominately composed of silt-sized soil particles, and coarse-grained QAL (CG-QAL) predominately composed of sand-sized soil particles.

Significant parts of the CEI hub are built on fill soils. These areas include historic lakes that were filled with dredged fill, or reclaimed land built upon the Willamette River shoreline. The areas of built-up land can be observed by comparing historic maps with recent satellite images. Figure 2-1 shows a historic map of parts of the CEI hub and the presence of Kittridge and Guilds Lake. It is evident in Figure 2-1 that these lakes were filled in and currently infrastructure exist on these reclaimed lakes, including fuel storage tanks on the former Kittridge Lake. Uncompacted fill is of particular concern for earthquake hazards since without ground improvement efforts the ground is likely soft and susceptible to large ground deformations from strong earthquake shaking.

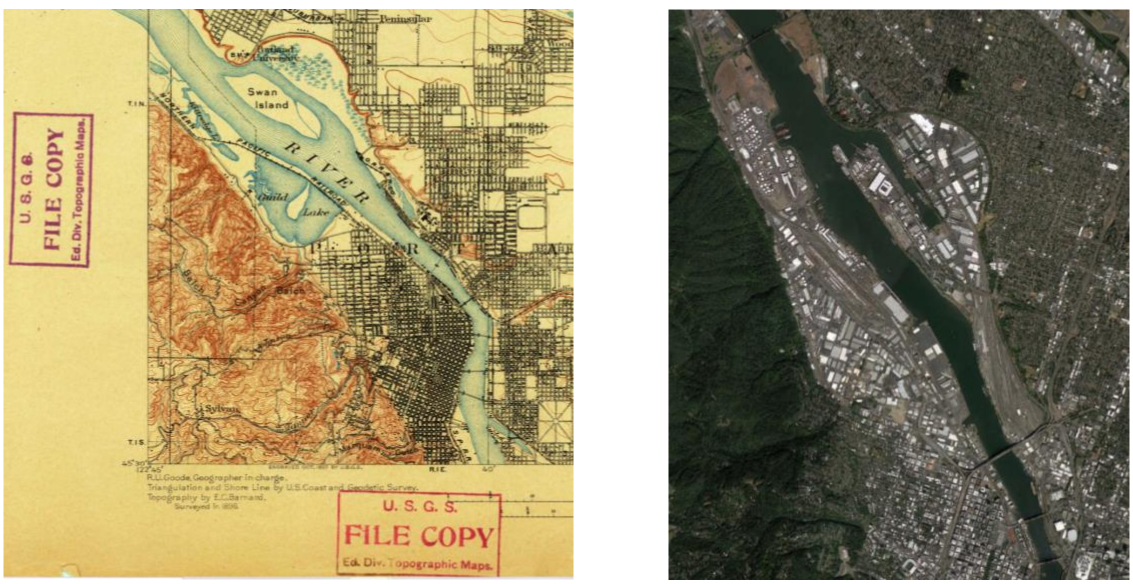


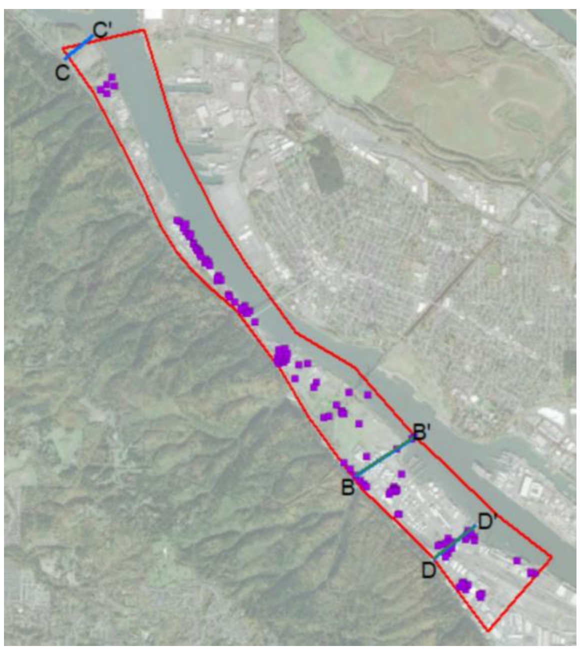
Figure 2-1. *Reclaimed land through engineered fill in the CEI hub area (a) Portland-area map showing historic lakes that underlie the CEI hub (USGS 1901), (b) satellite view of the Portland-area (image dated 13-August-2020 from Google Earth).*

2.2 Stratigraphic profiles

Three profile locations were selected for analysis in an effort to consider the ground conditions along the length of the CEI Hub. These profiles are shown in Figure 2-2 and are described as:

- B-B’: Profile selected to be ‘representative’ general location in the CEI hub. This profile underlies several fuel tanks.
- C-C’: Profile selected because it is proximal to a 2019 PSU research site and with detailed geotechnical data from the GeoDesign (2016) study. The site is managed by Portland General Electric (PGE).
- D-D’: Profile runs through historic lake Kittridge that was filled with dredged material. Currently, fuel storage tanks are located on the north-west end of the historic lake.

Figure 2-2. *Location of generalized stratigraphic profiles in the CEI hub. Square symbols are locations of geotechnical boreholes in the O-13-12 report.*



The approximate cross sections of CRB, WCRB, QAL, and FIL units for the profiles B-B’, C-C’, and D-D’ are shown in Figure 2-3 to Figure 2-5, respectively. The site conditions for this study were synthesized from historic geotechnical data from throughout the CEI hub. These data were obtained from the Roe et al. (2013) report and O-13-12 database that includes GIS data of location of geotechnical explorations, geologic units encountered in explorations if available, and a shear-wave velocity model for each geologic unit. The City of Portland provided historic geotechnical engineering reports that were analyzed for the O-13-12 database. Ground surface elevations were estimated with DOGAMI bare earth lidar data from the Portland and Linnton quadrants and with river models from Dr. Scott Wells (Portland State University, personal communication).

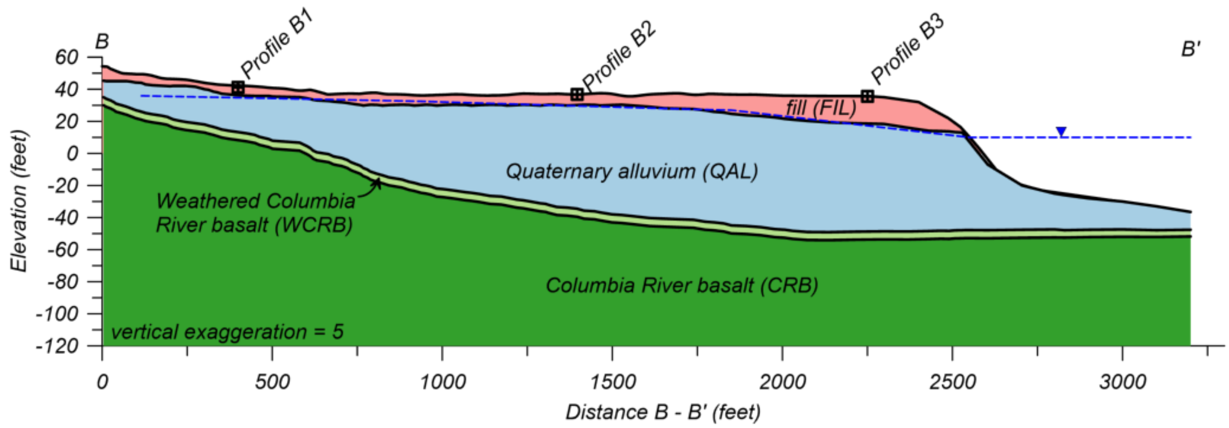


Figure 2-3. *Generalized stratigraphy for B-B' profile.*

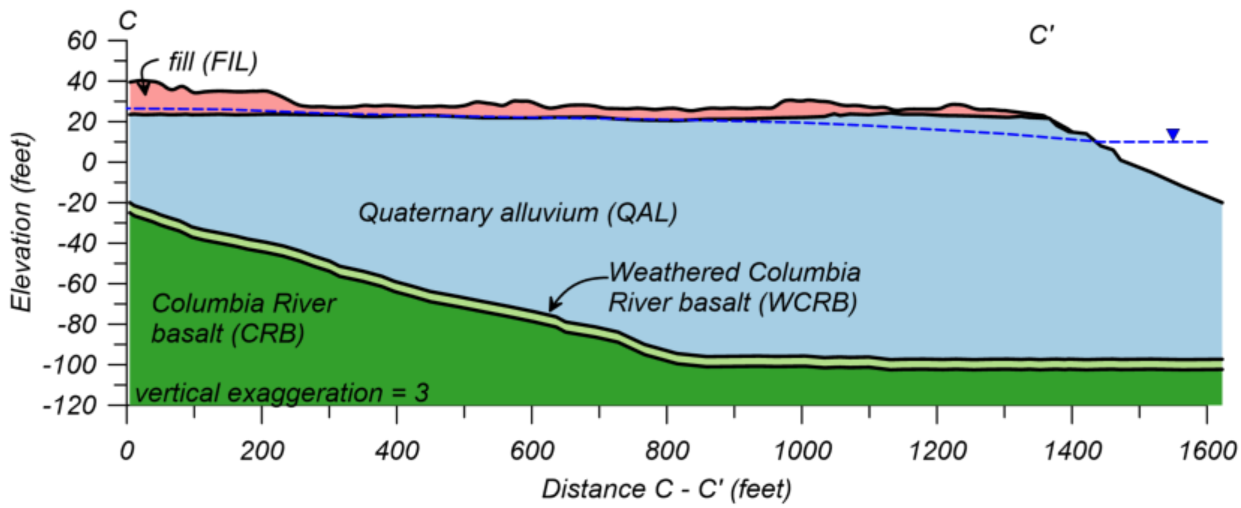


Figure 2-4. *Generalized stratigraphy for C-C' profile.*

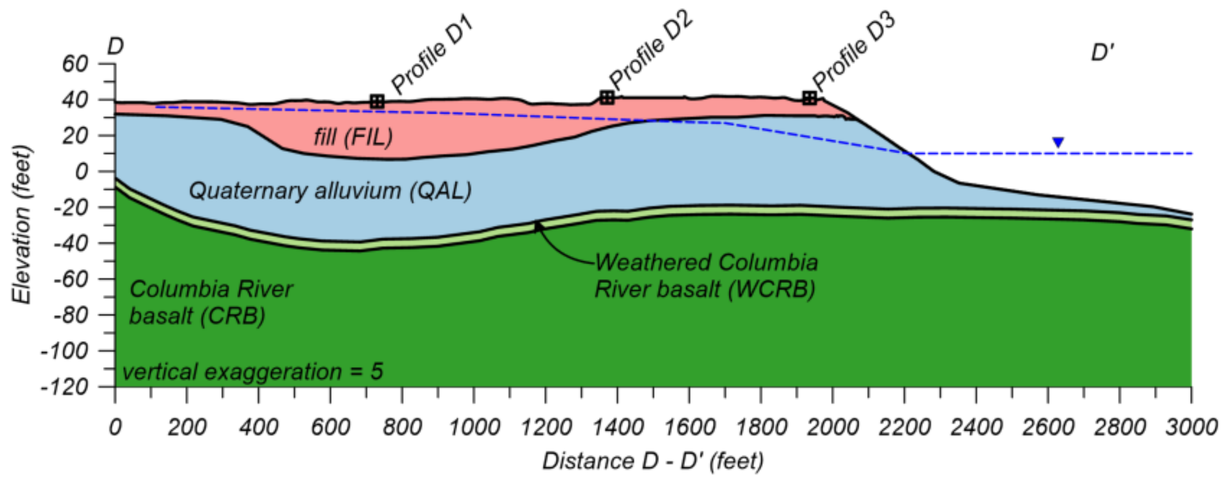


Figure 2-5*. Generalized stratigraphy for D-D' profile***.

The stratigraphy of the B-B' profile (Figure 2-3) was determined from borehole reporting of fill thickness, depth to bedrock, and general trends of bedrock depth from the Tualatin Mountains to the Willamette River. Throughout the area of the CEI hub, the Tualatin Mountains run approximately parallel to the Willamette River and CEI hub. Generally, fill thickness increases in thickness towards the Willamette River, with the thickest soil deposits along the riverbank. The B-B' profile was selected for analysis because several geotechnical reports with borehole data were available near the profile and the profile covers an area where fuel storage tanks are located. The B-B' profile is considered a typical profile for the CEI hub area.

The C-C' profile (Figure 2-4) was selected for analysis because of the authors' experience in the area. Geotechnical data for the C-C' site came from Portland State University's Harborton research site (Moug et al. 2020) and GeoDesign (2016). The profile is located about 700 m north of nearby fuel storage tanks.

The D-D' profile (Figure 2-5) was selected for analysis because it is located on large amounts of placed fill. The profile runs over historic Kittridge Lake that was filled for reclaimed land. The presence of the historic lake was inferred from historic maps. Figure 2-6 shows the profile location with a section of a historic Portland map from the USGS overlain. The presence of the filled in lake was also inferred from borehole data around the D-D' profile. The depth to WCRB and CRB indicate an elevation depression consistent with the location of the lake.

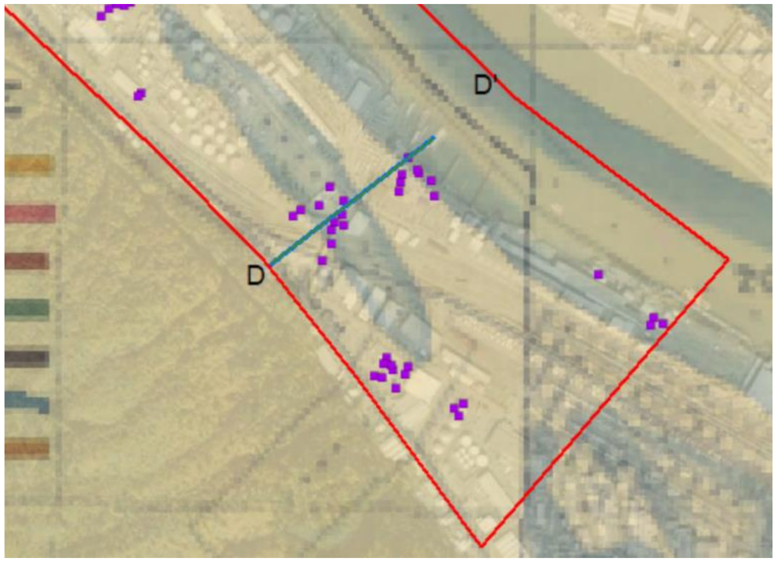


Figure 2-6. *Location of profile D-D' compared with a historic map from USGS.*

The groundwater table in the CEI hub is controlled by the level of the Willamette River and drainage from the Tualatin Mountains. The Willamette River levels were estimated from USGS data recorded at the Morrison Bridge, and shown in Figure 2-7. The Willamette River elevation typically has two annual high levels. One high level occurs in the winter due to precipitation and another high level occurs in the late spring due to snow melt. The analyses for this study were performed assuming a Willamette River elevation of 10 feet. The water table elevation in the stratigraphic profiles was estimated to be consistent with the Willamette River level and with observed water levels reported with borehole logs in the geotechnical reports.

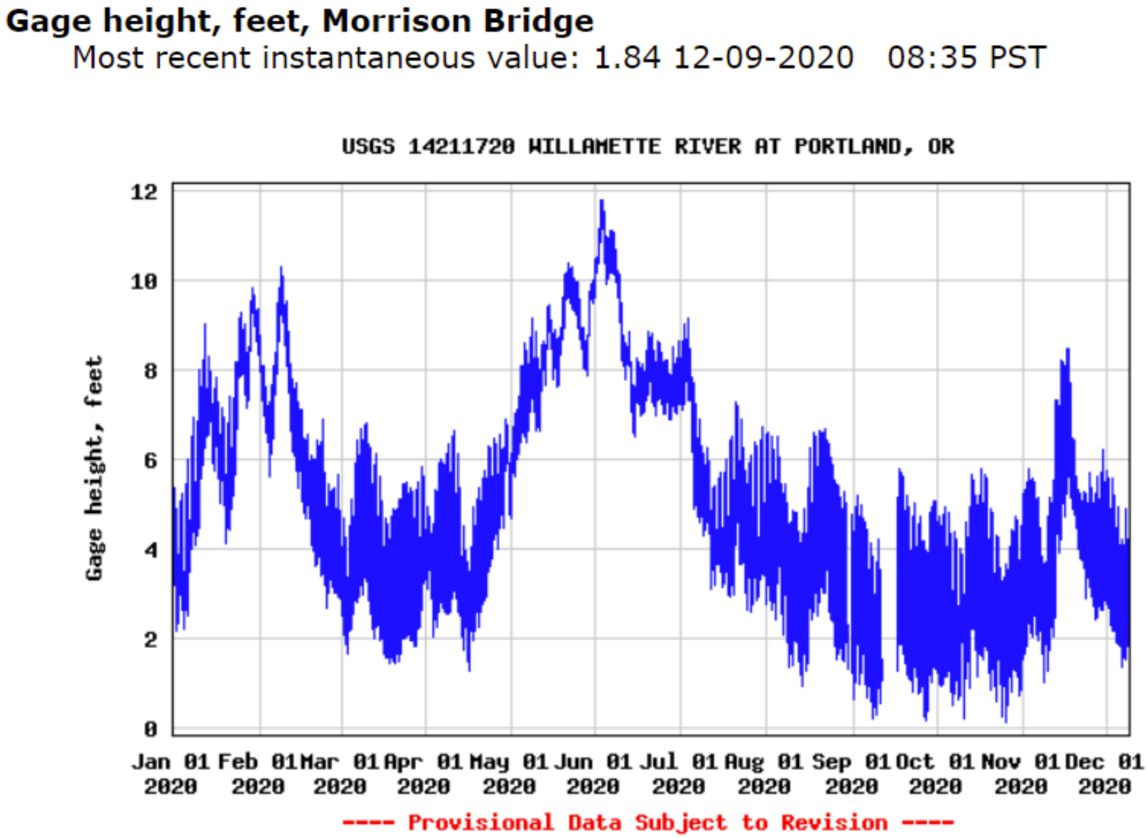


Figure 2-7. *Willamette River elevation recorded at the Morrison Bridge from https://waterdata.usgs.gov/usa/nwis/uv?site_no=14211720.*

3 EARTHQUAKE SCENARIOS

The numerical simulations performed in this study aim to predict the magnitude and patterns of ground deformations due to a full rupture CSZ earthquake. Despite other geological faults in the immediate area, the study focused on CSZ given the higher likelihood of occurrence and the significantly larger geographical impacts. CSZ earthquakes are infrequent enough that there are no recorded time histories from the last CSZ megathrust event. To overcome this limitation, recently developed physics-based simulations of ground motions from the M9 project were used to account for unique features of a CSZ rupture in the Pacific Northwest.

3.1 M9 Project Background

This study used synthetic ground motions developed by Frankel et al. (2018) for the M9 project to model a CSZ earthquake event. The M9 Project is a collaboration between the U.S. Geological Survey (USGS) and the University of Washington (UW) to reduce the potentially devastating effects of a CSZ earthquake by advancing seismic research, methodologies, and engineering and community practices. A key portion of the M9 research was the development of a seismic model of the Pacific Northwest, which was used to produce thirty simulations of a CSZ full rupture megathrust earthquake. Frankel et al. (2018) developed a suite of 30 synthetic ground motions for Mw 9.0 earthquakes on the CSZ by combining results of 3D finite-difference simulations with finite-source, stochastic synthetics. The suite consists of 30 scenarios (herein referred to as "ground motions") of a potential CSZ earthquake, each considering a different hypocenter location and rupture parameters.

The 3D finite-difference simulations used for long periods utilize the 3D velocity model of the Pacific Northwest developed by Stephenson et al. (2017). This P- and S-wave velocity model includes the crust and upper mantle up to a depth of 60 km, with the subducting slab and sedimentary basins as key features. The sedimentary basins are subdivided into Quaternary and Tertiary geologic units. The M9 motions were developed for outcrop motions from Vs = 800 m/s, which is the approximate Vs of the CRB unit.

3.2 Ground Motion Selection

The M9 motions used in this study was accessed via the CSZ@PDX online tool (m9csz.cee.pdx.edu). The tool provides spatial visualization of the M9 simulations in the form of map zones with selectable geographic coordinates in a grid pattern. The ground motion acceleration time histories were extracted from a grid point that falls within the boundary of the CEI hub. The CEI hub is also located within the Portland basin as shown in Figure 3-1 therefore, the selected ground motions inherently include the potential basin effects. The location of the grid point where the motions were extracted is shown in Figure 3-2 and the coordinates are listed in Table 3-1. All 30 motions are used for 1D site response, and 13 selected motions are used for

2D modeling. Only the x-component of the ground motion acceleration time histories were used in this study.

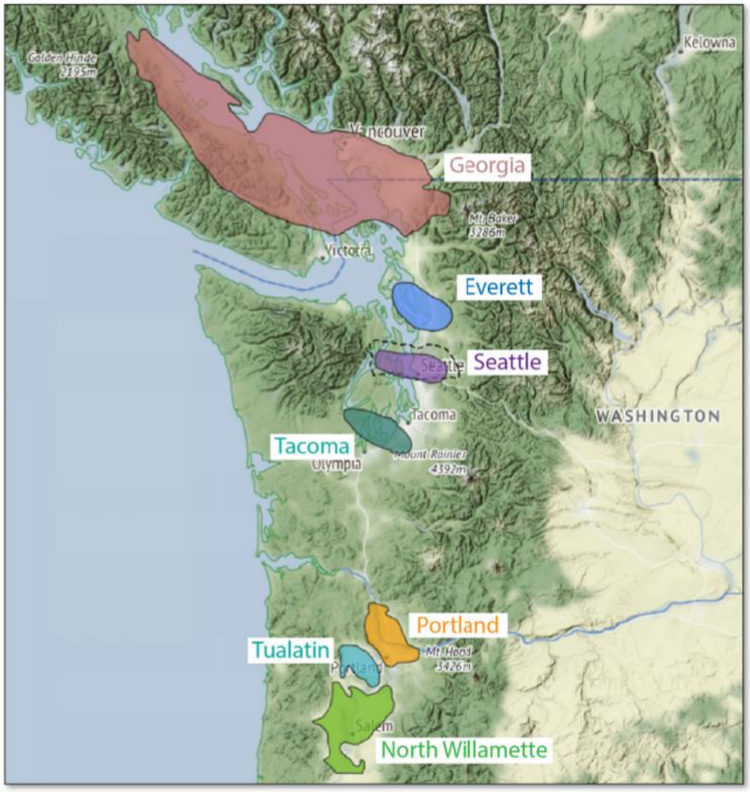


Figure 3-1. *Basin locations in the Pacific Northwest (Bozorgnia and Stewart 2020).*

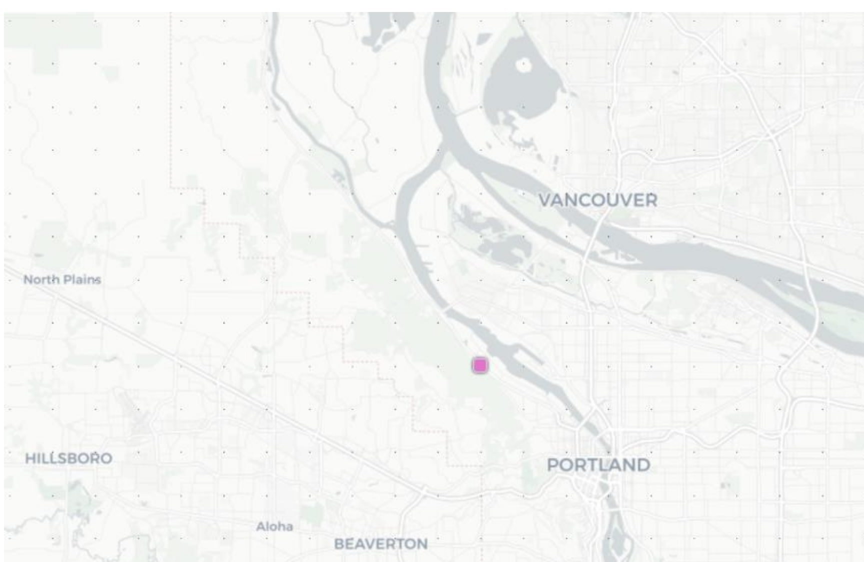


Figure 3-2. *Location of the M9 ground motions within the CEI hub used in this study.*

Table 3-1: Coordinates of the Selected Time Histories in the CEI Hub

Designation	Latitude (degrees)	Longitude (degrees)	Basin
CEI	45.58	-122.74	Portland

3.3 Ground Motion Characteristics and Comparison to Code-Based Spectra

The acceleration time histories for the 30 outcrop ground motions are shown in Figure 3-3 which illustrated the long duration characteristics of these motions. The strong motion duration ($D_{5\text{-}95}$) for these motions ranges between 65 sec and 184 sec with a mean value of 139 sec.

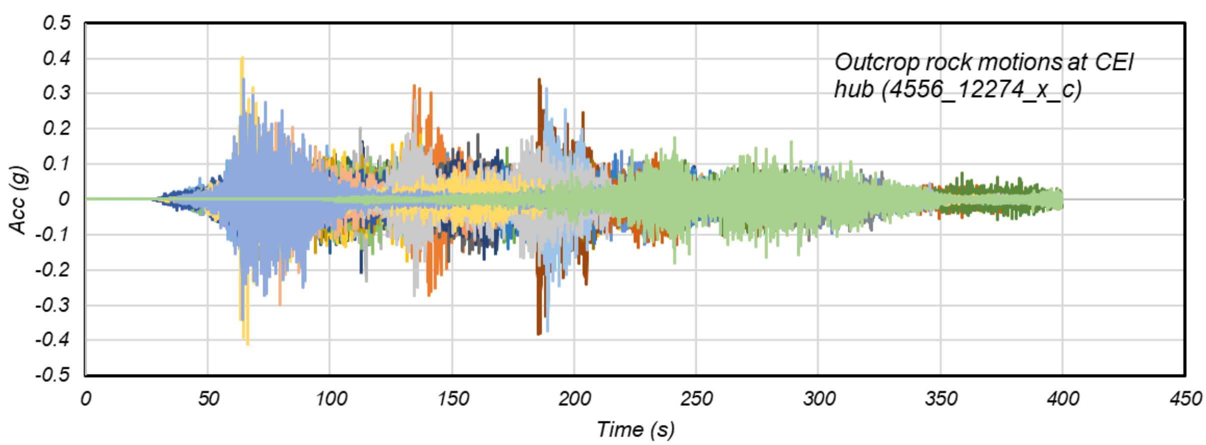


Figure 3-3. *Acceleration time histories of M9 rock ground motions at the CEI hub.*

Figure 3-4 shows the acceleration response spectra of all 30 motions along with the median, median +1 standard deviation, and median -1 standard deviation. The peak ground acceleration (PGA) ranges between 0.11 g to 0.41 g with a median value of 0.19 g. The basin effects are evident from the large spectra accelerations estimated for periods between 0.8 sec and 1.5 sec.

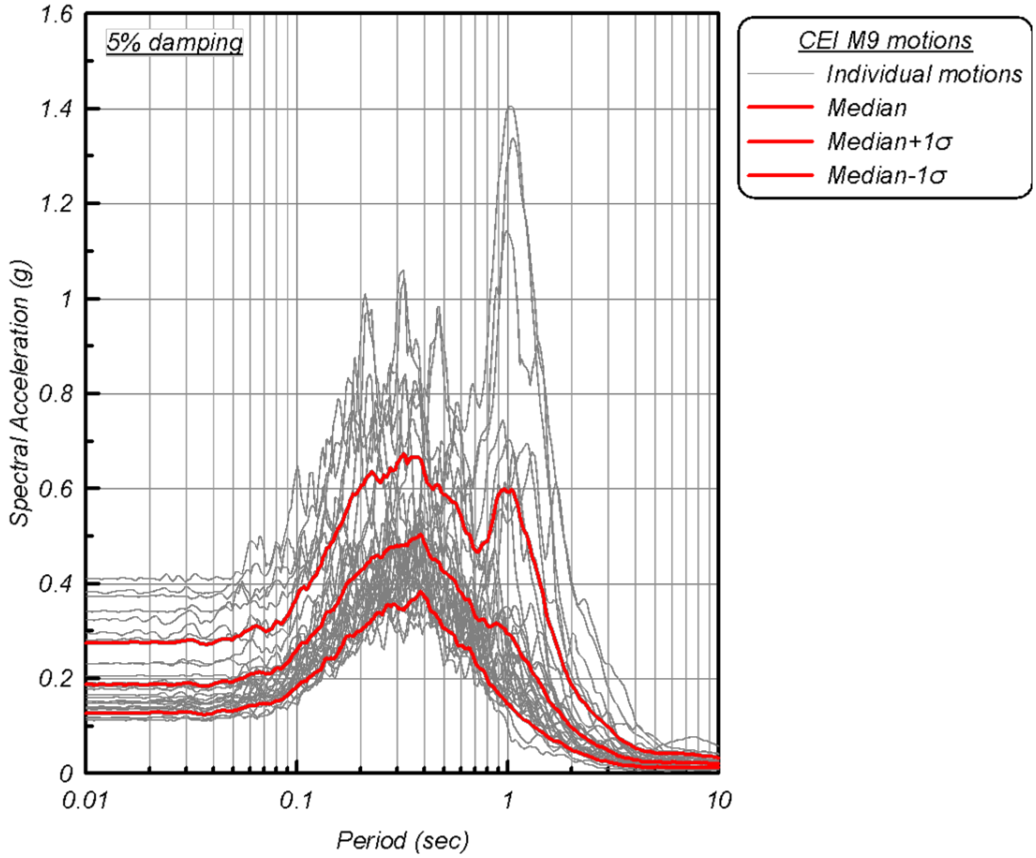


Figure 3-4. *Acceleration response spectra of M9 rock ground motions at the CEI hub*

Figure 3-5 shows the comparison between the spectral accelerations of the M9 motions used in this study and the predicted spectra using BC Hydro, an empirical ground motion prediction model developed by Abrahamson et al. (2016) specifically for subduction earthquakes and commonly used for CSZ ground motion estimation. The BC Hydro spectra in this figure is developed for an interface event with a Magnitude 9, source to site distance of 100 km, and a shear wave velocity in the top 30 meters of soil, Vs,30 equal to 800 m/s (Site Class B/C). Comparing the synthetic M9 motions that are specifically developed for a CSZ megathrust earthquake with empirical predictive models that are developed based on historic earthquakes provides an insight into the uncertainties associated with predicting the CSZ ground motions in the region. The median spectra from M9 motions are larger than the median spectra from BC Hydro for most oscillator periods.

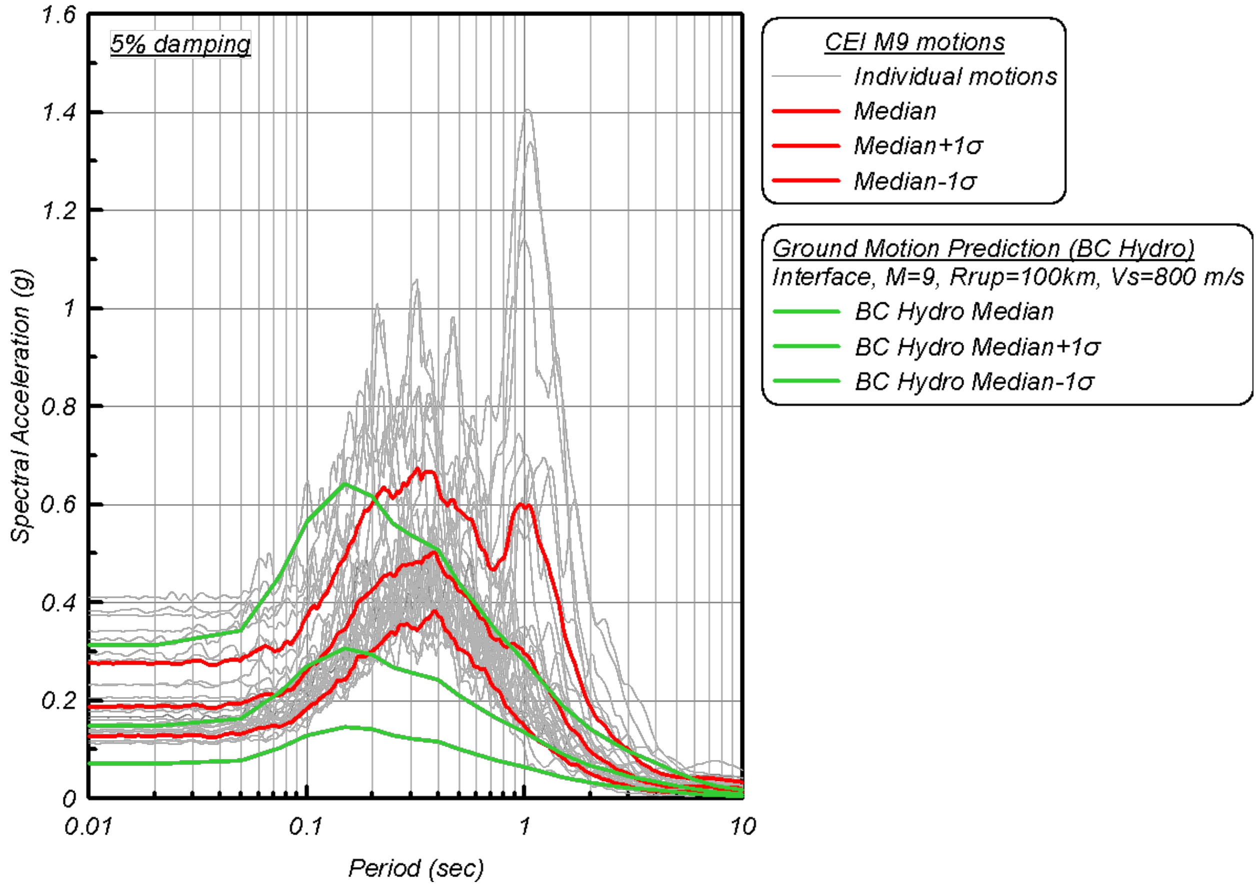


Figure 3-5. *Acceleration response spectra of M9 rock ground motions at the CEI hub compared to predictive ground motion model BC-Hydro.*

Figure 3-6 compares the spectral accelerations of the M9 outcrop motions with the probabilistic spectra (PSHA) developed from the 2014 USGS probabilistic seismic hazard model. The PSHA spectra are shown for uniform hazards corresponding to 1000 year and 2475 year return periods as an example, as these levels of shaking are usually used in building and highway bridge seismic design codes (e.g. ASCE 7, AASHTO 2014). For reference, this figure also includes risk-targeted maximum considered earthquake (MCE_R) and design earthquake (DE) spectra developed based on site-specific ground motion procedures in ASCE 7 (2016). New tanks and other non-building structures must be designed using ground motions defined in ASCE 7. The median M9 motions are smaller than the ASCE 7 - DE spectra for periods smaller than 0.4 sec and larger than 1.5 sec and are comparable to DE spectra for periods between 0.4 sec and 1.5 sec. However, the code-based spectra do not capture the geologic effects in the M9 motions which is manifested as large spectral accelerations in a number of ground motions for periods between 0.7 sec to 2 sec.

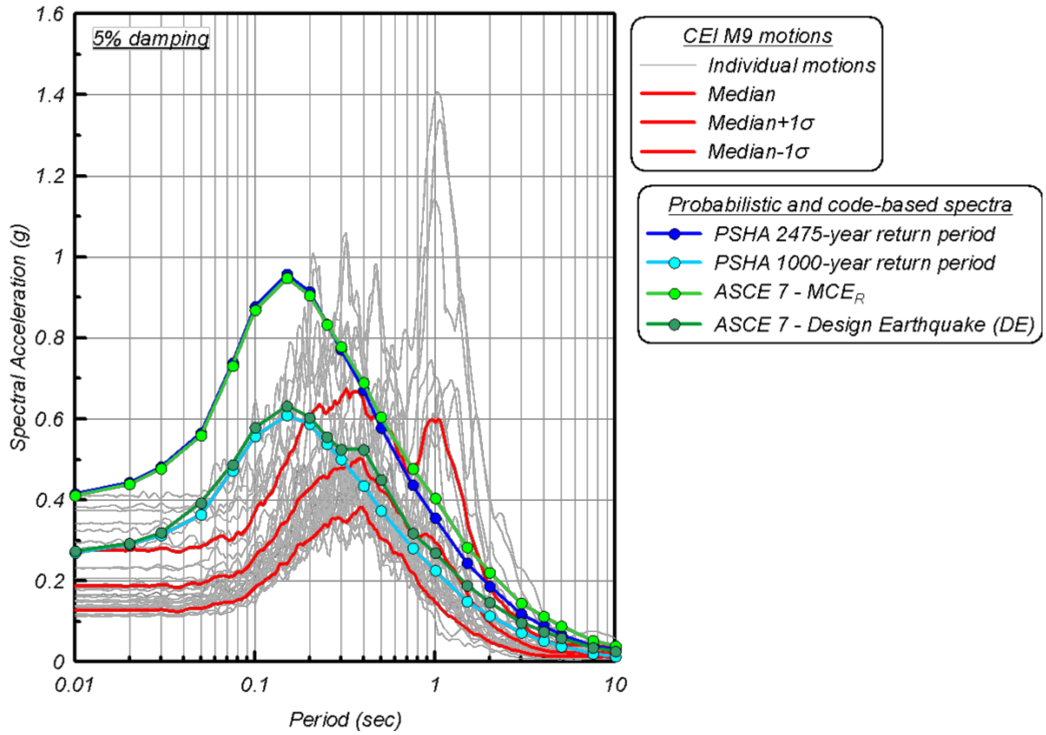


Figure 3-6. *Acceleration response spectra of M9 rock ground motions at the CEI hub compared to probabilistic and code-based spectra.*

3.4 Selected Subset of Ground Motions for 2D Analyses

The two-dimensional (2D) analyses in this study are performed for a smaller number of ground motions due to the computational time required to analyze the response for each ground motion. Four subsets of ground motions were selected comprising a total of 13 ground motions. These ground motions and their corresponding subsets are listed in Table 3-2. The spectral accelerations of the ground motions within each subset are shown in Figure 3-7.

Table 3-2. *Subset of Ground Motions for 2D Analysis*

Subset	Ground Motion #
Median	05, 07, 10, 33
Median +1σ	03, 04, 12, 30
Median -1σ	17, 20, 24, 26
Maximum	09

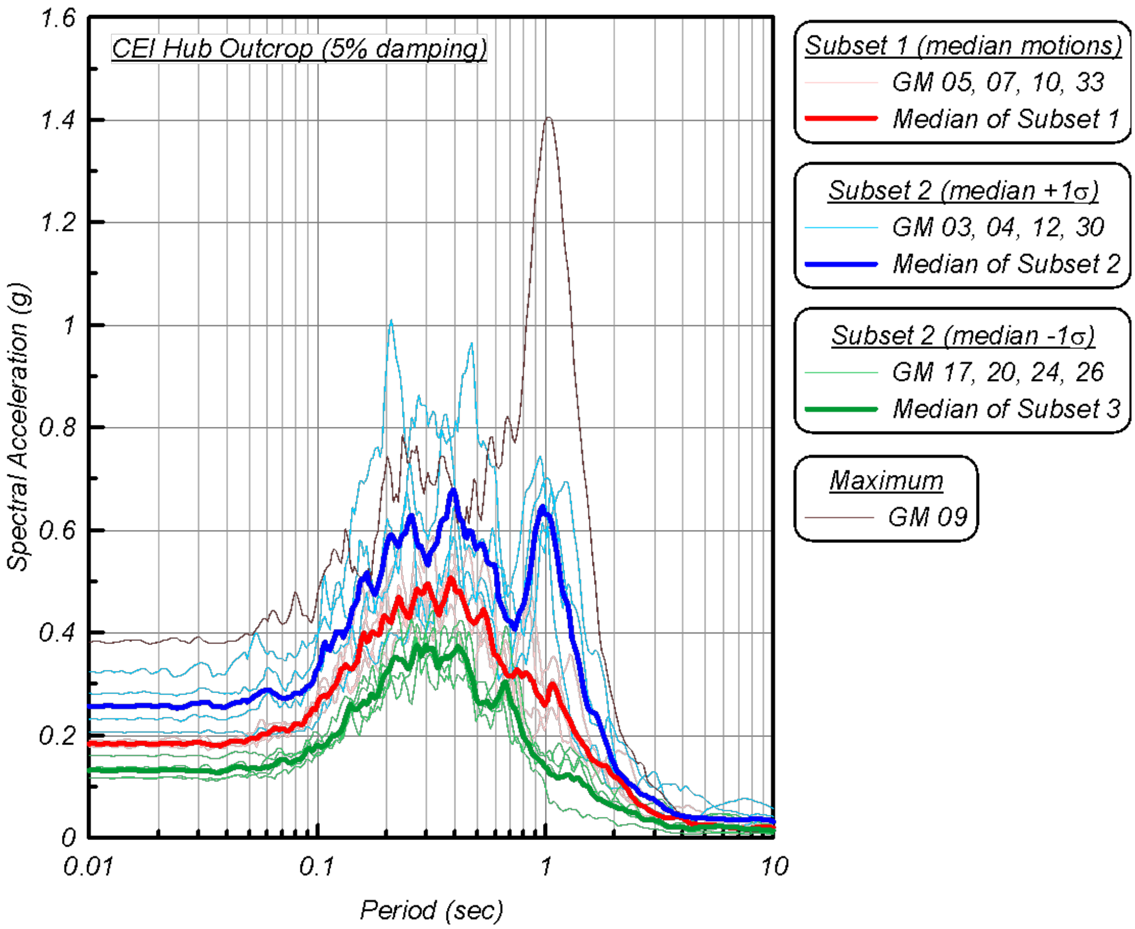


Figure 3-7. *Acceleration response spectra for four subsets of CEI M9 rock motions.*

4 GROUND DEFORMATION ANALYSIS

4.1 Methodology for 2D Analysis

Earthquake-induced ground deformations were estimated at profile locations B-B’ and D-D’ through two-dimensional (2D), effective stress, coupled, non-linear dynamic analysis (NDA). The 2D NDA simulated site responses to nine ground motions from the M9 project. The simulated responses were used to estimate lateral deformations and settlement. These deformations could then be used to estimate damage to overlying fuel storage tanks and other infrastructure in the CEI hub.

The 2D NDA was performed with FLAC 8.0. Figure 4-1 and Figure 4-2 show the 2D FLAC mesh developed for Profiles B-B’ and D-D’, respectively. Given the spatial variability of the soil properties of the alluvium layer (QAL) within the study area, two different types of soil behaviors were assumed to model the dynamic response of the QAL unit. FG-QAL soil behavior was modeled with PM4-Silt (Boulanger & Ziotopoulou 2018) to simulate the response as clay-like behavior susceptible to cyclic softening. CG-QAL soil behavior was modeled with PM4Sand (Boulangre & Ziotopoulou 2017) to simulate the response as sand-like behavior susceptible to liquefaction. The analyses were performed using both constitutive models to envelope the likely range of ground deformations. In general, the sand-like behavior resulted in larger deformations compared to the clay-like behavior. Therefore, it is recommended to perform detailed subsurface investigations specifically focused on characterizing the dynamic behavior of QAL unit in future seismic vulnerability studies of the CEI hub. The two constitutive models have been extensively calibrated and validated using case histories and used in vulnerability assessment of important earth structures (e.g. Boulanger 2019, Boulanger et al. 2019). The development of excess pore pressure during cyclic loading and the resulting contraction and dilation of the soils are explicitly simulated in time domain in these analyses.

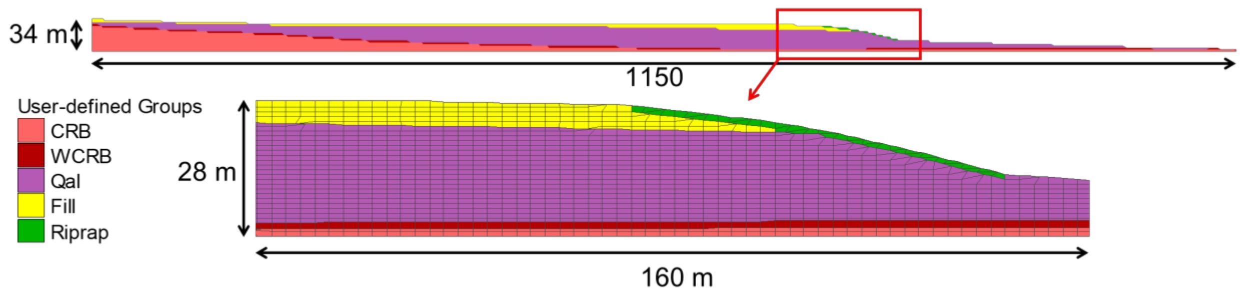


Figure 4-1. *Cross section of Profile B-B' in FLAC.*

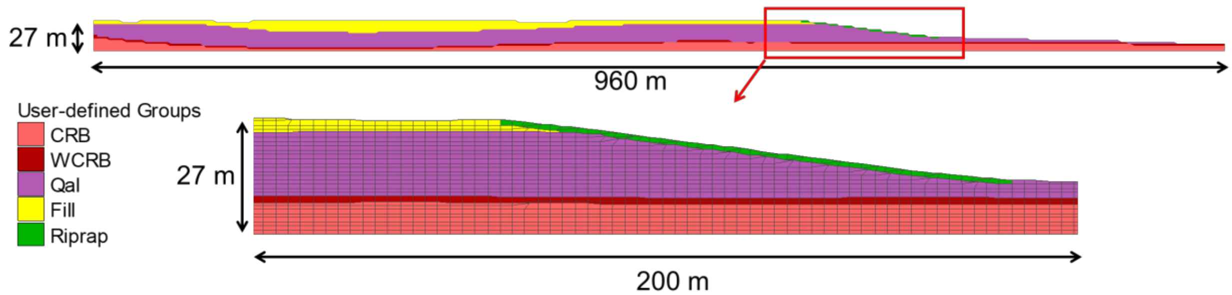


Figure 4-2. *Cross section of Profile D-D' in FLAC.*

The FIL layer was modeled using PM4Sand in areas where the fill was under the ground water. In areas where FIL was above the ground water, it was modeled using Mohr-Coulomb failure criteria in combination of a nonlinear stress-strain behavior characterized using the Itasca-S3 model (Itasca 2016). The S3 model is a three-parameter sigmoidal shaped backbone curve that simulates the nonlinear stress-strain behavior. The model parameters were fit to approximate target shear modulus reduction curves selected from the available literature for similar soil types, plasticity characteristics, and depth. The rock units (WCRB and CRB) and the half space were modeled as elastic materials with different shear moduli corresponding to their representative shear wave velocities. A thin layer of riprap was modeled at the slope face to prevent local slope failures since those failures did not affect the global deformations within the studied area. The rip rap was modeled using the Mohr-Coulomb failure criteria. The soil units, soil properties, and constitutive models used in FLAC are shown in Table 4-1. Idealized Profile and Soil Properties in the FLAC ModelTable 4-1. A detailed description of the calibration of the constitutive model parameters are provided in the next section.

The model was subjected to one-dimensional horizontal dynamic loading at the base of the model using the acceleration time histories described in previous sections. The ground motions were applied as outcrop motions to the base of the model using the compliant-base procedure of Mejia and Dawson (2006). The compliant-base was modeled using the quiet boundary in FLAC. In this procedure a shear stress time history compatible with the stiffness of the half-space is applied to the base of the model.

A small amount of Rayleigh damping was assigned to the soil elements to account for small-strain damping in soil elements and numerical high-frequency noise due to mesh discretization. The Rayleigh damping was characterized by a minimum damping ratio of 1% at a center frequency of 5 Hz.

Table 4-1. *Idealized Profile and Soil Properties in the FLAC Model*

Soil Unit in FLAC Model	Description	Model in FLAC	Vs (m/s)	Total Unit Weight (kN/m^3)	c or Su (kPa)	ϕ(°)	G/G_{max} [2]	Vertical Permeability k (m/s)[3]
Fill (dry)	Course-grained fill, above water table	Mohr-Coulomb and Itasca-S3	182	15.5	-	33	EPRI 0 - 6 m	5e-5
Fill (submerged)	Course-grained fill, below water table	PM4Sand	Pressure [1] Dependent	19.5	-	33	EPRI 6 m - 15 m	5e-5
CG-Qal	Course-grained alluvium (sand-like)	PM4Sand	Pressure Dependent [1]	19.8	-	35	EPRI 6 m - 15 m	5e-7
FG-Qal	Fine-grained alluvium (clay-like)	PM4Silt	Pressure Dependent [1]	16	Depth dependent [4]	30	Darendeli, PI=15, 1 atm	5e-7
Riprap	Granular rockfill	Mohr-Coulomb	182	18.1	15 [5]	45	-	1e-3
WCRB	Weathered Columbia River Basalt	Elastic	296	20.4	-	38	-	1e-3
CRB	Columbia River Basalt	Elastic	800	20.4	-	38	-	1e-3
CDSM	Cement Deep Soil Mixing	Mohr-Coulomb	265	18.1	517 [6]	0	-	5e-5
-	Half Space	Elastic	800	-	-	-	-	-

Notes:
1. Vs in PM4Sand and PM4Silt models are pressure-dependent and calculated using the G0 input parameter.
2. Target curves approximated with Itasca-S3 model or a hyperbolic function embedded in PM4Sand/PM4Silt
3. Horizontal permeability is assumed to be two times the vertical permeability.
4. Depth dependent undrained shear strength based on Su/σ'v=0.354.
5. Pseudo cohesion in rockfill to account for interlocking of rocks at shallow depths based on Dickenson and McCullough (2004)
6. Including a reduction factor of 0.3 based on the areal replacement ratio of 30%

4.2 Selection of model parameters

The numerical analyses required calibration of soil models to reasonably predict the soil response to earthquake shaking. This section focuses on how available geotechnical and geologic data were synthesized to select model parameters for FG-QAL, CG-QAL, FIL, WCRB, and CRB. Generally, geotechnical data for the CEI hub from DOGAMI database O-13-12 were limited to Atterberg limits, moisture contents, and field visual soil classifications. To aid constitutive model calibration, the O-13-12 data were supplemented with additional cone penetration test (CPT) profiles and laboratory test data.

The CPT profiles were measured at the Portland General Electric (PGE) site located north of the CEI hub. The profiles were available through GeoDesign (2016) and from the Portland State University study described in Moug et al. (2020). Although these CPT profiles are not located at the hypothetical site, the soil types and geology at the CPT locations is consistent with those reported in boreholes near the hypothetical site, therefore these CPT profiles are considered to reasonably represent soil types in the CEI hub for this generalized study.

An example CPT profile performed by ConeTech Inc. for PSU is shown in Figure 4-3. The soils are considered part of the QAL geologic unit. The CPT data showed two distinct soil types based on the Robertson (2009) soil behavior type index (I_c): clay-like soils ($I_c > 2.6$) referred to as FG-QAL in this report and sand-like soils ($I_c < 2.6$) referred to as CG-QAL. Fine grained and coarse-grained alluvial deposits are reported throughout the CEI hub: Wang et al. (2013) report that the distributions of fine-grained and coarse-grained soils in the QAL unit reflect sediment deposition patterns of the Willamette River. Based on borehole records from other areas of the CEI hub, the dominance of the coarse-grained and fine-grained soils does not show a consistent pattern and the presence of either soil type depends on the Willamette River’s historic depositional patterns. The PM4Silt model is used to analyze soil profiles with FG-QAL. The PM4Sand model is used to analyze soil profiles with CG-QAL.

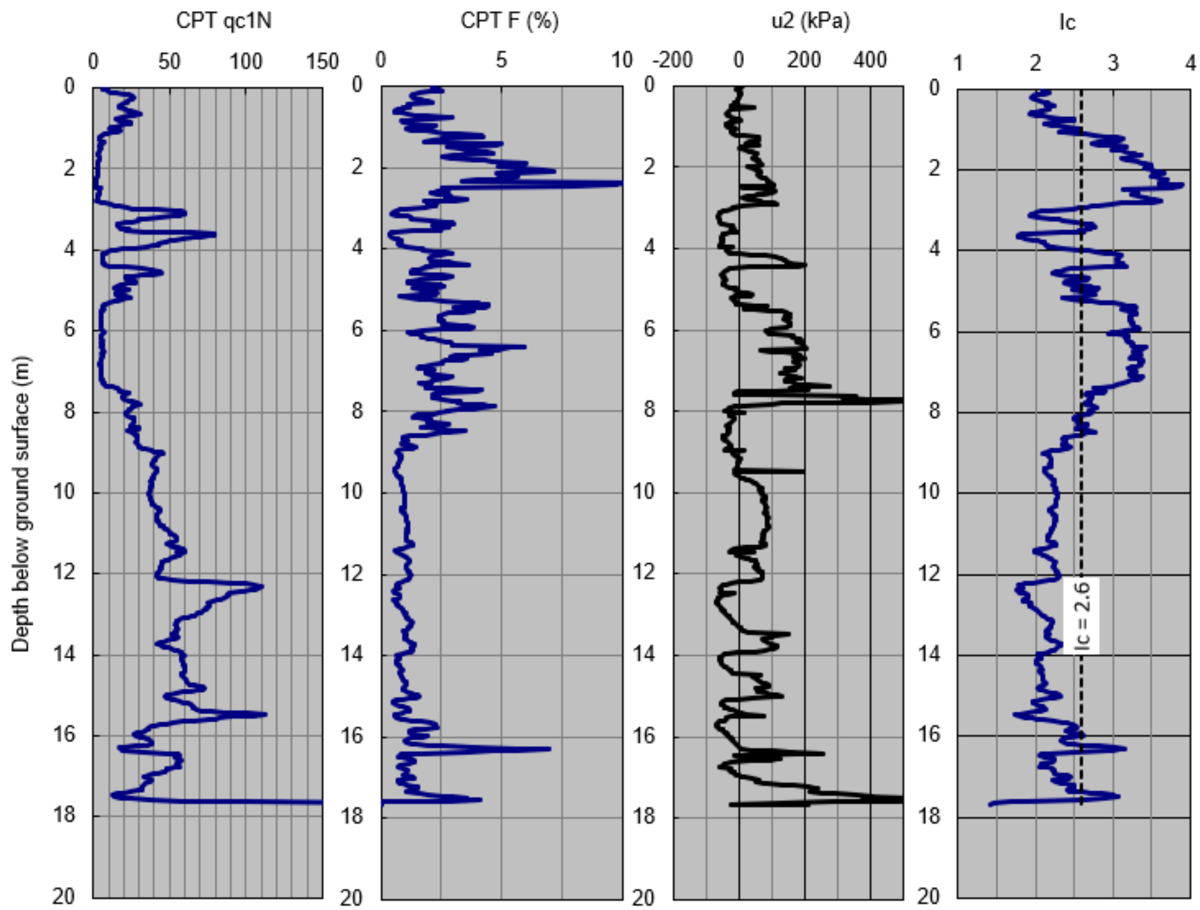


Figure 4-3. *CPT-05 profile from PSU's research site north of the CEI hub (Portland General Electric site). Profiles show two types of QAL soils: clay-like QAL with I_c > 2.6 and sand-like QAL with I_c < 2.6.*

4.2.1 Columbia River Basalt (CRB) and Weathered CRB (WCRB)

The WCRB and CRB units were modeled with elastic models. Therefore, the primary focus of model parameter selection was shear wave velocity. Shear wave velocities (V_s) with depth were estimated with the Roe et al. (2013) data for CRB and WCRB. The V_s data were collected within 30m depth of the surface in the Portland, Oregon area. Although the V_s models for CRB and WCRB in Roe et al. (2013) model Vs increasing with depth, single V_s values were assigned for this project's analyses: 800 m/s for CRB and 300 m/s for WCRB. The V_s of 800 m/s for CRB was consistent with measured values in Roe et al. (2013 and is consistent with the design of M9 motions.

4.2.2 *Fine-grained alluvium (FG-QAL)*

FG-QAL was modeled with PM4Silt. PM4Silt captures the cyclic response, including excess porewater pressure generation, of fine-grained soils with clay-like cyclic softening behavior. The parameters were calibrated with Roe et al. (2013) V_s data and laboratory test data. A summary of the PM4Silt parameters for FG-QAL are in Table 4-2.

Table 4-2. *Selected model parameters for CG-QAL and FG-QAL*

Model Parameter[a]	CG-QAL calibration (PM4Sand)	FG-QAL calibration (PM4Silt)	FIL calibration (PM4Sand)
G_o	650	650	850
G_{exp}	-	0.75	-
h_o	default	0.6	default
h_{po}	0.30	40	0.7
ϕ_{cs}	35	30	default
Dr	0.53	-	0.36
s_u/σ'_v	-	0.354	-
$n_{b,wet}$	-	1.0	

[a] other model parameters use default values

The modeled PM4Sand relationship of small strain shear modulus (G_{max}) with depth is compared against data from Roe et al. (2013) and shown in Figure 4-4. G_{max} relates to V_s and soil density. The relationship of G_{max} versus depth was calibrated to Vs measurements in QAL from O-13-12. The model parameters G_o and G_{exp} were selected to approximate the G_{max} relationship with depth. Since there was no differentiation between coarse-grained and fine-grained QAL in O-13-12, the calibration of the G_{max} versus depth relationship for PM4Silt and PM4Sand was calibrated to be approximately to be consistent.

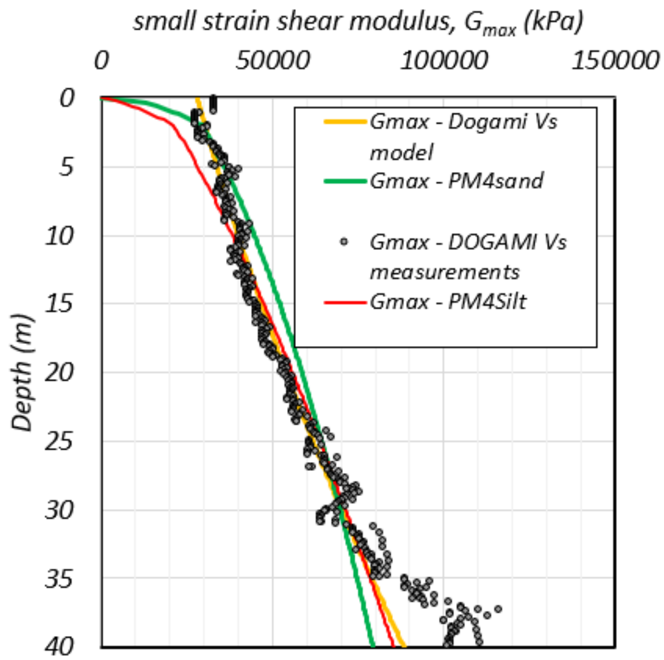


Figure 4-4. *G_{maz} versus depth for QAL unit, including the PM4Silt and PM4Sand calibrated relationships.*

The modulus reduction (G/G_{max}) relationship was calibrated with single element simulations of undrained direct simple shear (UDSS) for selection of parameter h_o. The modulus reduction relationship for PM4Silt parameters was calibrated to agree with Darendelli (2001) relationship for soil with plasticity index (PI) of 15 at 1 atmosphere of overburden stress. This relationship is shown in Figure 4-5 compared with Darendelli (2001) and Vucetic & Dobry (1991) at PI = 0 and 15.

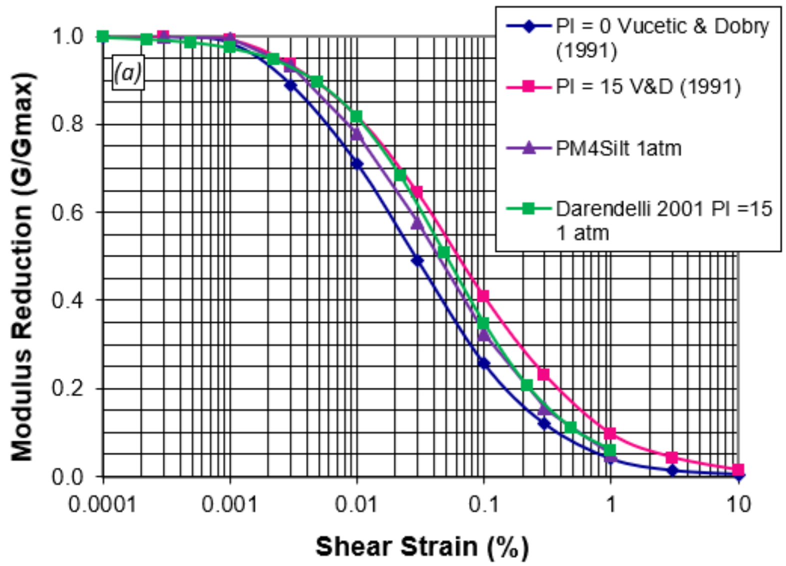


Figure 4-5. *Dynamic calibration for FG-QAL with PM4Silt shear modulus reduction relationship.*

Additional PM4Silt model parameters that control shear behavior and cyclic strength were calibrated to monotonic and cyclic UDSS test results. These tests were performed on fine-grained soils from two sites that are considered to be underlain by similar soils as the CEI hub. The first site (referred to as Terminal 5) is located on the Willamette River, close to the confluence with the Columbia River. The second site is managed by Bonneville Power Administration (referred to as BPA) and is located in North Portland on the Willamette River. The results of undrained shear strength (s_u) normalized by the vertical effective stress at the start of testing (σ'_{vc}) is shown in Figure 4-6. These test results are for initial over consolidation ratio (OCR) values of 1, 2 and 3. The testing at various OCR values allowed a relationship between s_u/σ'_{vc} and OCR to be approximated as shown in Figure 4-6. None of the monotonic UDSS tests displayed peak stress-strain behavior, therefore the model parameter $n_{b,wet}$ was set to 1.0.

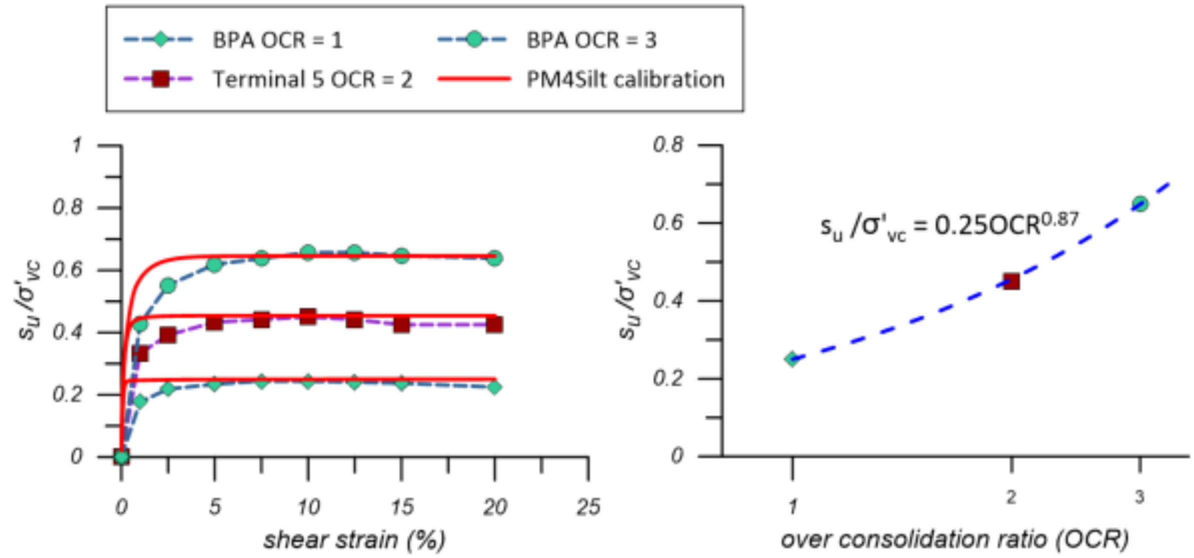


Figure 4-6. *Monotonic undrained direct simple shear test results on FG-QAL soils at OCR = 1, 2, and 3.*

This geologic history throughout the CEI hub suggests normally consolidated to lightly over-consolidated soils since they have not undergone historic loading and unloading. The soils may be lightly overconsolidated due to aging effects. The CPT data for soils with I_c>2.6 were used to interpret OCR, and then estimate s_u/σ_{vc}' based on the relationship to OCR in Figure 4-6. The estimated OCR is 1.5 based on CPT profiles with the Chen & Mayne (1994) relationship between q_t and preconsolidation stress. Therefore, the approximated s_u/σ'_{vc} for the PM4Silt model is 0.354.

The critical state friction angle (ϕ'_{cs}) was approximated as 30 degrees based on monotonic UDSS tests from s_u/σ_{vc}' ratios at high strains in Figure 4-6. The final calibration priority for FG-QAL was to approximate a CRR for a magnitude 7.5 earthquake based on results of cyclic laboratory tests. Results from cyclic UDSS testing from Terminal 5 and BPA sites are shown in Figure 4-7. The cyclic UDSS tests were performed at three OCR levels: OCR = 1, 2 and 3. CRR was approximated as the cyclic shear ratio (CSR) that results in 3% single amplitude shear strain after 15 uniform cycles (N=15) of loading. The model parameter h_{po} was adjusted to approximate the CRR at OCR = 1.5 in Figure 4-7. With an h_{po} value of 40, the simulated CRR at 15 uniform cyclic cycles is about 0.28. The simulated single element calibration results are shown in Figure 4-8.

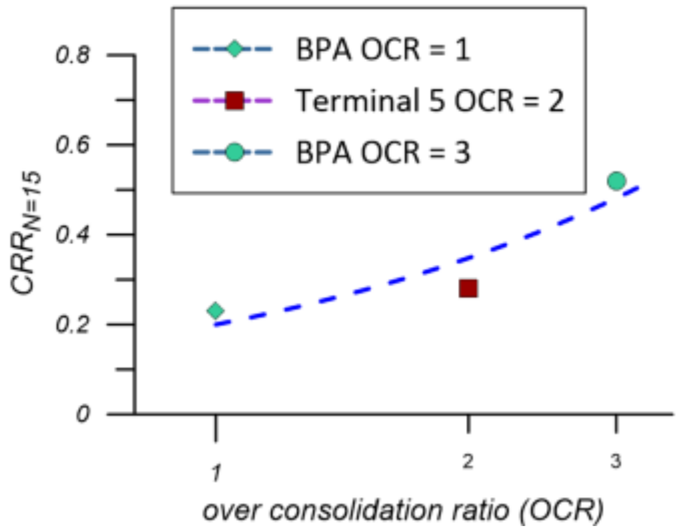


Figure 4-7. *Cyclic UDSS testing at OCR = 1, 2, and 3 from O-08 and O-09 sites.*

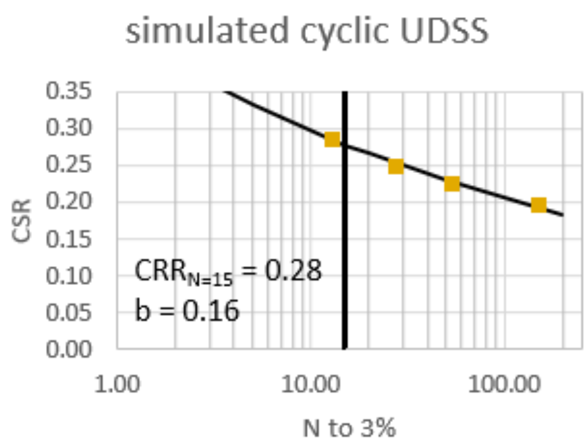


Figure 4-8. *Simulated cyclic UDSS testing with PM4Silt to calibrate model parameter h_{po} for FG-QAL behavior.*

4.2.3 Coarse-grained alluvium (CG-QAL)

Seismic properties of CG-QAL soils, including G_{max} values with depth and G/G_{max}, were calibrated with a similar approach and to similar values as for FG-QAL. The G_{max} relationship to depth is shown in Figure 4-4 and the G/G_{max} relationship is shown in Figure 4-9. The parameters

G_o and h_o were selected to achieve these relationships. The G/G_{max} relationship was calibrated to approximate the relationships for sand characterized in EPRI (1993) and Seed & Idriss (1970).

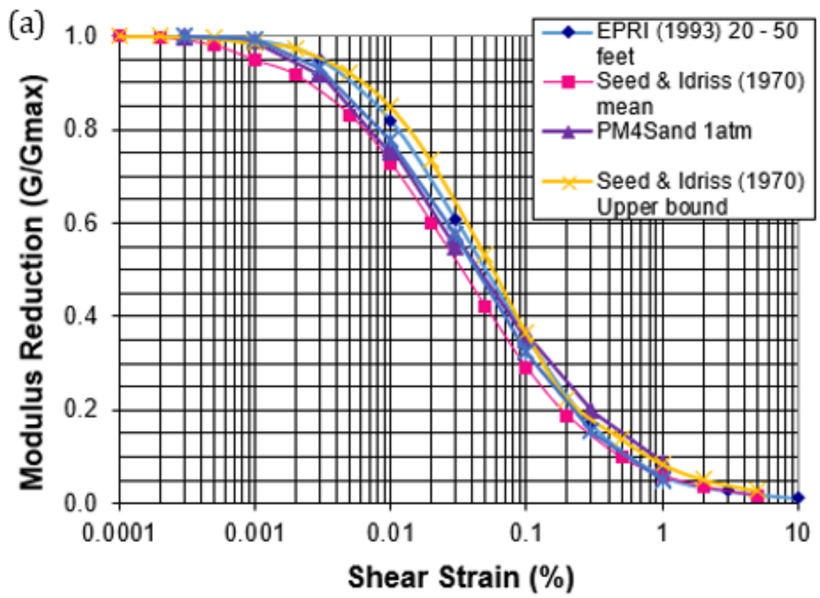


Figure 4-9. *Dynamic calibration for* CG-*QAL with PM4S*and *shear modulus reduction relationship.*

Calibration of cyclic strength behavior of CG-QAL was primarily performed with CPT data since soil-specific laboratory data were not available. Based on 9 CPT profiles from GeoDesign (2016) and Portland State University's study at the PGE site, the sand-like soils of CG-QAL had a representative q_{c1N} value of approximately 60. Additionally, CPTu data indicate an approximately 20% fines content estimated with the Boulanger & Idriss (2016) method. Therefore, q_{c1N} corrected to the equivalent clean sand value ($q_{c1n,cs}$) was approximately 90, which has an equivalent relative density (Dr) of 53% and CRR at magnitude 7.5 of 0.13 based on Idriss & Boulanger (2014). The ϕ_{cs} was estimated as 35 degrees from CPT data, which may slightly over-estimate the actual values. The h_{po} = 0.3 value was selected to have CRR in UDSS single element simulations approximately equal to 0.13. The simulated single element results to 3% single element strain are shown in Figure 4-10.

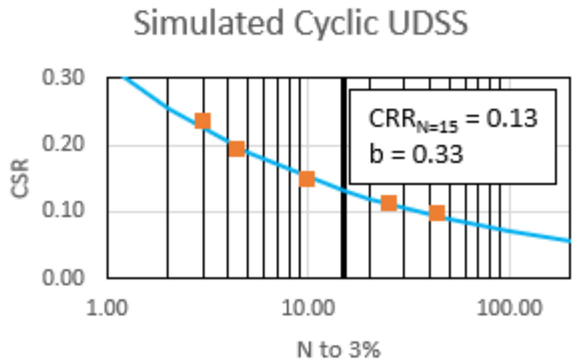


Figure 4-10. *Simulated results from cyclic UDSS with the selected PM4S*and *parameters* for CG-QAL.

4.2.4 Placed Fill (FIL)

For profile B-B' the FIL unit is above the water table, and therefore is not considered to be susceptible to liquefaction. The FIL soil in this profile was modeled with the Mohr-Coulomb and Itasca S3 models. FIL in the D-D' profile does occur below the water table and is considered susceptible to liquefaction and earthquake induced ground deformations. Therefore, a PM4Sand calibration was developed for FIL in the D-D' profile.

The shear modulus for FIL was based on a limited number of V_s data points. Although V_s data for placed fill soils are included in Roe et al. (2013), it was assumed that these data were from various locations in Portland and not exclusively from the CEI hub area. Additionally, Roe et al. (2013) did not distinguish between compacted fill and uncompacted fill. V_s for fill in the CEI hub was approximated from data collected by seismic CPT (SCPT) in GeoDesign (2016) and CH2M Hill (2006) geotechnical report (numbered GT_001453 in O-13-12). These data are summarized in Figure 4-11, along with an approximate best fit of shear wave velocity of 600 feet/s (183 m/s). Based on this shear wave velocity data, the G_o value for the PM4Sand FIL calibration was approximated as 850. This G_o value resulted in a shear wave velocity value of about 180 m/s at about 6m depth, which is approximately the middle of the deepest part of FIL in the D-D' profile.

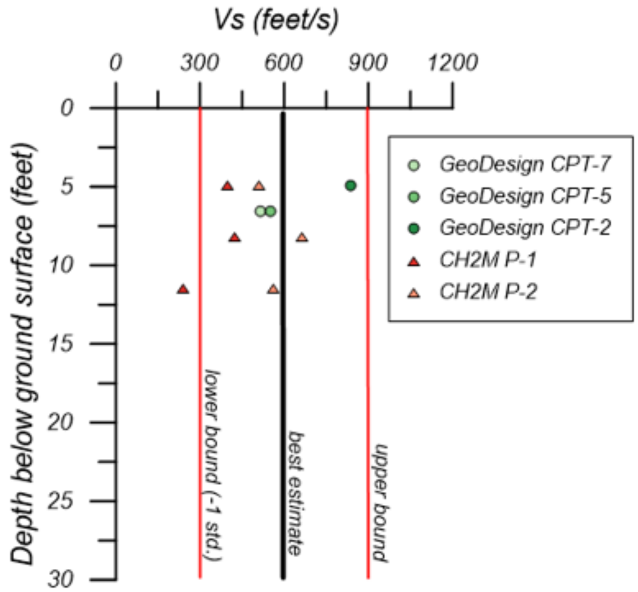


Figure 4-11. *Shear wave velocity (V_s) measurements from FIL in the CEI hub, including the best estimate of V_s for FIL.*

Two CPT profiles, measured near the D-D' profile, were reported in GeoEngineers (1995) report number GT_000311 in O-13-12. These profiles are shown in Figure 4-12 and Figure 4-13. Based on the section of these CPT profiles in FIL, the q_{c1N} is estimated at 52, with an approximate fines content of 10% based on Boulanger & Idriss (2016). Therefore, the equivalent clean sand q_{c1N} ($q_{c1N\text{-}cs}$) is characterized as 62. This $q_{c1N\text{-}cs}$ value corresponds to a relative density of approximately 36%. The h_{po} value was adjusted until a cyclic resistance ratio (CRR) value of 0.10 for a magnitude 7.5 motion was achieved. This CRR value was estimated from the CPT data using Boulanger & Idriss (2016). This calibration to CRR was performed with single element simulations of undrained direct simple shear, as shown in Figure 4-14.

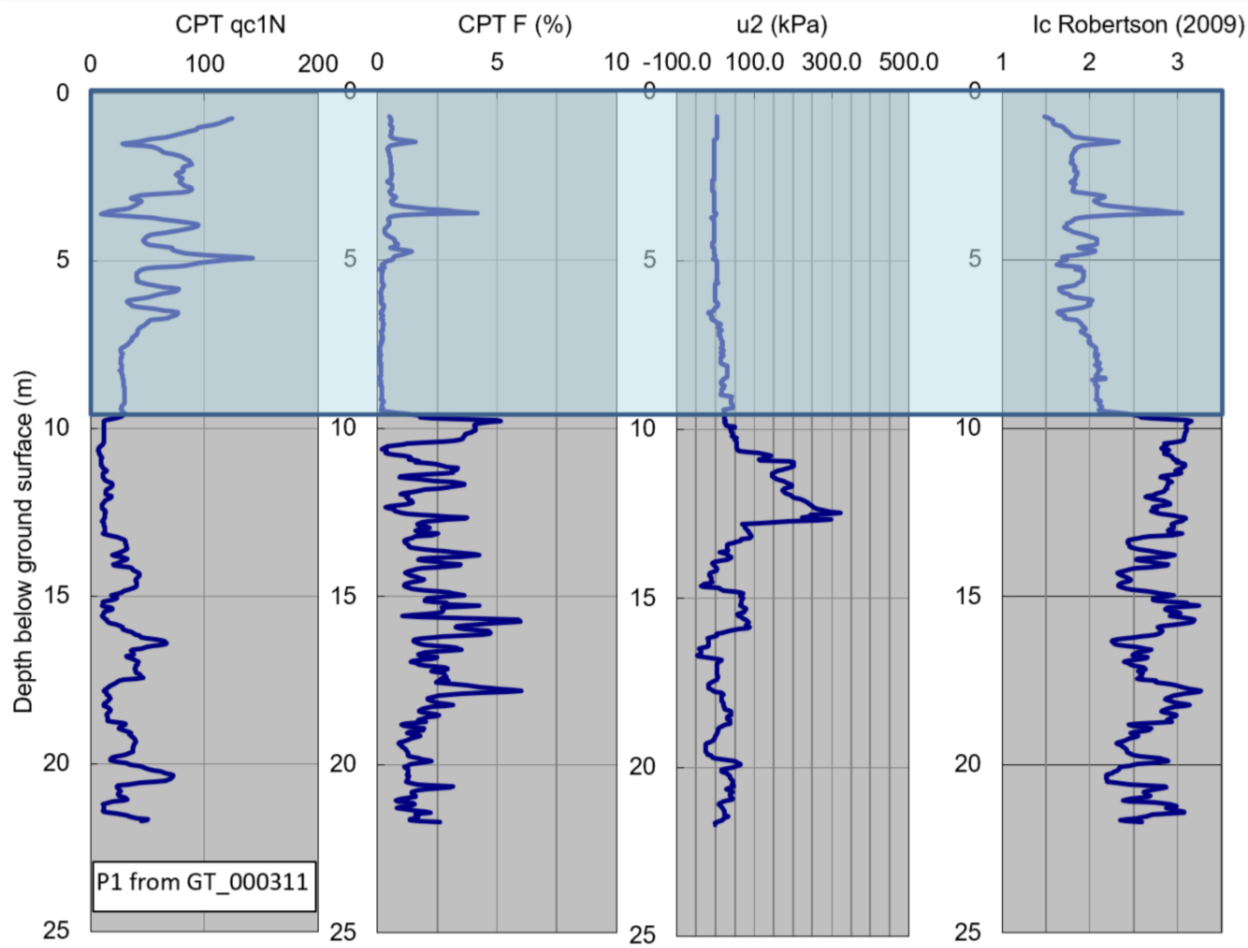


Figure 4-12. *CPT data profile P1 located near profile D-D' with presence of FIL. CPT data from report 000311 (GeoEngineers 1995).*

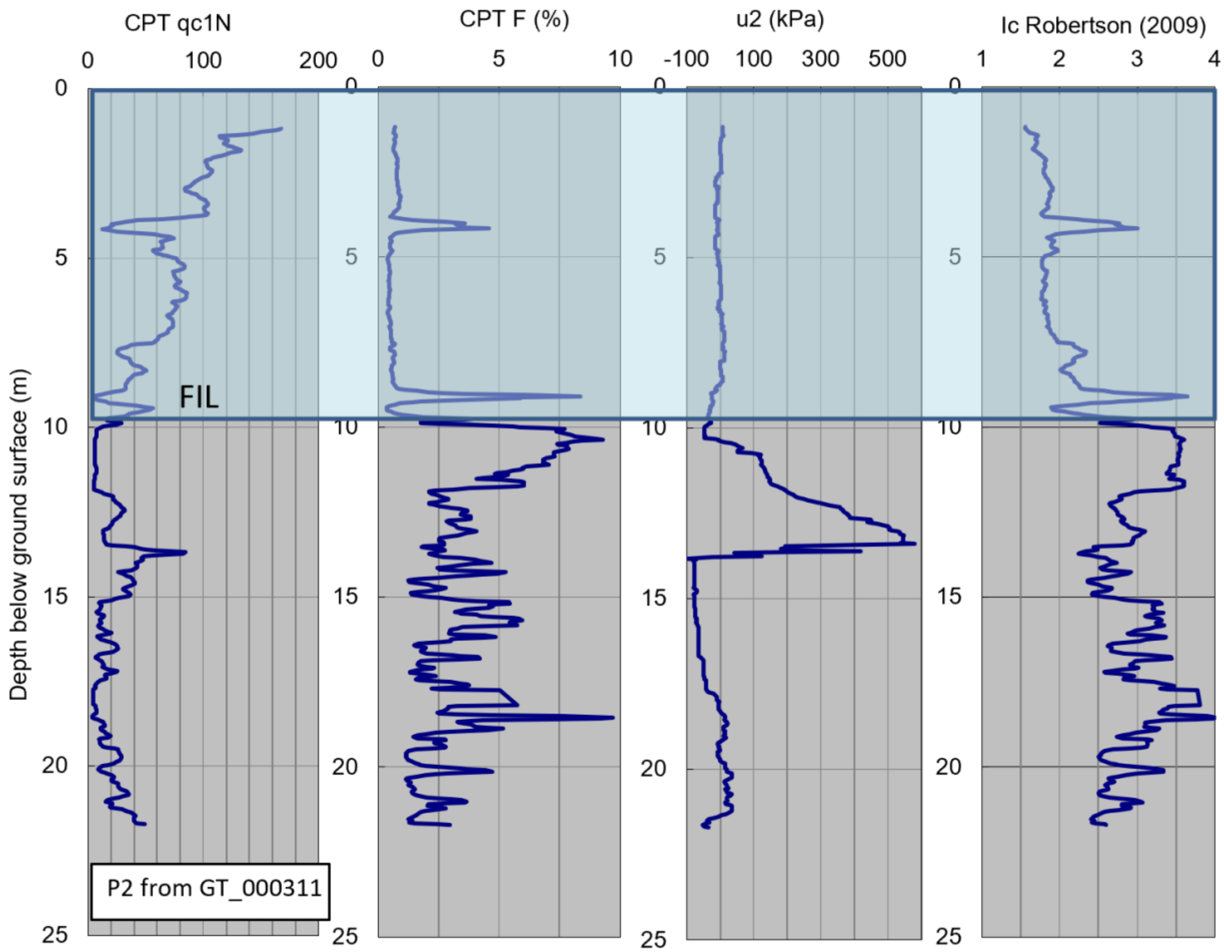


Figure 4-13. *CPT data profile P2 located near profile D-D' with presence of FIL. CPT data from report 000311 (GeoEngineers 1995).*

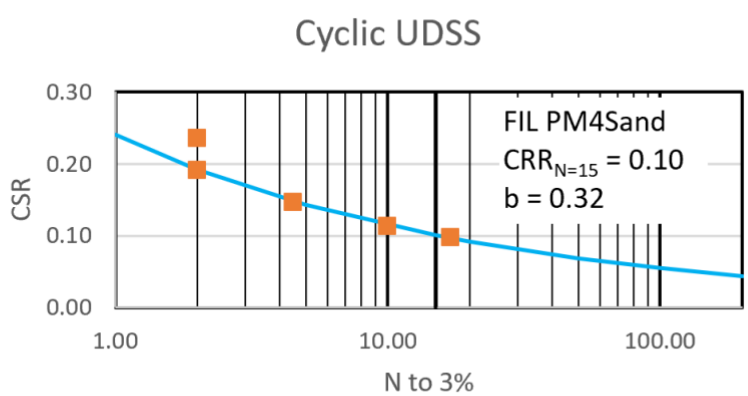


Figure 4-14. *Simulated undrained direct simple shear (UDSS) for calibration of FIL for PM4Sand.*

5 EARTHQUAKE INDUCED GROUND DEFORMATION

Ground deformations from shaking in the CEI hub due to full rupture of the Cascadia Subduction Zone were estimated for two profiles in the CEI hub: B-B', and D-D' as shown in Figure 2-3 and Figure 2-5, respectively. Ground deformations were estimated with 2D NDA analysis. Analysis of profile C-C' will be completed with additional work, however, considering the similarly of profile C-C' to B-B', the deformations in the area are not expected to be notably different.

5.1 Analyses Results

Representative results of the simulation performed on cross section B-B' is presented here as an example for ground motion #5 which represents the median intensity motion among the M9 ground motions. While the analyses were performed using both fine grained and course grained assumptions to simulate the cyclic behavior of the alluvium unit, the example presented here is for the case where the alluvium unit was modeled assuming course grained behavior (CG-Qal) subjected to sand-like liquefaction. It is important to note that this assumption resulted generally in larger deformations compared to the case where the alluvium was modeled using fine grained, clay-like behavior.

Figure 5-1a shows contours of excess pore pressure ratios (defined as excess pore pressure due to cyclic loading at the end of motion normalized by initial vertical effective stress). For clarity, the contours are shown for the regions closer to the slope by the Willamette River. The soil units are shown as a reference. The contours show that the pore pressure ratios range between 50% to 100% within the alluvium unit. Figure 5-1b shows the time history of pore pressure build up for Point A as an example. The softening associated with the excess pore pressure results in accumulation of large shear strains within the soil. Figure 5-1c shows the contours of maximum shear strain increments (indicative of the accumulated shear strains in the soils) which illustrates the location of subsurface failure zones that develop due to cyclic loading. Figure 5-1d shows the shear stress - shear strain loops during the ground motion at Point A as an example. The softened response of soil and the accumulation of shear strains up to 40% is due to high excess pore pressures. Figure 5-1e shows the contours of permanent lateral ground deformations at the end of shaking. Lateral displacements are the largest at the top of the slope close to the free face and decrease as we move inland away from the slope. Figure 5-1f shows the time history of lateral ground deformations at Point B which is located approximately 10 meters from the top of the slope.

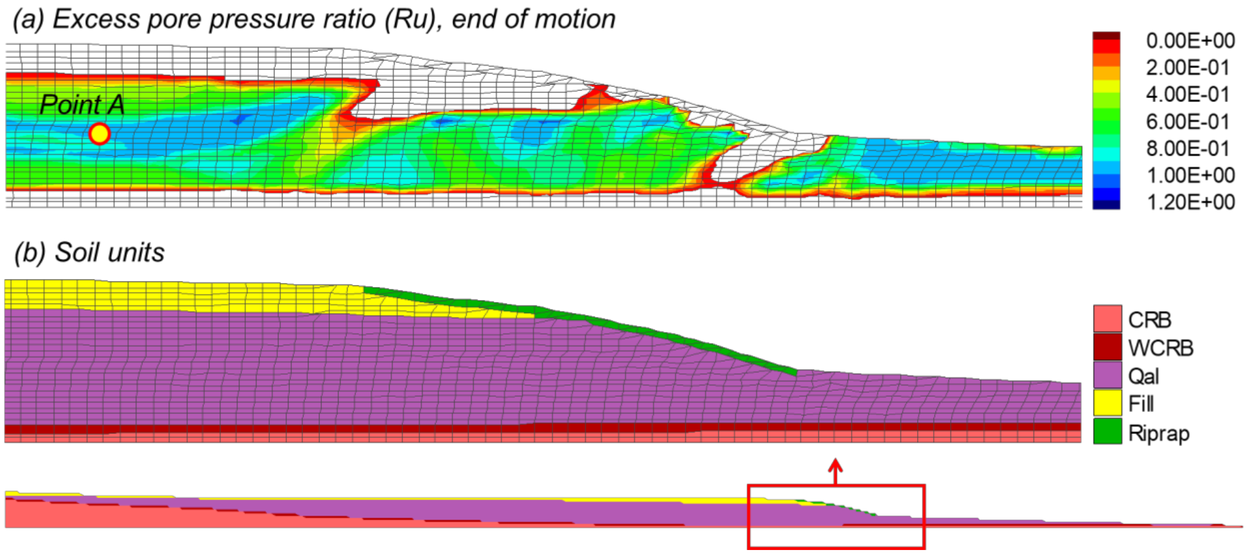


Figure 5-1a: *(a) Contours of excess pore pressure ratios at the end of ground motion #5 in Profile B-B' obtained from 2D nonlinear dynamic analysis in FLAC, and (b) soil units*

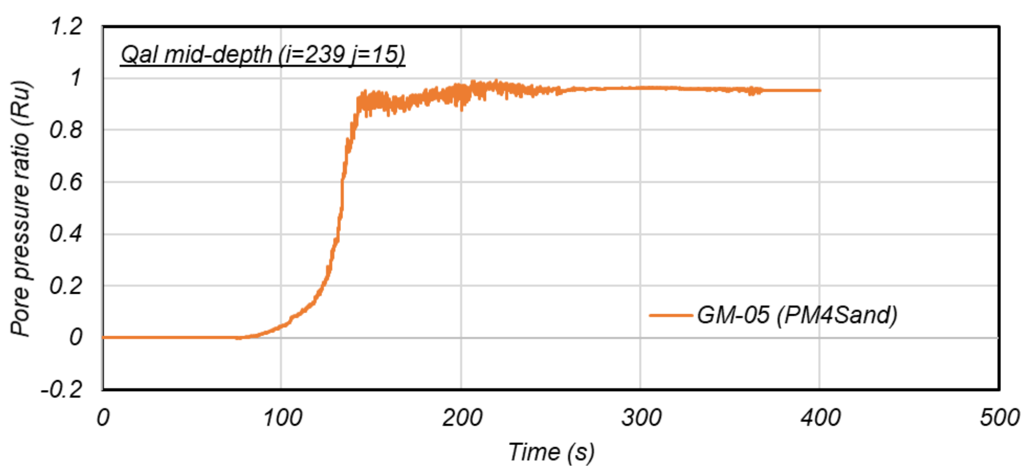


Figure 5-1b: *Time history of excess pore pressure ratio for Point A within the alluvium unit in Profile B-B' during ground motion #5*

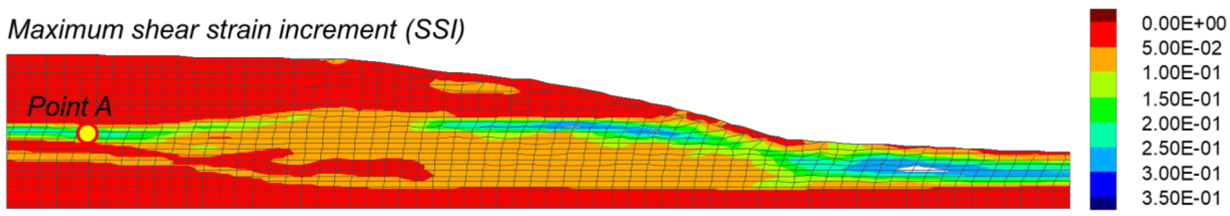


Figure 5-1c: *Contours of maximum shear strain increment at the end of ground motion #5 in Profile B-B' obtained from 2D nonlinear dynamic analysis in FLAC*

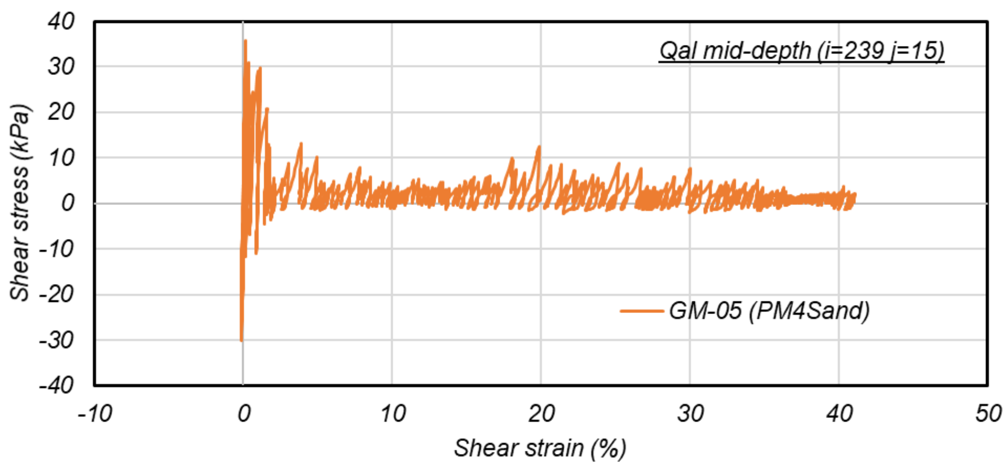


Figure 5-1d: *Shear stress versus shear strain for Point A located within the alluvium unit in Profile B-B' during ground motion #5*

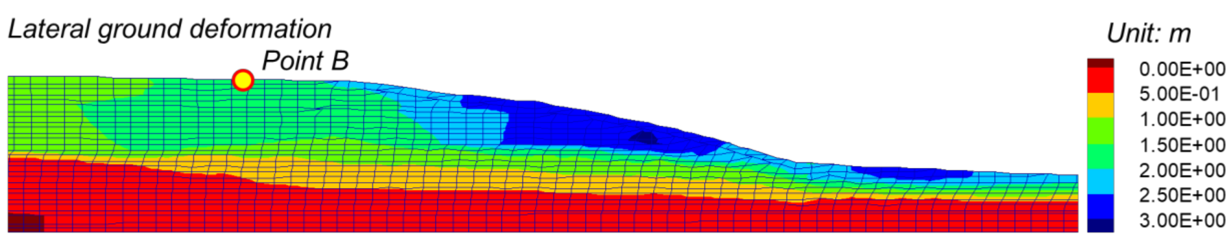


Figure 5-1e: *Contours of lateral ground deformation at the end of ground motion #5 in Profile B-B' obtained from 2D nonlinear dynamic analysis in FLAC*

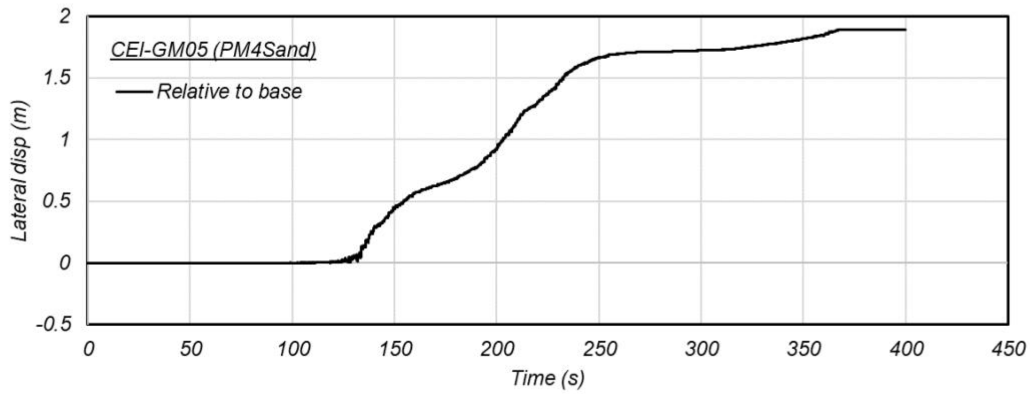


Figure 5-1f: *Time history of lateral ground deformation at Point B in Profile B-B' during ground motion #5*

5.2 Ground Deformations

5.2.1 Ground Settlement

Ground settlement was estimated as the amount of post-liquefaction reconsolidation settlement. Post-liquefaction reconsolidation settlement was estimated from the simulated maximum shear strains during earthquake loading in the FLAC 2D model using the Yoshimine et al. (2006) relationship between volumetric strain, relative density, and maximum shear strain. These maximum shear strains were recorded for the simulations at three profile locations for the model, as indicated by B1, B2, and B3 in Figure 2-3, and D1, D2, and D3 in Figure 2-5. Representative results for a simulation with CG-QAL are shown in Figure 5-1 from a simulation loaded by GM05. The maximum shear strain is concentrated between 14 and 21 m depth. Settlements estimated for CG-QAL with GM05 at the B3 location are estimated to be about 0.23 m.

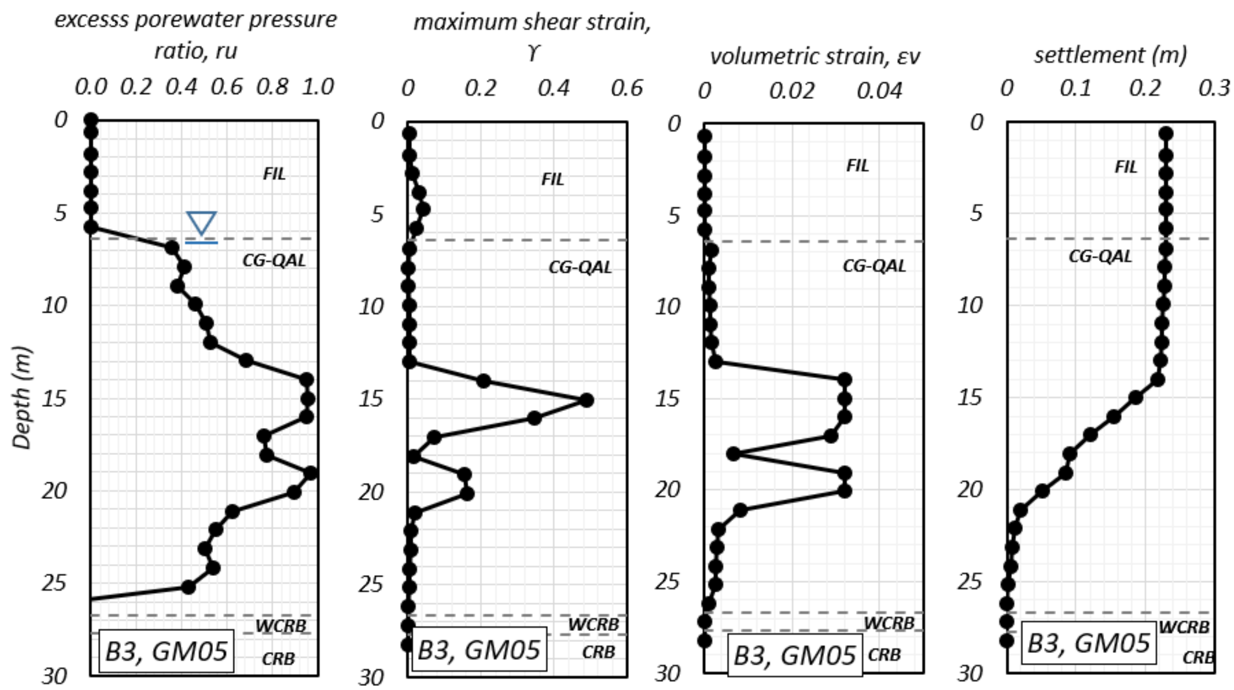


Figure 5-1. *Post-liquefaction reconsolidation settlement estimates at location B3 with coarse-grained QAL and loading from GM05.*

Settlement for soils with FG- QAL was also estimated from a relationship between excess pore pressure ratio (r_u) at the end of shaking and volumetric strain. This relationship was characterized in Wijewickreme et al. (2019) through a study on fine-grained soils. The relationship between post-cyclic loading consolidation and r_u is shown in Figure 5-2.

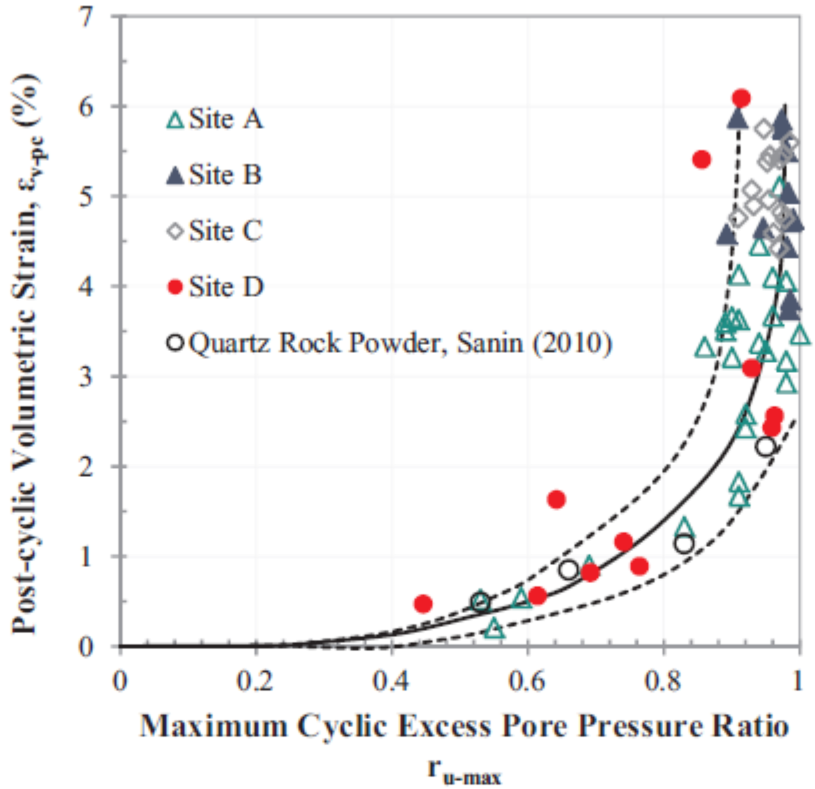


Figure 5-2. *Data of post-cyclic volumetric strain vs. excess pore pressure ratio for fine-grained soils (from Wijewickreme et al. 2019).*

Estimates for post-liquefaction reconsolidation settlement at location B3 for the case of FG-QAL loaded with GM05 are shown in Figure 5-3. The estimates with Yoshimine et al. (2006) and Wijewickreme et al. (2019) are comparable and show that small levels of settlement (less than 6 cm) are expected for this case.

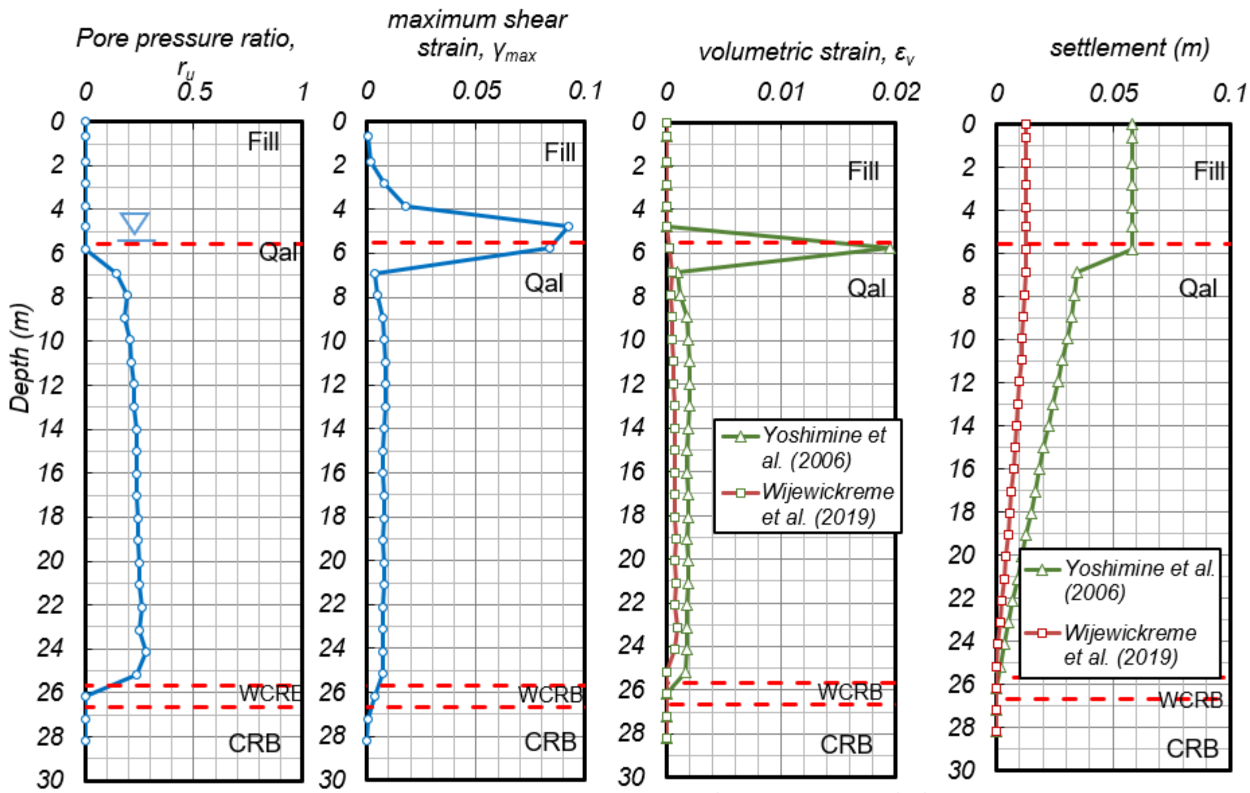


***Figure 5-3.** Post-liquefaction consolidation settlement estimates at location B3 with fine-grained QAL and loading from GM05. Settlement estimated with maximum shear strains with Yoshimine et al. (2006), and final excess pore pressure ratio with Wijewickreme et al. (2019).*

An example of the profiles for settlement estimates for D1 are shown in Figure 5-4. The analyses for D-D' and D1 indicate that the FIL unit is a concern for earthquake-induced liquefaction and post-liquefaction consolidation settlement. The profiles indicate that CG-QAL and FIL for this profile are susceptible to excess pore pressure generation up to 100%.

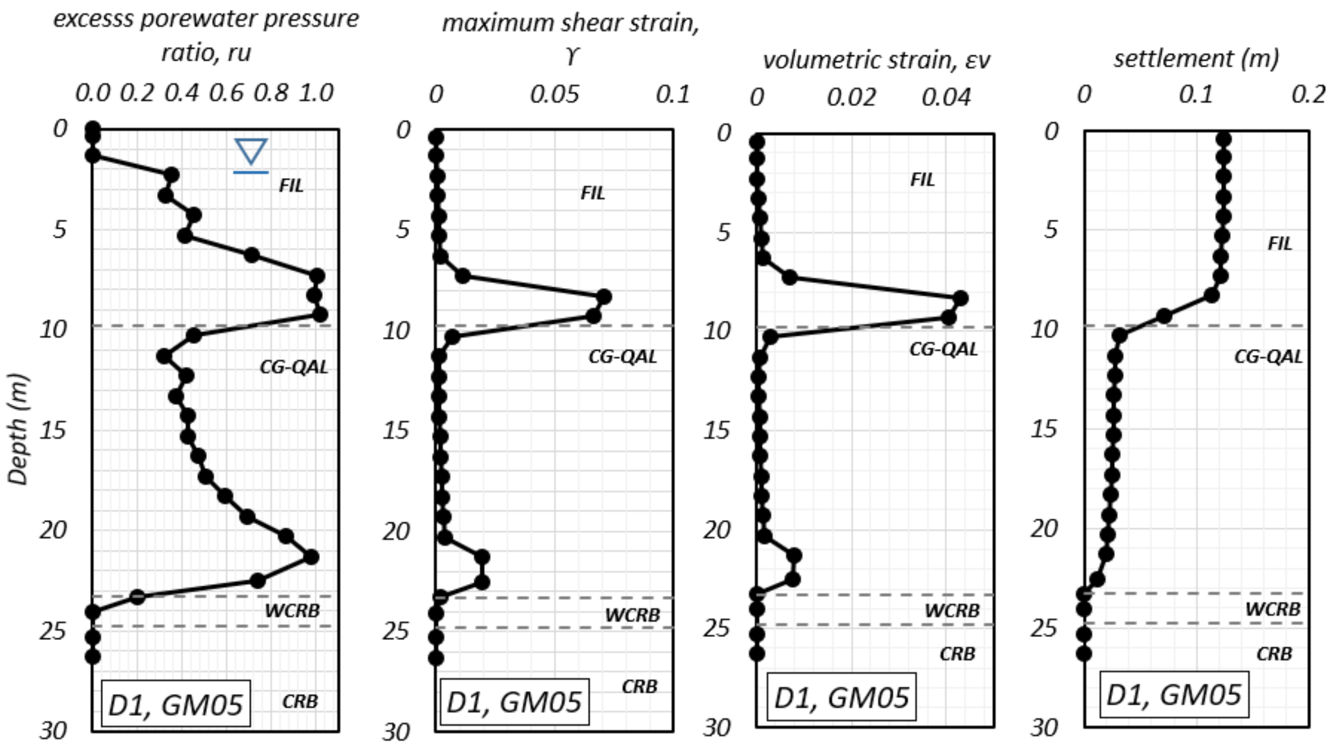


Figure 5-4. *Post-liquefaction consolidation settlement estimates at location D1 with coarse-grained QAL and loading from GM05. Settlement estimated with maximum shear strains with Yoshimine et al. (2006).*

The summary of estimated post-liquefaction consolidation settlements at B1, B2 and B3 are shown in Figure 5-5 for a site composed of FG-QAL and Figure 5-6 for CG-QAL. Since CG-QAL appeared to be the soil unit most susceptible to ground deformations for profile B-B', the settlement analysis at profile D-D' was prioritized for CG-QAL. The estimates of post-liquefaction consolidation settlement at D1, D2 and D3 are shown in Figure 5-7 for CG-QAL. A summary of underlying stratigraphy and average estimated settlement for each profile location is provided in Table 5-1.

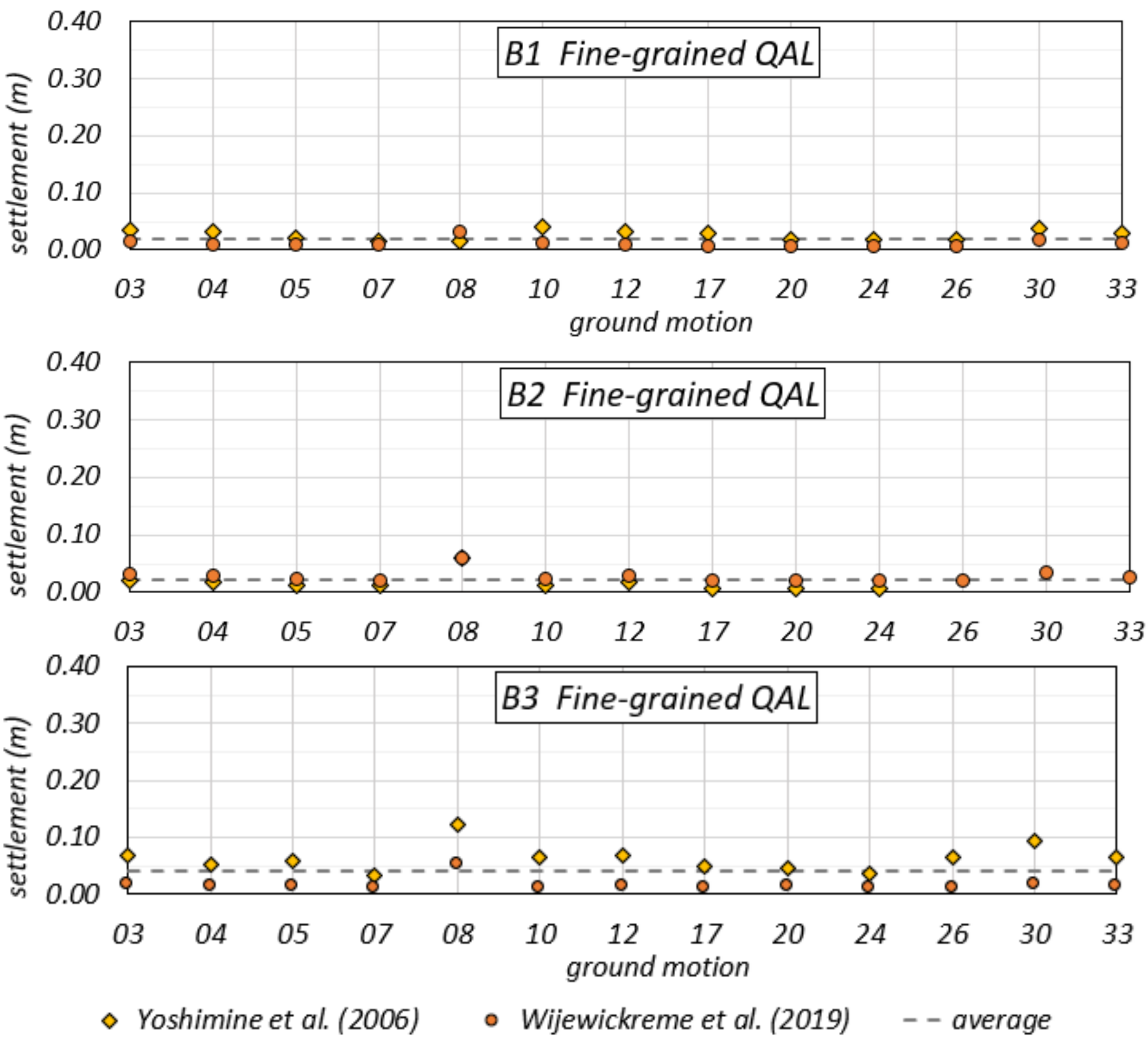


Figure 5-5. *Post-liquefaction consolidation settlements estimated at locations B1, B2, and B3 in profile B-B' for* FG-*QAL. Settlement estimated with maximum shear strain from 2D analysis with Yoshimine et al. (2006) and final excess pore pressure ratio with Wijewickreme et al. (2019) methods.*

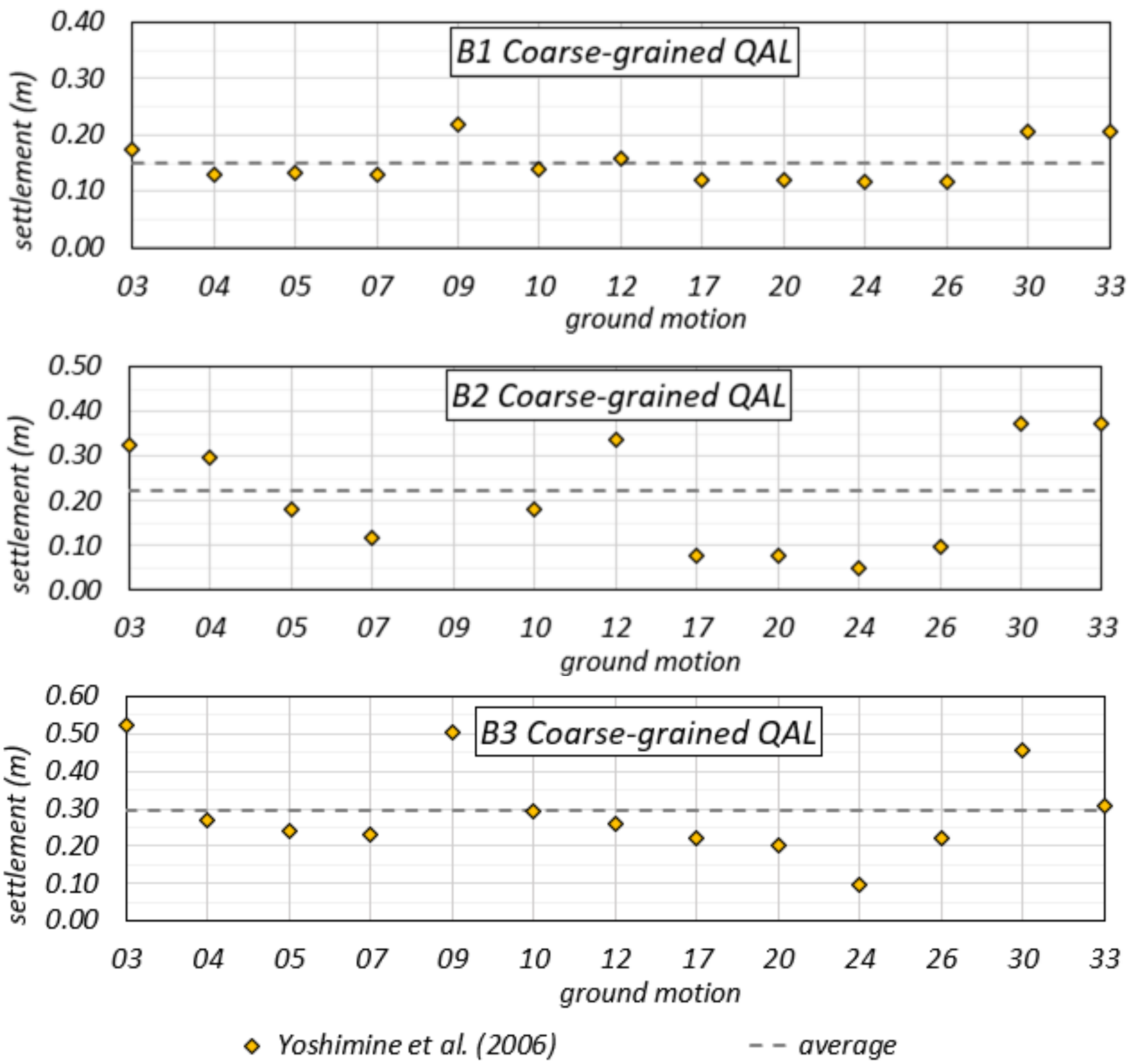


Figure 5-6. *Post-liquefaction consolidation settlements estimated at locations B1, B2, and B3 in profile B-B' for* CG-*QAL. Settlement estimated with maximum shear strain from 2D analysis with Yoshimine et al. (2006) method.*

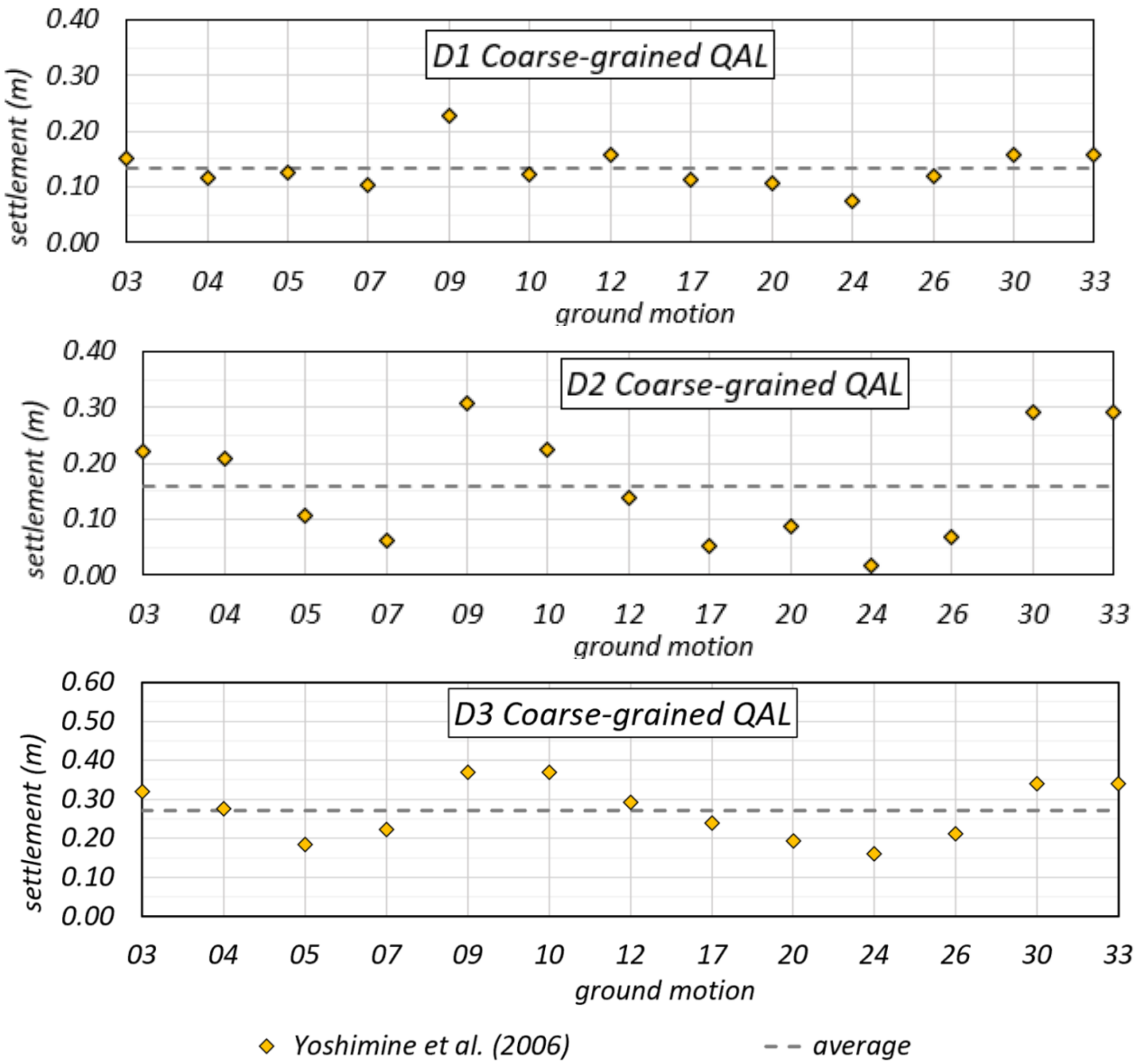


Figure 5-7. *Post-liquefaction consolidation settlements estimated at locations D1, D2, and D3 in profile D-D' for* CG-*QAL. Settlement estimated with maximum shear strain from 2D analysis with Yoshimine et al. (2006) method.*

__Table 5-1.__ Summarized settlements estimated from 2D NDA analysis at profiles B-B' and D-D'.

Profile Location	Approximate FG-QAL beneath water table thickness (m)	Approximate CG-QAL beneath water table thickness (m)	Approximate FIL beneath water table thickness (m)	Estimated post-liquefaction consolidation settlement[a] (m)
B1	-	8	0	0.15
	8	-	0	0.02
B2	-	20	0	0.22
	20	-	0	0.02
B3	-	20	0	0.29
	20	-	0	0.04
D1	-	12.5	8	0.13
D2	-	15.8	1.5	0.16
D3	-	12.4	0	0.27

[a]average settlement estimate based on 13 simulated ground motions

Sites with underlying CG-QAL and FIL appear to be the most vulnerable to liquefaction and post-liquefaction consolidation settlements. The CG-QAL soils appear susceptible to excess porewater pressure build up during earthquake loading, leading to liquefaction and post-liquefaction consolidation settlement. The estimated settlements for the locations underlain by CG- QAL range from 0.15 to 0.29 m for CG-QAL thicknesses of 8 m to 29 m, respectively.

5.2.2 Lateral Deformation

Lateral ground deformation was estimated for profile B-B' and D-D' with 2D NDA analysis. These deformations were interpreted directly from the displacements in the analysis results. The earthquake-induced lateral deformations at profile B-B' with CG-QAL are shown in Figure 5-8. Lateral deformations appear to be a concern throughout the B-B' profile. This appears to be due to lateral deformations towards the river free face (located at approximately 750m on the profile in Figure 5-8) and from the slightly sloping ground (up to 2% grade) between about 0m and 250 m on the profile. The results estimate lateral deformations between 1m (GM24) and 6m (GM30) at the river free face. The deformations decrease away from the free face to between 0m (GM24) and 2.5m (GM09), then may increase due to slightly sloping ground to between 0.5m (GM24) and 3.5m (GM30 and GM09).

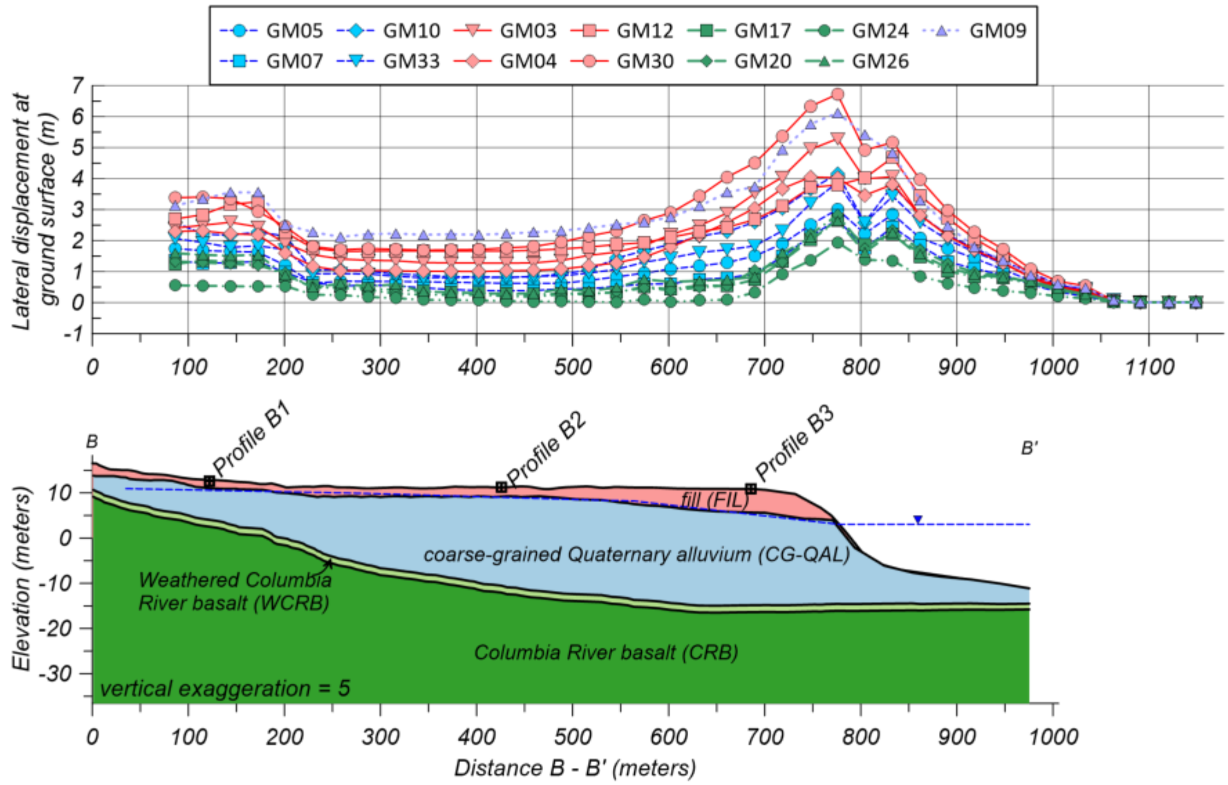


Figure 5-8. *Simulated lateral deformations for profile B-B' with coarse-grained QAL.*

Lateral deformations were also simulated for profile B-B' with FG-QAL. The simulated lateral deformations are plotted in Figure 5-9. Lateral deformations primarily occur at the river free face and are estimated to be between 1 m (GM24, GM26, GM20, GM17) and 2 m (GM30 and GM09). Lateral deformations appear to be negligible by approximately 150 m inland from the free face (600 m on the B-B' profile). There appears to be very small potential lateral deformations due to slightly sloping ground between 0m and 250m on the profile, with deformations mostly below 0.5 m.

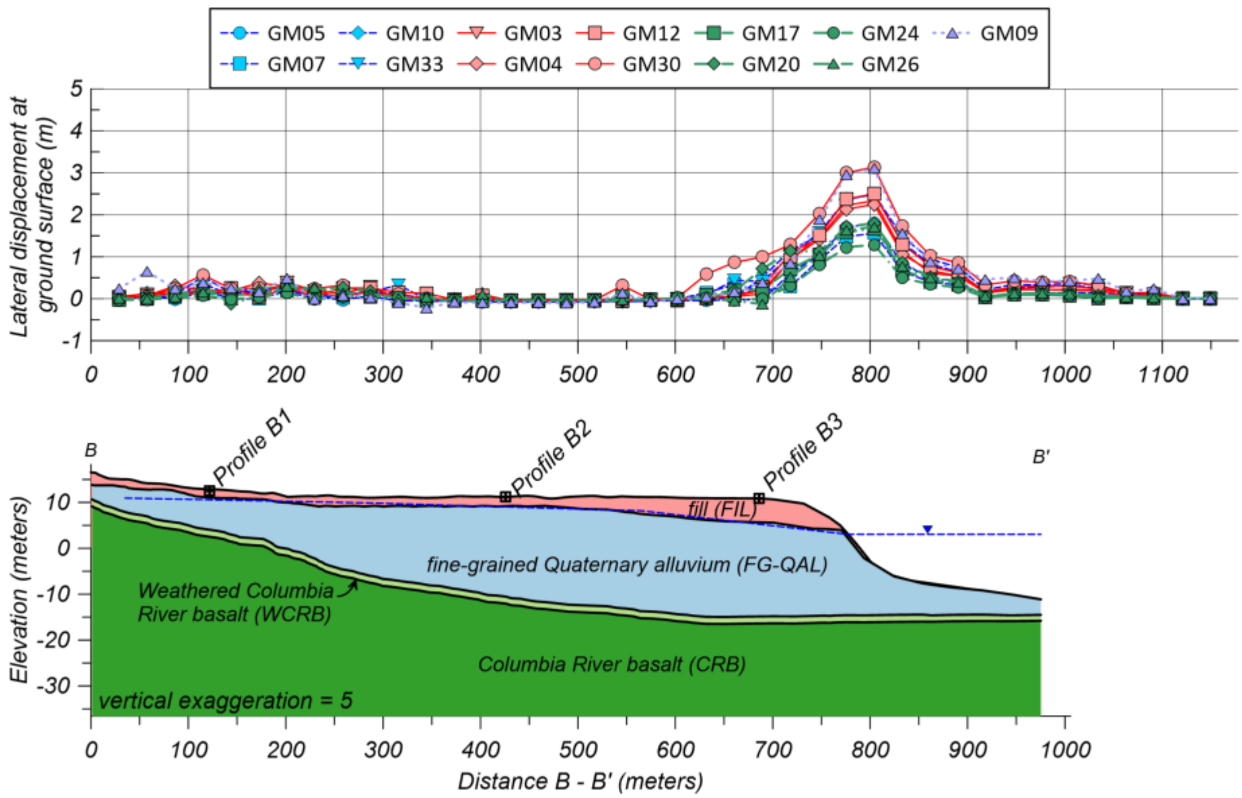


Figure 5-9. *Simulated lateral deformations for profile B-B' with fine-grained QAL.*

The earthquake-induced lateral deformations at profile D-D' with CG-QAL are shown in Figure 5-10. The results estimate lateral deformations between about 1m (GM24) and 6m (GM09) at the river free face (estimated at 725m on the D-D' profile). Lateral deformations decrease away from the free face and are reduced to what appear to be negligible amounts by 425 m from the river free face (about 300m on the D-D' profile).

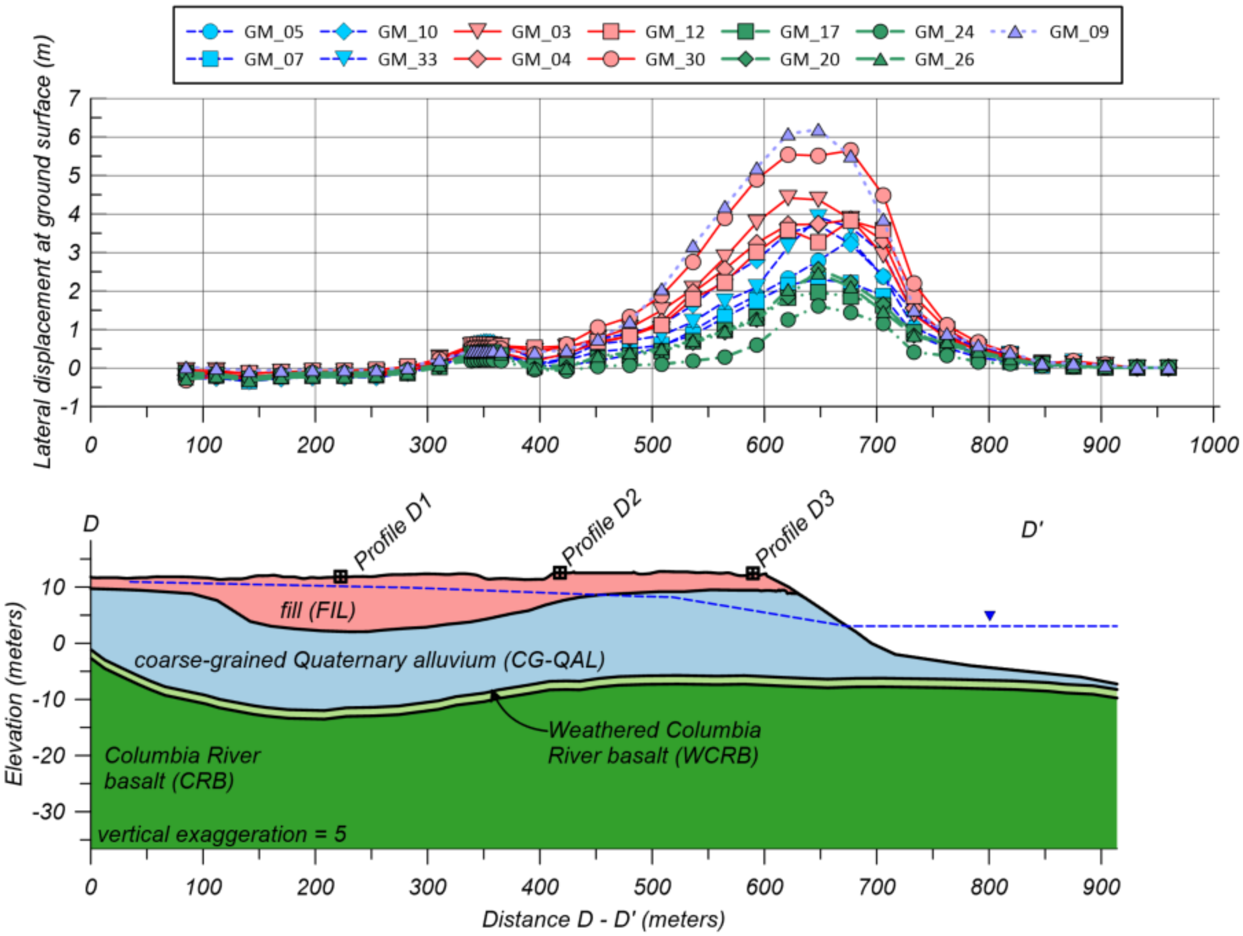


Figure 5-10. *Estimates of lateral ground deformations at profile D-D' with coarse-grained QAL based on 2D NDA.*

It is estimated that lateral deformations at D-D' for FG-QAL will be notably less than the estimated amounts with CG-QAL. Although the estimated lateral deformations are likely notably less for FG-QAL than CG-QAL throughout the CEI hub, the FG-QAL deformations are still capable of causing infrastructure damage. Ground improvement methods might be considered to mitigate earthquake-induced ground deformation hazards to infrastructure in the CEI hub, with particular focus on lateral deformations near the river free face.

6 MITIGATION OF GROUND DEFORMATION

The 2D NDA analysis indicates that lateral deformations are a primary geohazard concern for a CSZ event in the CEI hub, particularly when CG-QAL is present. A set of 2D NDA with CG-

QAL were performed for profile B-B' with some areas of CG-QAL replaced with cement deep soil mixing (CDSM).

CDSM is a ground improvement technique where a section of soil approximately 2m wide is strengthened by mixing it with a binding agent (e.g., cement, flyash). CDSM at the CEI hub would be expected to run parallel to the Willamette River. The bottom depth of the CDSM units depend on the thickness of the alluvium soils. The CDSM grid simulated in this study is assumed to be 45 m wide with an area replacement ratio of 30%. The primary objective of CDSM is to reduce the consequence of liquefaction in terms of ground deformations.

Ground improvement options in the CEI hub are relatively limited. The methods are limited because there few options for ground improvement with silts (similar to FG-QAL) or sands with fines content (similar to CG-QAL). Additionally, there are few ground improvement methods that can be applied beneath existing structures such as the fuel storage tanks. CDSM can be used for soils with fines, and it can be applied over a large area with the aim of limiting ground deformations over large areas of the CEI hub. Jet grouting, where soil columns up to about 4.5m in diameter are formed through high-pressure injection of concrete through the soil profile, similarly strengthens soil and can be applied beneath existing structures. However, jet grouting is more costly than CDSM (Condon Johnson, personnel communication). Ground improvement options, including CDSM and jet grouting, should be further explored to understand ground improvement options for the CEI hub.

The effect of CDSM on lateral deformations was examined by replacing sections of soil along profile B-B' with material that approximates a soil-cement mixture. The sections were assigned a strength of approximately 510 kPa. This strength accounts for the initial soil-cement mixture strength (about 1700 kPa), with a 30% reduction that accounts for the area replacement ratio. CDSM sections were simulated near the edge of the Willamette River (called CDSM1), and about 250 m from the river's edge (called CDSM2)

The profile B-B' with CDSM improvements was subjected to GM05. Lateral displacements with CDSM1, and with CDSM1 and CDSM2 were compared to the case with no ground improvement. The results are summarized in Figure 6-1 across profile B-B'.

The simulated results indicate that there is likely a reduction in lateral spreading near the river's edge when soil is improved near the river at location CDSM1. This appears to reduce lateral deformations inland from the CDSM section (essentially, to the left of CDSM1 in Figure 6-1) from about 1m to about 0.25m. Including CDSM2 in the simulations do not appear to affect lateral deformations.

CDSM at equivalent CDSM1 locations throughout the CEI hub might reduce earthquake induced lateral deformations due to movement towards the river free face. This may be an option to reduce ground deformations in areas where several fuel storage tanks and additional infrastructure are located within about 300 m of the river's edge.

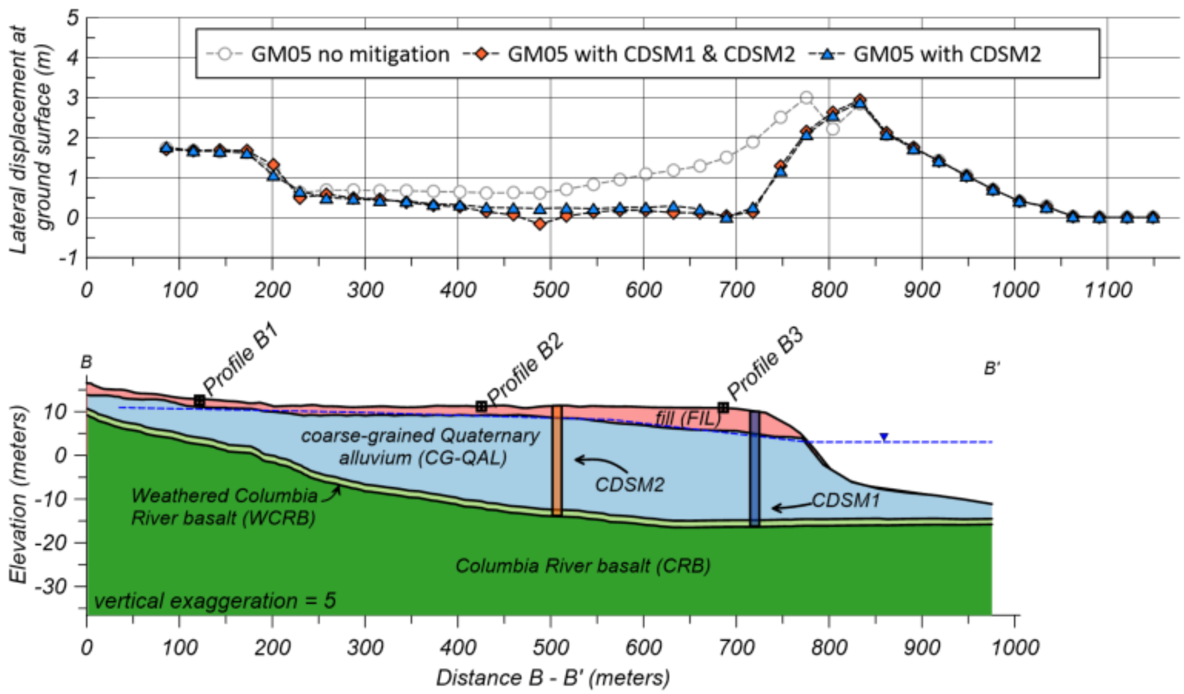


Figure 6-1. *2D NDA simulation results from GM05 at B-B' profile with CG-QAL. Simulations were run with ground improvement via cement deep soil mixing (CDSM) at one location (CDSM1) and at two locations (CDSM1 & CDSM2).*

7 OBSERVATIONS FROM RESULTS OF GROUND DEFORMATION ANALYSES

The analyses presented herein indicate that earthquake-induced ground deformations will be a primary concern in the CEI hub. Ground deformations due to a magnitude 9 Cascadia

Subduction Zone earthquake were evaluated for two soil profiles in the CEI hub through 2D non-linear deformation analysis. The analyses relied upon geologic and geotechnical data from various sites along the Willamette River, and published geologic reports. The analysis looked at how the presence of fine-grained or coarse-grained alluvial soils affect earthquake hazards using two different soil model calibrations. Analyses were performed for high water table levels, that represent annual winter conditions. Synthetic ground motions from the M9 project were used to simulate earthquake loading in the Portland area from a full Cascadia Zone Rupture.

The analyses looked at ground deformations due to post-liquefaction consolidation settlement and earthquake-induced lateral ground deformations. The levels of ground deformation appear to primarily depend on earthquake ground motions, soil types that are present, distance from the free face of the Willamette River, thickness of alluvial and placed fill soils, and ground slope. Post-earthquake consolidation settlement is expected to be up to about 0.30m for locations that are underlain by coarse-grained alluvial soils (CG-QAL) and uncompacted fill (FIL). Settlements will be larger where QAL and FIL beneath the water table is thickest. Locations underlain by fine-grained QAL (FG-QAL) with no FIL beneath the water table are expected to produce post-liquefaction consolidation settlements up to about 0.05m.

Earthquake-induced lateral deformations are expected to be large near the free face of the Willamette River edge for both FG-QAL and CG-QAL soils, with deformations likely being larger when CG-QAL is the dominant soil type. This analysis indicates that fuel infrastructure located within approximately 300m of the free face, and infrastructure located on or near slightly sloping ground will be especially vulnerable to earthquake-induced lateral deformations. Lateral deformations may be between 1m and 7m when underlain by CG-QAL, and up to 3m when underlain by FG-QAL.

The hazards due to earthquake induced ground deformations may be mitigated through ground improvement techniques. Application of ground improvement will be limited due to the presence of fine-grained soil types and existing structures. Cement deep soil mixing over distances close to the Willamette River edge may mitigate some of the hazard of liquefaction-induced lateral deformations. Analyses of this mitigation near the river free face showed lateral deformations near the river free face are reduced to less than 0.5m inland from the mitigation effort.

8 LIQUID PRODUCT STORAGE FACILITIES

All facility information used to develop the database was procured using the most recent versions of official Facility Response Plans (FRP) on file with the Oregon DEQ, including: tank dimensions, ages, contents and capacities; secondary containment; and facility layouts. FRPs were obtained for the following facilities: Kinder Morgan Linnton, Kinder Morgan Willbridge, Chevron Willbridge, Zenith Energy Terminals, McCall Portland Terminal, Nustar Portland Terminal, Phillips 66, Pacific Terminal Services, Trans Montaigne, and Tidewater Industrial Center. Note that Tidewater Industrial Center of Vancouver, WA data is included in this analysis, though it is the only facility not located in what has been referred to as the CEI Hub on the Willamette River.

8.1 Storage Tanks

Only those tanks identified as having maximum capacities greater than 100,000 gallons are included in the database, and thus the database represents only a portion of the available tanks, but over 98% of the liquid products. Any gaps in the tank data regarding average capacity were addressed using an assumption of 76% maximum capacity, based on the aggregate average value of established data; this is particularly important for the Phillips 66 data, for which no recorded average capacity exists in the documentation. Locations for individual tanks were cross-referenced using aerial imagery to produce GIS map features with as much accuracy as possible. Figures 8.1 and 8.2 show an overview of the CEI Hub and the liquid product storage facilities (excluding Tidewater Industrial Center).

8.2 Pipelines

Information for the Kinder Morgan Energy Pipeline, Olympic Pipeline, and Portland Airport Pipeline procured via the most recent versions of official FRPs on file with the Oregon DEQ, in addition to Oregon DOT, Energy Information Administration, and City of Portland. Pipeline routes mapped using established pump station locations, city building ordinance specifications, existing pipeline layouts, and aerial imagery. Any gaps in the established pipeline routes were estimated visually.

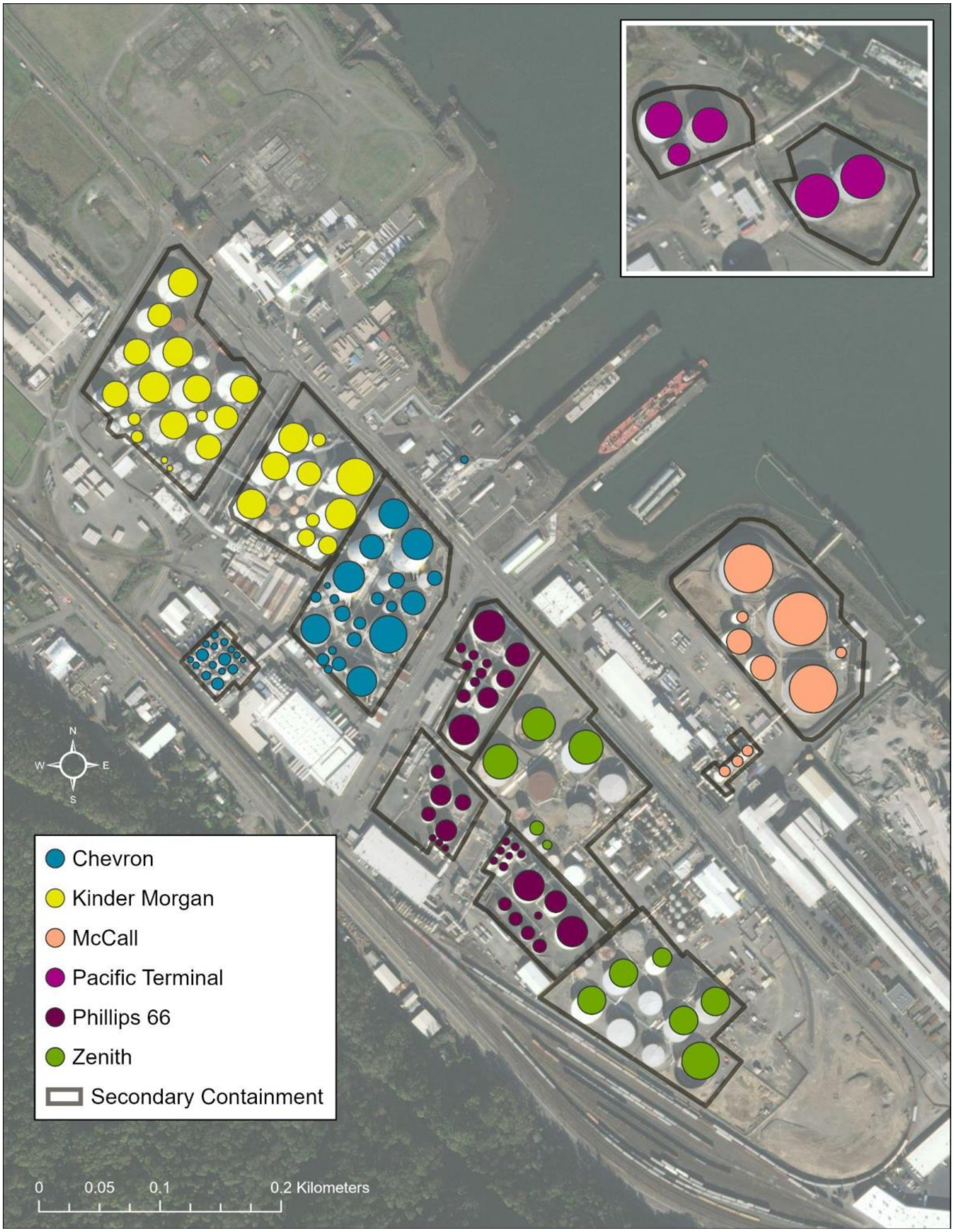


Figure 8-1. *Overview of the main CEI Hub located at Willbridge Terminal.*

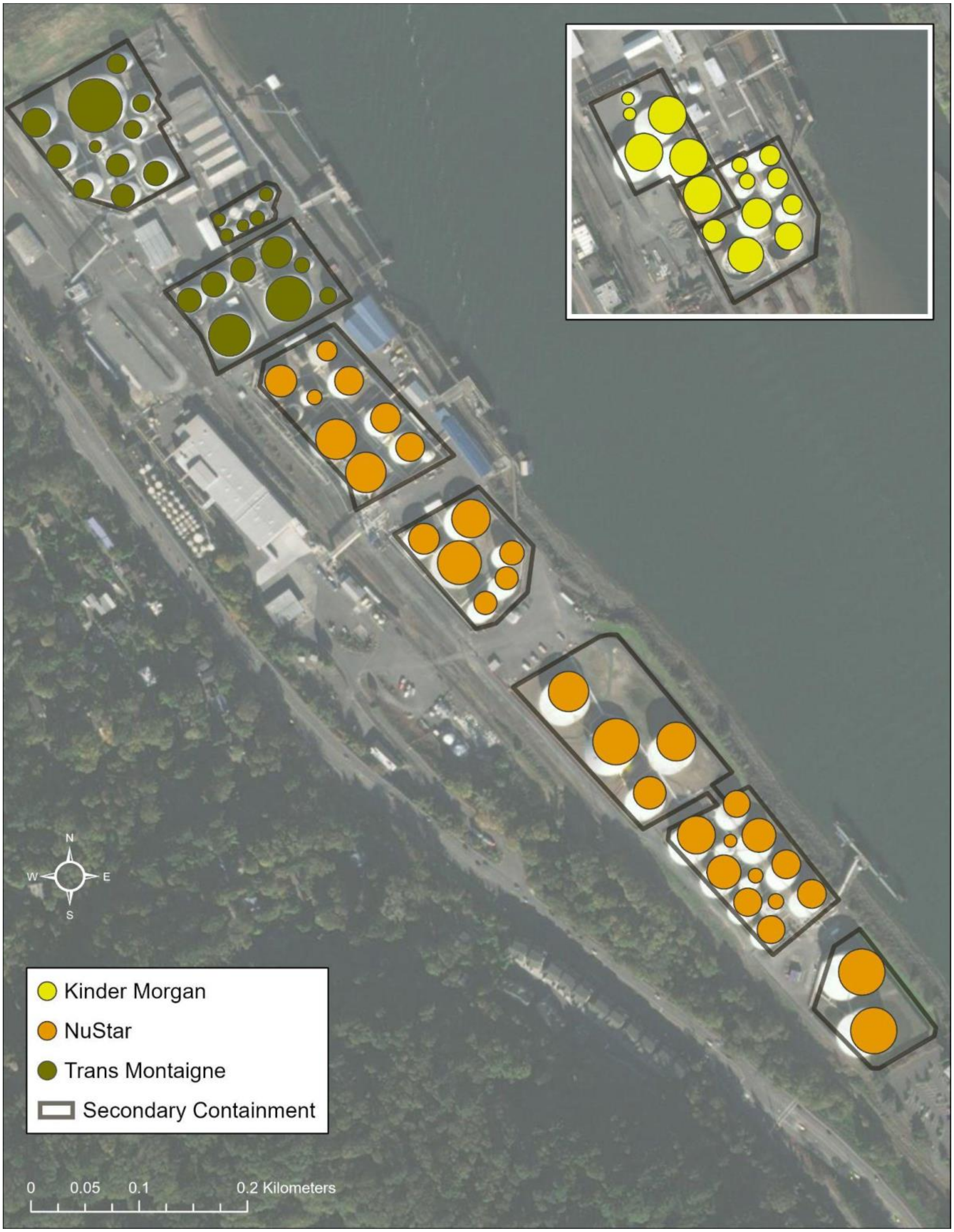


Figure 8-2. *Overview of the upper CEI Hub located at Linnton terminal.*

8.3 Volumetric Data

The Hub tanks store on average 202,426,791 gallons (270,605 tonnes) of petroleum products, including diesel, gasoline, crude oil, base oil, biodiesel, and jet fuel. Additionally, the Hub tanks store 17,902,214 gallons of other hazardous materials such as oily wastewater. This study classifies fuel types based on their American Petroleum Institute gravity index. The API gravity is an indicator of the relative density of a petroleum product compared to water; greater gravity values indicate less dense products (more likely to float on water). The classification structure for tank contents is broken down in Table 8-1. Note that crude oils can vary greatly in their densities (API gravity = 15 - 45), but this study assumes that all crude in the Hub falls under the 'Heavy' category.

Substance Class	API Gravity	Examples
LIGHT	> 31.1	Diesel, jet fuel, gasoline
MEDIUM	22.3 - 31.1	Motor oils, lubricants
HEAVY	10 - 22.3	Asphalt, bunker oil, crude
BIODIESEL	25.7 - 33.0	
OTHER	NA	Contaminated waste water
EMPTY	NA	

Table 8-1: *Substance classification of fuels and other hazardous materials*

It is also worth noting the fluctuation in product throughput due to seasonality, with certain times of the year experiencing dramatically higher or lower volumes; this study primarily considers average volumes, but makes note of maximum capacities for reference. Figures 8-3 and 8-4 summarize a breakdown of each product type by volume housed at the Hub.

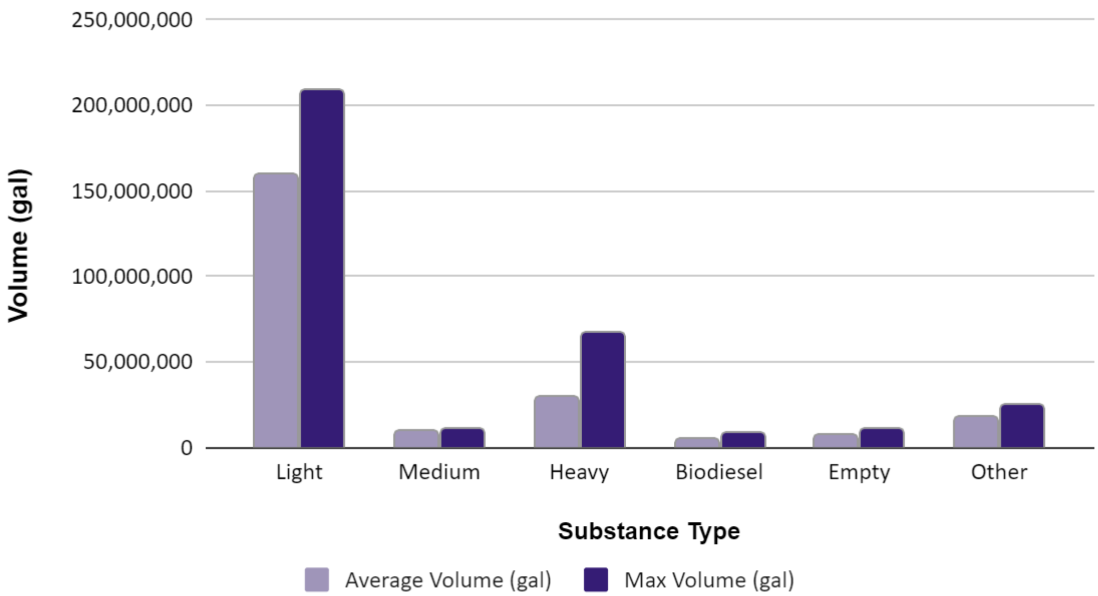


Figure 8-3. *Volumetric contributions of each material type stored in tanks.*

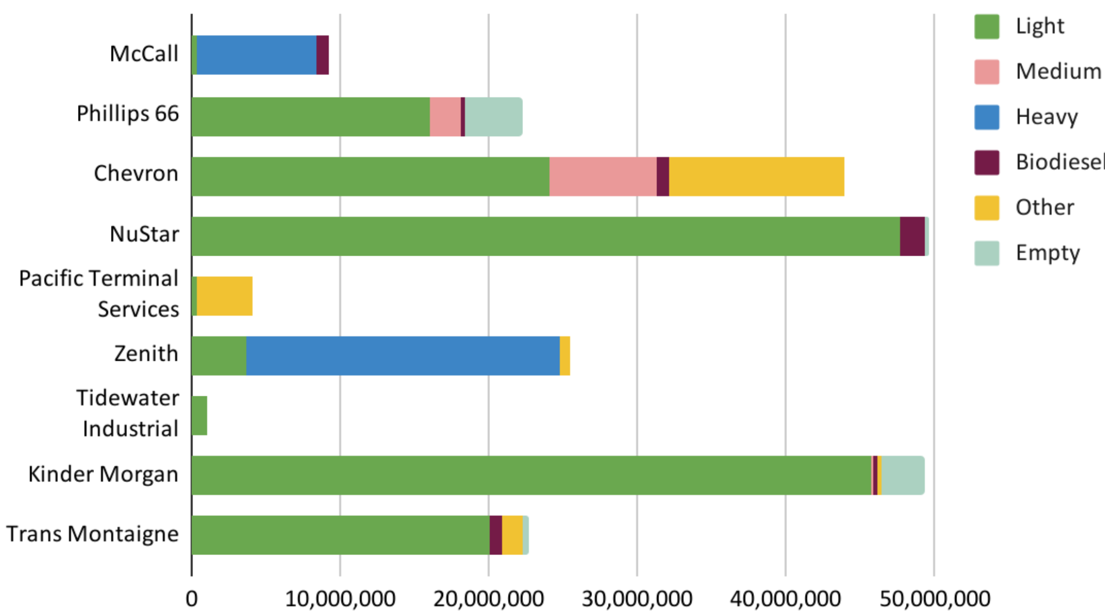


Figure 8-4. *Volumetric contributions of each material type at individual facilities.*

8.4 Secondary Containment

According to the EPA, each facility must specify discharge and drainage controls within their contingency plans, including secondary containment systems. It is common for these systems to employ dikes, berms, or other retaining walls sufficient to capture the volume of the largest breakout tank within the system; modifications to the base surface of the area are also used to retard the infiltration of a spill to the soil and ultimately the water table (e.g. gravel fill, asphalt/concrete paving). Table 8-2 summarizes the secondary containment systems in place at each facility, including the containment volume documented for individual lots (per FRP contingency planning), as well as a calculated total volume (based on the sum of tank capacities within a given lot); in several cases, the total volume of tank products within a secondary containment system exceeds the containment volume.

In the likely event of lateral shifting of the soil following an earthquake, these containment structures and the enclosed tanks are prone to failure, resulting in loss of product to the surrounding area and ultimately to the Willamette River. As shown in Table 8-3, the eastern containment barriers of each area are within 10 - 500 m of the water's edge, potentially allowing post-seismic access to the river, where spill spreading rapidly accelerates at the surface.

Table 8-2: Facility lots and secondary containment systems

	Facility	Containment Volume (gal)	Tanks Volume (gal)	Containment Floor	Containment Structure
Lots	Kinder Morgan Linnton Terminal	4,936,535	4,540,706	Earthen	Concrete Wall
	Kinder Morgan Linnton Terminal	2,848,433	1,373,299	Earthen	Concrete Wall
	Kinder Morgan Linnton Terminal	9,226,955	5,766,844	Earthen	Concrete Wall
	Kinder Morgan Willbridge Terminal	2,302,487	16,250,346	Earthen	Concrete Wall
	Kinder Morgan Willbridge Terminal	6,219,498	21,380,058	Earthen	Concrete Wall
	Chevron Willbridge	7,142,246	40,106,459	Earthen	Concrete Berm
	Chevron Willbridge	760,040	3,616,963	Earthen	Concrete Berm
	Phillips 66	4,575,564	9,968,955	Gravel	Concrete Wall
	Phillips 66	4,150,608	4,285,178	Gravel	Concrete Wall
	Phillips 66	4,296,390	9,133,093	Gravel	Concrete Wall
	Zenith Energy Terminals	27,673,842	4,737,087	Concrete	Concrete Berm
	Zenith Energy Terminals	30,538,242	15,754,978	Earthen	Concrete Berm
	McCall Portland Terminal	12,600,000	8,376,270	Earthen	Ashpalt Berm
	McCall Portland Terminal	NA	855,736	Earthen	Asphalt Berm
	Nustar Portland Terminal	5,444,729	8,400,000	Earthen	Concrete Wall
	Nustar Portland Terminal	5,580,941	23,773,863	Earthen	Concrete Berm
	Nustar Portland Terminal	4,010,540	7,943,030	Earthen	Concrete Wall
	Nustar Portland Terminal	4,539,290	9,535,608	Earthen	Concrete Wall
	Pacific Terminal Services Portland Terminal	5,363,400	2,016,000	Earthen	Concrete Wall
	Pacific Terminal Services Portland Terminal	2,700,601	2,100,000	Earthen	Earthen Berm
	Tidewater Industrial Center	501,046	101,045	Concrete	Cinder Block
	Trans Montaigne	5,261,130	9,443,866	NA	Concrete Wall
	Trans Montaigne	281,400	125,571	NA	Concrete Wall
	Trans Montaigne	3,622,080	11,492,460	NA	Concrete Wall

*Table 8-3: **F**acility lots and proximity of secondary containment barrier to river's edge*

	Facility	Containment Volume (gal)	Tanks Volume (gal)	River Wall Length (m)	Distance to River (m)
Lots	Kinder Morgan Linnton Terminal	4,936,535	4,540,706	101	76.8
	Kinder Morgan Linnton Terminal	2,848,433	1,373,299	45	76.4
	Kinder Morgan Linnton Terminal	9,226,955	5,766,844	120	14.4
	Kinder Morgan Willbridge Terminal	2,302,487	16,250,346	157	163.8
	Kinder Morgan Willbridge Terminal	6,219,498	21,380,058	212	238.6
	Chevron Willbridge	7,142,246	40,106,459	156	157.6
	Chevron Willbridge	760,040	3,616,963	75	442.7
	Phillips 66	4,575,564	9,968,955	115	162.0
	Phillips 66	4,150,608	4,285,178	124	347.5
	Phillips 66	4,296,390	9,133,093	186	394.4
	Zenith Energy Terminals	27,673,842	4,737,087	326	171.3
	Zenith Energy Terminals	30,538,242	15,754,978	221	458.2
	McCall Portland Terminal	12,600,000	8,376,270	277	18.2
	McCall Portland Terminal		855,736	40	231.8
	Nustar Portland Terminal	5,444,729	8,400,000	107	22.8
	Nustar Portland Terminal	5,580,941	23,773,863	287	20.1
	Nustar Portland Terminal	4,010,540	7,943,030	90	19.6
	Nustar Portland Terminal	4,539,290	9,535,608	145	35.7
	Pacific Terminal Services Portland Terminal	5,363,400	2,016,000	96	23.5
	Pacific Terminal Services Portland Terminal	2,700,601	2,100,000	105	38.1
	Tidewater Industrial Center	501,046	101,045	48	322.5
	Trans Montaigne	5,261,130	9,443,866	81	28.1
	Trans Montaigne	281,400	125,571	38	21.4
	Trans Montaigne	3,622,080	11,492,460	136	51.3

8.5 Spill Cleanup and Response Organizations

The protections and appropriate spill response options for the general region of the CEI Hub, as well as downstream locations likely to be affected, are outlined in the Lower Columbia River Geographic Response Plan; this document is a collaborative effort of the Oregon DEQ, Washington Department of Ecology, US Coast Guard, US EPA, and other local, state, and tribal agencies. The primary goals of the plan are to collect, exclude, divert, or deflect oil-on-water spills at various staging areas dependent on the location specified; the leading techniques are mechanical in nature, including booming, skimming, and vacuuming materials. The plan does not incorporate other more efficient response techniques such as in-situ burning and aircraft assisted dispersants, nor does it allow for the attractively inexpensive 'natural cleansing' technique, due to the sensitivity and importance of the various habitats along the Willamette and Columbia rivers. As such, response efforts are likely to be more time-consuming and costly, as well as comparatively inefficient, as shown in Table 8-4 (Etkin 2000).

Table 8-4: *Relative effectiveness of oil spill cleanup techniques based on past reporting*

Method	Reported Field Effectiveness
Dispersants	80-90%
In-Situ Burning	90-98%
Mechanical Containment and Recovery	10-20%
Natural Cleansing	Up to 90% (under right conditions)
Manual Removal	Varies

Each facility is required to establish and identify a contract with a specified Oil Spill Response Organization (OSRO) per the Oil Pollution Act of 1990 as part of the contingency plan. Facilities at the CEI Hub are contracted with Clean Rivers Cooperative, a Pacific Northwest-based nonprofit organization, and/or its response contractor, NRC Environmental Services. In collaboration, these OSROs can draw on manpower and resources (thousands of feet of boom, skimmers, vacuums, aircraft, etc.) from across the Pacific Northwest (including Washington and California) in numbers appropriate to handle a spill of catastrophic magnitude. However, it is highly likely that access to the CEI Hub will be drastically impeded in the wake of a subduction zone earthquake, including the loss of major bridges, as well as obstruction of main waterways and roads; this may relegate the response effort to crew and resources immediately available on the scene. These include the Portland branch of CRC located at the CEI Hub, as well as several warehouses placed throughout the Hub at various facilities which house spill response equipment; unfortunately, these are supplied to address individual spills from a given facility and are significantly under-equipped to manage a catastrophic spill which spans much of the Hub.

8.6 Cleanup Cost Assumptions

Estimating the cost of a given oil spill is an inherently challenging and complex task, depending on several contributing factors such as: spill size, oil type, spill location, cleanup technique and effectiveness, environmental conditions, shoreline oiling, federal/local regulations and fines. The

Basic Oil Spill Cost Estimation Model (BOSCEM) was developed for use by the EPA and incorporates the first four spill-specific factors above to determine a base cleanup cost. It is worth noting that seasonal and weather conditions may dramatically affect true costs due to changes in river flow and tidal influence, water/air temperature, and wind velocity/direction; these changes may subsequently affect the extent of shoreline oiling, entrainment, and therefore final cleanup costs. These considerations are outside the scope of this model, however, and the general cleanup cost formula is given as

$$C_c = C_u \times M_m \times A \qquad \text{(Eq. 8.1)}$$

where Cc represents the total cleanup cost, Cu represents the response cost per-unit ($/gal), Mm the spill location medium modifier, and A the amount spilled (gal). The Cu value is a mixed value that incorporates the oil type, volume, response technique and effectiveness.

8.6.1 BOSCEM: Spill Size (A)

For the purposes of this report, spill size scenarios identified as medium, major, and catastrophic (per the definitions shown in Table 8-4) are outlined. It has been demonstrated that the cost per-unit of oil spill recovery decreases with increasing spill volumes, although the overall cost of larger spills is obviously more expensive; this is likely due to fixed costs associated with mobilizing a response effort, such as environmental monitoring and stand-by crews. This report assumes a volume of 10,000 gallons, 1,000,000 gallons, and 171,381,663 gallons to represent the minor, medium, and catastrophic (maximum) spill scenarios, respectively. These volumes exclude the non-petroleum products stored at CEI Hub such as asphalt, ethanol, waste oil, etc., which total over 26,000,000 gallons.

Table 8-5: *Spill volume categories defined by the EPA*

	Spill Volume (gal)	Spill Volume (bbl)
Minor	< 100	< 2.4
Medium	100 - 10,000	< 240
Major	10,000 - 1,000,000	< 24,000
Catastrophic	> 1,000,000	> 24,000

8.6.2 BOSCEM: Oil Type, Cleanup Technique, and Effectiveness (C_u)

It is historically shown that costs associated with cleanup of heavier and crude fuels is on average higher than those for lighter or volatile fuels. Since the expected spill following a subduction zone earthquake would contain a mixture of heavy and light fuels, it's reasonable to assume that the cleanup effort will be proportional to the volumetric contributions of each fuel type; therefore, this report will assume weighted values of per-unit costs depending on each fuel type's percentage of the total spill volume, as shown in Equation 2. Each respective oil type cost per-unit for a catastrophic spill is listed in Table 8-5, along with the volumetric percentage contributions of each type (light, heavy, crude, and volatile); these values assume the use of mechanical cleanup techniques operating at a default effectiveness of 10% recovery. For smaller spills, the Ci values increase. The aggregate Cu value is assumed to be the sum of the Ci contributors, and is estimated at $29.32/gallon for the catastrophic spill scenario, for example. As previously mentioned, these scenario volumes exclude non-petroleum products, which likely incur their own unique cleanup challenges and costs; specifically, asphalt may significantly affect costs due to its tendency to solidify and sink on contact with the river water. Thus, this model is not inclusive of all cleanup response costs and potentially an underestimate in all spill scenarios.

$$(0.46)\,C_{light} + (0.36)C_{volatile} + (0.14)C_{crude} + (0.04)C_{heavy} = C_u \quad \text{(Eq. 2)}$$

Table 8-6: *Summary of cost per-unit values obtained from the BOSCEM model indicators*

Substance	Oil Type	Cost per-unit by oil type ($/gal)	% of Volumetric Contribution	C_i ($/gal)
Diesel	Light	26	46%	11.90
Gasoline	Volatile	7	29%	2.02
Crude	Crude	82	14%	11.83
Jet Fuel	Volatile	7	7%	0.48
Base Oil	Heavy	77	4%	3.08
		Totals	**100%**	**29.32**

8.6.3 BOSCEM: Medium Modifier (M_m)

A spill at CEI Hub is best approximated as a shoreline to open water spill location, though downstream shoreline oiling may involve riparian environments such as wetlands; many opportunities for the oil slick to travel to more vegetated environments exist, including the proximal slack water around Sauvie Island. These shoreline oiling interactions are expected to increase cleanup costs, as indicated by the tendency for more vegetated mediums to exhibit higher medium modifiers for the model (Table 8-6). However, for ease of calculations a medium modifier of 1.0 is chosen under the assumption that all spill product remains in the main current and can be modeled as a shoreline/open water spill.

Table 8-7: *Medium cost modifier values from the BOSCEM model indicators*

Medium	Cost Modifier Value
Open Water/Shore	1.00
Soil/Sand	0.60
Pavement/Rock	0.50
Wetland	1.60
Mudflat	1.40

8.7 Cleanup Cost Analysis Results

As shown in Table 8-7, the cleanup cost per-unit (Cu) increases with decreasing spill size, but the overall costs (Cr) are positively correlated, with a catastrophic spill ultimately costing an order of magnitude more than a spill size less than or equal to 1,000,000 gallons. It is worth noting that the BOSCEM model was developed in 2004 and these costs may need to be adjusted for inflation.

Table 8-8: *Cleanup costs for spill scenarios estimated by the BOSCEM model*

Scenario	*A* (gal)	M_m	C_u ($/gal)	C_c
Medium	10,000	1.00	116.83	**$1,168,334**
Major	1,000,000	1.00	59.80	**$59,802,058**
Catastrophic	171,381,663	1.00	29.32	**$5,024,583,323**

While the BOSCEM model attempts to encompass foreseeable costs associated with cleanup and recovery of a spill, there are also civil penalties imposed by the Oil Pollution Act of 1990 (OPA 90) which are dependent upon the cleanup response itself. These include fines of $1,000 per barrel spilled or $25,000 per day of recovery, which could result in maximum civil penalties of over $4 billion for a catastrophic spill (Table 8-8). Each responsible party has a limit of liability of $350 million, per the OPA 90.

A total response cost of about $9 billion for a catastrophic spill of approximately 170 million gallons of mixed oil is reasonable when compared to historic spills, such as Deepwater Horizon in 2010; this event discharged over 200 million gallons of crude oil into marine waters and ultimately incurred a cleanup cost of $40 billion. Indeed, as mentioned prior, these costs are likely underestimates due to several simplifying assumptions and approximations, including:

- Omission of non-petroleum product cleanup costs
- Omission of shoreline and wetland impacts on cleanup costs (assuming open water)
- Omission of groundwater contamination cleanup costs
- Assumption of rapid and sufficient response efforts in the wake of constraints imposed by regional damage caused by the subduction zone earthquake

The responsible parties are liable for up to $350 million in cleanup and recovery costs, and may draw upon the Oil Spill Liability Trust Fund (OSLTF) for up to $1 billion, which leaves a significant financial remainder to be addressed by either the State of Oregon or the Federal government in the event of a catastrophic spill.

Table 8-9: *Total response costs associated with cleanup and civil fines for spill scenarios*

Scenario	Volume (gal)	Cleanup Cost	Fines	Total Response Cost
Minor	10,000	$293,200	$238,095	**$531,295**
Medium	1,000,000	$29,320,000	$23,809,524	**$53,129,524**
Catastrophic	171,381,663	$5,024,910,359	$4,080,515,786	**$9,105,426,145**

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APPENDIX - ASSESSMENT REPORT FROM OREGON SOLUTIONS

Results from effort by Oregon Solutions that conducted parallel and complementary to the engineering investigations is included in this appendix. The aggressive timeline of this study and the time required for the interview-based approach had not allowed for full integration into the body of the report.

Critical Energy Infrastructure Hub

Assessment Report

Oregon Solutions | June 2021

Acknowledgements
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CONTENTS

1. INTRODUCTION

In spring 2020, the Oregon Office of Governor Kate Brown and the Oregon Office of Emergency Management asked researchers at Portland State University and staff at Oregon Solutions to "conduct a hazard mitigation study to evaluate and recommend real-time options to mitigate product flow from the Critical Energy Infrastructure (CEI) hub… following a major earthquake and catastrophic failure at the hub."[1] Funds for this study were appropriated by the Oregon Legislature in 2019.[2]

For nearly ten years, policymakers, public agencies, first responders, and researchers have been working to prepare and plan for a major subduction zone earthquake. Knowledge of the region's exposure to such a quake was initially reported in the late 1980s after geologists found the first scientific evidence of past subduction zone events in the Pacific Northwest. This evidence was later verified by further research in the mid-1990s.

The CEI hub was built 100-years ago, on fill from the construction of the Port of Portland, well before there were state seismic codes.[3] Researchers are concerned about the site's potential risk from soil liquefaction— a process where soil can "behave temporarily as a viscous liquid"[4]—during an earthquake, and that several of the existing tanks were built before modern seismic standards were put in place.

To better understand how the site might perform if a Cascadia Subduction Zone Event (CZE) occurred today, researchers are looking at scenarios (what and how big), reach (where and when), impacted communities (who and how), mitigation best practices, and benefits and costs. Oregon Solutions' focus for this assessment report was on *impacted communities*—those who have a direct interest in the hub or who could be impacted if the hub is damaged in a CZE (e.g., first responders, industry sectors, natural resource managers, cultural leaders, transportation/infrastructure leaders, civic leaders). The following assessment report details our findings.

ABOUT OREGON SOLUTIONS

About Oregon Solutions
Oregon Solutions is the state of Oregon's program to help communities address community-based problems and opportunities through sustainable solutions. We do this by creating a neutral forum for collaboration where businesses, governments, nonprofits, community-based organizations, sovereigns, and other stakeholders can align resources and pool efforts to achieve desired results.

Oregon Solutions Process
Oregon Solutions' engagement starts with an assessment. When invited, Oregon Solutions begins an assessment to explore whether and how a collaborative approach might be structured to address a particular community issue. The assessment is composed of a series of one-on-one or small group interviews. If an assessment finds there is a project that can be conducted by Oregon Solutions, it will go before the governor for consideration of a designation as an Oregon Solutions project.

[1] FINAL_CEI_Hub_Risk_Study_March 2020-fr Gov Office.
[2] Available online at HB 5050 (2019), https://olis.oregonlegislature.gov/liz/2019R1/Downloads/MeasureDocument/HB5050/Enrolled.
[3] Prior to 1974, Oregon had no state seismic codes, https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.
[4] Available online at https://www.britannica.com/science/soil-liquefaction.

2. METHODS

This assessment report is the product of interviews conducted by Oregon Solutions with parties and stakeholders representing key interests related to the CEI hub. Between October 2020 and May 2021, Oregon Solutions interviewed fifty-six individuals representing city, county, state, tribal, and federal government, as well as neighborhood associations, civic groups, energy associations, and the energy sector.

The team could not interview every individual with an interest in the CEI hub. We made every effort to reach out to entities and individuals who could provide diverse perspectives on the seismic resiliency of the hub. Our goal with assessment interviews is that all interested parties feel their perspectives and interests are represented by those interviewed. A list of those interviewed and their affiliations can be found in appendix C.

Most interviews were held by phone or Zoom videoconferencing. Before each interview, individuals were briefed about the purpose of the assessment. All interviews were voluntary and lasted approximately one hour. Interviewees were informed that the final report would aggregate responses into key issues without individual attribution.

3. INTENT OF THE ASSESSMENT REPORT

This report is *not* intended to be a comprehensive review of all issues published, reported on, or discussed about the CEI hub. Instead, this assessment report reflects what Oregon Solutions heard from interviewees at a single point in time, and it is an overview for stakeholders and policymakers about the key topics of interest to parties interested in the hub.

4. BACKGROUND

4.1. History

Much has been written in recent years about how "a big quake along [the Cascadia subduction zone] fault line could affect the cities of Seattle, Tacoma, Portland, Eugene, Salem, and Olympia,"[5] as well as coastal and other rural communities. Even as recently as a few decades ago, most people had little awareness of the region's risk, instead believing the northwest corner of North America was insulated from the type of high-risk hazards experienced in other parts of the country.

"The discovery of the Cascadia subduction zone stands as one of the greatest scientific detective stories of our time,"[6] wrote Kathryn Schulz in her influential 2015 *New Yorker* piece. It was a discovery gleaned from decades of geologic research, source material research, and a reassessment of previously known traditional stories of native peoples. Beginning with continental drift, a controversial theory from 1912, decades of research led

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[5] Available online at https://www.groundworkscompanies.com/about/articles/worst-us-cities-for-earthquakes/.

[6] Available online at https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

to discovery of plate tectonics in 1966. The knowledge of plate tectonics helped lead to the detection of fault lines along the Pacific Northwest in the 1970s,[7] followed by a 1980s finding that the Copalis River's ghost forest in Washington state had been "wiped out all at once from a rush of sea water."[8] Tree-ring evidence pegged that event to have occurred sometime between August 1699 and May 1700.[9]

4.1.1. Traditional stories

Virtually all of the northwest region's Native Americans and First Nation peoples have stories of earthquakes, which were lamentably discounted. Several tribes tell a remarkably similar story of a particularly destructive earthquake and tsunami-like flooding along the region's coastlines:

- Elders from the Huu-ay-Aht First Nation tribe have passed down stories of an earthquake-generated tsunami that washed away an entire village.[10]
- The Kwakwaka'wakw (Kwakiutl) from the north end of Vancouver Island tell stories of a night-time earthquake that leveled all of the homes in their communities.[11]
- The Cowichan tell stories of an earthquake that caused a landslide burying an entire village.[12]
- The Makah tell of a nighttime tsunami that killed all who failed to flee inland.[13]
- The Quileute people tell stories of a powerful flood that left canoes as far inland as the Hood Canal.[14]

Even more tribes tell stories of other tribes being wiped out by a nighttime tsunami,[15] while another tribe recounts stories of saltwater floods.[16]

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7 Available online at https://www.businessinsider.com/the-cascadia-subduction-zone-was-discovered-in-1970-2015-7#:~:text=The%20Cascadia%20Subduction%20Zone%20Was,The%20word%20%22Insider%22.&text=The%20word%20%22Insider%22.,-The%20word%20Business&text=A%20leading%2Dedge%20research%20firm%20focused%20on%20digital%20transformation.

8 Ibid.

9 Available online at http://www1.udel.edu/PR/Messenger/04/03/ghost.html#:~:text=Their%20analysis%20revealed%20that%20all,August%201699%20and%20May%201700.

10 Available online at https://web.archive.org/web/20150928200523/http://indiancountrytodaymedianetwork.com/2012/03/11/traditional-knowledge-informs-japan-style-earthquake-danger-us-canada-102404.

11 Available online at https://web.archive.org/web/20150724120448/http://oceanlink.island.net/SOLE/LP/FN/1700_tsunami.pdf.

12 Ibid.

13 Available online at https://en.wikipedia.org/wiki/1700_Cascadia_earthquake.

14 Available online at https://web.archive.org/web/20160823235547/http://indiancountrytodaymedianetwork.com/2012/11/06/haida-gwaii-quake-brings-home-importance-quileute-relocation-legislation-144214.

15 Available online at https://en.wikipedia.org/wiki/1700_Cascadia_earthquake.

16 Available online at https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

4.1.2. Orphan Tsunami

In 1996,[17] researchers reviewed 1400-years of written records of tsunamis in Japan that included "one incident [that] has long stood out for its strangeness,"[18] a tsunami that had no discernible origin given there was a lack of a detectable earthquake to coincide with its arrival on January 27, 1700. This tsunami came to be known as an Orphan Tsunami.[19]

When paired with traditional stories from Native American and First Nation peoples, and the written record of Japan's Orphan Tsunami, this scientific detective story was solved. We now know that the greater Pacific Northwest has experienced forty-one subduction earthquakes over the last 10,000 years—an average of one every 250 years.[20] They happen at "highly variable intervals and can range widely in size."[21] The last subduction zone earthquake occurred on January 26, 1700, and researchers believe there is a 33 to 37 percent likelihood we are due for another significant subduction zone quake in the next fifty years.[22]

4.2. Today

Over the last few decades, knowledge of the region's exposure to subduction zone earthquakes has spurred a flurry of code reviews; enhanced trainings for first responders; retrofits and rebuilds of public and private infrastructure; outreach and education on disaster preparedness; funding of early warning systems; and ongoing research and updated policy recommendations focused on resiliency and mitigation (see appendix B for a sampling).

When the Oregon Seismic Safety Policy Advisory Committee (OSSPAC) wrote their 2013 *Oregon Resilience Plan*, they were pointedly clear that when the next CZE happens, it will be the state's "greatest challenge in history,"[23] causing thousands of deaths and approximately $32 billion in economic losses. They argued we "need to start preparing now by assessing the vulnerability of our buildings, lifelines, and social systems, and then developing and implementing a sustained program of replacement, retrofit, and redesign to make Oregon resilient to the next great earthquake." They noted that "we know how to engineer buildings, roads, and power lines to withstand this earthquake; the hard part will be to find the will, commitment, and persistence needed to transform our state."[24]

In our own earlier assessment report on the CEI hub, we mentioned that many of Oregon's buildings and much of its critical infrastructure were constructed before the region's

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[17] Satake, K., et al, "Time and Size of a Giant Earthquake in Cascadia Inferred from Japanese Tsunami Records of January 1700," *Nature* 379, 246–249 (1996)
[18] Available online at https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.
[19] Available online at https://pubs.usgs.gov/pp/pp1707/pp1707.pdf.
[20] Available online at https://www.youtube.com/watch?v=76b_WGzCI54.
[21] Available online at https://www.oregon.gov/oem/Documents/01_ORP_Cascadia.pdf.
[22] Available online at https://www.groundworkscompanies.com/about/articles/worst-us-cities-for-earthquakes/
and https://www.youtube.com/watch?v=76b_WGzCI54.
[23] Available online at https://www.oregon.gov/oem/Documents/01_ORP_Cascadia.pdf
[24] Ibid.

seismic exposure was widely understood. This includes Oregon's primary liquid fuel storage facility, the CEI hub, which receives 90 percent of the state's liquid fuel supply (with roughly 70 percent arriving by pipe and another 30 percent arriving by tanker barge), and 100 percent of the jet fuel for Portland's airport.[25] Tanks on the site were also constructed "before we understood that the soil beneath the CEI hub is highly susceptible to liquefaction and lateral spreading."[26] The majority of the fuel tanks "were built fifty or more years ago," while some are "more than 100 years old."[27] Today, some of the tanks have been updated to modern seismic codes.

Because of the location of the CEI hub and the broad population it serves, it is understandable there is a great deal of interest in mitigating it from the impacts of a CZE to preserve the hub itself, to best prepare impacted communities and first responders for what they need, and to clarify who will respond in order to save lives. We know that earthquakes and other naturally occurring geophysical disasters can cause "hardship, loss of life, or damage to infrastructure, the environment, the economic well-being, or other things that humans value."[28] To prepare for and respond to such disasters, emergency responders are trained not only about mitigation, but also about preparedness, response, and recovery.[29] For such severe events, impacted communities also need to have developed mitigation strategies and activities in order to best be able to survive and recover from this kind of disaster.

This assessment report focuses singularly on mitigation. Our full research team has used the following definitions for mitigation to guide our work across our respective disciplines:

- In a traditional approach, mitigation is a *set of activities* done pre-earthquake to make a facility or property less susceptible to damage from an earthquake. In the case of the CEI Hub, this could be actions like seismically retrofitting facilities or hardening sub-surfaces.
- Another mitigation approach could be to have *materials* in place or *processes* identified that would enable property owners to better manage the negative effects of an earthquake. In the case of the CEI Hub, this could be pre-staging booms to catch oil released into the river if tanks fail, or commitments from emergency responders to prioritize response to the CEI Hub in case of a CZE.

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[25] Available online at https://www.newyorker.com/magazine/2015/07/20/the-really-big-one.
[26] Available at https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf.
[27] Available online at https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf
[28] Available online at https://link.springer.com/referenceworkentry/10.1007%2F978-1-4020-4399-4_155.
[29] Available online at https://training.fema.gov/emiweb/downloads/is111_unit%204.pdf. While this assessment report focuses solely on mitigation, we've included FEMA's definitions for all four: *mitigation*– actions that should be taken to prevent or reduce the cause, impact, and consequences of disasters; *preparedness*–planning, training, and studying what activities can help for things that cannot be mitigated; *response*–responding in the immediate aftermath of a disaster when business and other operations do not function normally, and when personal safety and well-being depend on the level of preparedness; *recovery*– restoration efforts that occur concurrently with regular operations and activities, and that a recovery period from a disaster can be prolonged.

The Oregon Solutions portion of this research project focuses on *impacted communities.* As a research team, we have defined impacted communities as those who have a direct interest in the hub or who could be impacted if the hub is damaged in a CZE (e.g., first responders, industry sectors, natural resources managers, cultural leaders, transportation/infrastructure leaders, and impacted communities).

5. FINDINGS

This section details findings from assessment interviews. Note that findings do not reflect a point of view of the National Policy Consensus Center, Oregon Solutions, or any of our team members. Instead, findings reflect what we heard from interviewees. During these interviews, we asked interviewees their perspectives on a variety of topics related to mitigation and collaboration; interview questions can be found in appendix A. Questions focused on what interviewees felt they need to adequately survive a CZE if it were to happen today, what barriers to preparedness remain, and what support is needed in order to achieve mitigation.

This section includes an overarching frame that emerged through our interviews, as well as findings related to our assessment questions. We have incorporated content from interviews and from research; information to give the reader a clear understanding of the ongoing efforts to prepare for a CZE; questions that came forward when looking at Oregon's liquid energy assets; and interviewees' general interest in an educational cross-sector collaborative process to advance knowledge between critical parties. We did not include comments that were not germane to the scope of this assessment. These findings are not listed in any order of significance.

5.1. Two-Pronged Approach for Mitigation—Local and Statewide

When interviewed about how impacted communities should prepare to mitigate for a CZE, assuming the CEI hub could be catastrophically damaged, one expert said that policymakers, industry leaders, emergency responders, and others should prepare and plan on two levels: local and statewide. It is evident that any immediate damage to the hub, and therefore mitigation steps necessary to help prevent that damage, have to happen locally. But, given the need that emergency responders across Oregon will have for liquid fuel in the wake of a CZE, this interviewee stressed that mitigation activities must be considered not just locally but also statewide, and explained the following.

5.1.1. First level—local considerations

The first set of considerations is very local in nature and has a shorter overall duration in relation to the time when the hub might be catastrophically damaged. This first level includes the impacts experienced by the neighborhoods and other areas proximate to the hub. It will likely reflect the responses required in *the immediate aftermath* of a catastrophic event, and damage to this area could depend upon a variety of factors:

- The intensity, duration, and origin of the earthquake itself are factors.
- The time of day when the CZE occurs could impact corresponding response to initial damage at or near the site (e.g., whether people are at home, or traveling for work or school).
- If there are fires, evacuations could be necessary, and smoke and chemicals would likely be released into the air.
- If the storage tanks or pipelines are breached or broken, the soil and water of the surrounding area could be contaminated.
- There could be casualties of those who live near or work at the site and need immediate medical attention.
- Evacuation plans for those who work and live near the site would need to be implemented.
- There could be implications for survivors and nearby property if local emergency responders are needed at other neighborhoods first given the severity of the event or if they are unable to traverse damaged infrastructure to get to the hub.

5.1.2. Second level—statewide considerations

The second set of considerations is for communities statewide that depend on fuel from the hub. These considerations focus more on lifeline networks, response capability, and supply chains and would happen after the initial aftermath of a CZE.

- The needed timeframe for this statewide response would likely become clear three to five days after a CZE as supplies for emergency response are exhausted.
- Subduction zone earthquakes are significant because they impact an entire region, can last several minutes, and in the case of the Cascadia Zone, they can trigger a tsunami. In an event as severe as this, it is to be expected that local, state, and federal assets will be overwhelmed by the need to respond to a coastal tsunami and landslide damage.
- Mutual aid, which generally would be adequate for most serious events, would likely be challenged and unable to be deployed across the region if early emergency responders are occupied in their home or local territories.
- Because of the just-in-time network for fuel transmission and storage, fuel capacity could be in short supply three to five days after an event.
- Moreover, there would likely be a disruption of the general supply chain.
- Until local area emergency response is complete and damage is assessed—particularly damage to public infrastructure—it will be difficult to determine when supplies would be available to communities statewide. As a result, supply chains for rural and remote communities may require special consideration given distances and the likely need to consider prioritization of limited supplies.

Finally, this expert emphasized that, given the importance of the hub to the state's liquid fuel supply, any significant damage to the hub would be a statewide event. And given that our infrastructure is interdependent, this expert said it is essential for Oregon to conduct mitigation planning for local communities and for the state if we are to realize the benefits of a good recovery.

5.2. General Findings

5.2.1. Additional CEI hub preparedness is needed

Oregon is less than ten years into a fifty-year preparedness effort that was developed by OSSPAC in their 2013 *Oregon Resilience Plan*. The authors of this report hoped that if the plan were implemented, Oregonians would do the work to enhance our infrastructure resilience, help preserve our communities, and protect our state economy.[30]

We asked interviewees about their perspectives on how prepared, in general, their sector or community is if a CZE were to happen today. Nearly every interviewee said no, they are not yet prepared and most expressed concern. Some could not answer preparedness questions specific to the hub. In these instances, interviewees were actively engaged in preparedness activities for a broad array of natural disasters, but were less likely to have knowledge related to the mitigation or response needs of the hub.

We found that ***preparedness needs*** specific to the CEI Hub fell into four general categories:

1. Hub specific exercises and training (including worst case scenario exercises)
2. Fire response resources for the hub (private and public)
3. Human capital (professional and volunteer firefighters)
4. Material and logistics (equipment, communications, and supplies)

These responses offer policymakers, managers, and stakeholders a rough progress check and guidepost for ongoing preparedness work.

5.2.2. Hub specific exercises and training

Today, facility owners at the hub are required by the US Environmental Protection Agency to have a facility response plan that outlines their response strategies and defines "roles in the event of an oil spill, including who gets notified, where a release would go, and what could be impacted downstream." (See appendix E.) They are also required to conduct table top exercises and drills for their facilities as outlined in the guidance document of the National Preparedness for Response Exercise Program.

The training and exercises serve to disseminate knowledge about essential infrastructure, like the hub. From such exercises, several interviewees are aware of the hub's vulnerabilities, and there was an acknowledgement that some mitigation was in place already (e.g., emergency shut off and breakaway valves, concrete containment, worst-case scenario training at the facility-level, etc.), although these were not nearly sufficient. Some interviewees have participated in facility-level drills at the hub and say they are generally well done. Of these interviewees, most still say the drills do not provide the information and training they would want in order to prepare for a hub-wide worst case scenario.

[30] Available online at https://www.oregon.gov/lcd/NH/Documents/Apx_9.2.3_OR_Res_Plan_Final_OPT.pdf.

We heard about a number of other exercises and drills in the region focused on responding to a CZE in general or other disasters (e.g., ShakeAlert, wildfire, extreme precipitation and flooding, drought, etc.), and many have participated in the federally required worst case scenario drills for individual facilities at the hub. But nearly every interviewee remains concerned there has not been an exercise specific to worst case scenario impacts at the full hub. Almost all interviewees across all sectors told us they want a hub-wide worst case scenario exercise, and interviewees from across the state expressed that if one were held they would want to attend.

Interviewees also concurred that there is great need for local and statewide training or drills about the hub, and they want them to be cross-sector, integrated, and well-designed exercises:

- Thinking locally, many identified worries related to fire risk, environmental impacts, toxic gas, complications posed to disaster response by the presence of large quantities of oil in the Columbia River, the lack of a specific response team to address hub failure (e.g., absence of a fire station at the CEI hub), and CZE responders heavy reliance on fuel stored at the hub, including reliance on electricity and water.
- More broadly, most understood that a catastrophic failure of the hub would take a heavy toll on the Portland region and the state in terms of loss of life, damage to infrastructure and the state's economy, and harm to the local environment. Many interviewees feared that recovery would be slow and could result in a mass migration.

Of past large cross-sector drills in Oregon and out-of-state that attempted to model catastrophic events, a couple interviewees cautioned of poorly designed training by siloed sectors, training that failed to offer real world application. We heard that large exercises can be confusing if contractors hired to run the training know little about the diverse array of sectors at the table. In these examples, we heard that critical partners dropped out of these exercises, and as a consequence valuable information wasn't captured. These interviewees did not want the same loss of participation to happen during an exercise involving the hub.

5.2.3. Fire response resources for the hub

We heard concerns about the lack of a fire brigade[31] or firehouse, at the hub like what currently exists at the Portland International Airport.[32] There are six fire stations in the general vicinity of the hub. Traditional fire stations are charged with responding to their fire management area, meaning they would likely respond to their management area for triage in a CZE.[33] A few interviewees are aware that hub owners have contracts with

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[31] Available online at https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.156.
[32] Available online at https://www.portofportland.com/PublicSafety/Fire.
[33] Available online at https://orsolutions.org/wp-content/uploads/2019/03/CEI-Hub-final-5-6-19-1.pdf.

private companies who have expertise in hazardous materials response. Not everyone was clear about who the vendors are and their response capacity.

Some interviewees are concerned that the closest firehouse to the hub and the nearby neighborhood is on the opposite side of the St. Johns Bridge. They worry that if the St. Johns Bridge is damaged and cannot be crossed during a CZE, those at the hub and in the surrounding neighborhoods would have to fend for themselves. Most also expect that other local firehouses would respond to their assigned neighborhoods leaving the hub with an unverified level of response capacity.

5.2.4. Human capital—professional and volunteer firefighters

For those interviewees with knowledge about first responders, we heard about potential constraints in human capital available for response in the event of a CZE. In some areas, first responders live many miles or even a few towns away from where they report. If they are not on duty when a CZE occurs, it could be nearly impossible for them to report in if transportation infrastructure is moderately or severely damaged. This could put a strain on the on-duty first responders or on those who are able to get to their duty stations until other backup crews are available.

We also heard concerns about a downturn of people volunteering as community-based fighters over the last ten to fifteen years.[34] One of our interviewees said they have seen a 50 percent reduction in people volunteering as firefighters during that time period. Volunteer firefighters are first responders who are on-call and respond to emergencies alongside salaried firefighters. Today, it is less common to find all-volunteer crews in urban firehouses, but they remain common in rural settings.[35] Given that many small and rural firehouses depend heavily on volunteer firefighters, their waning ranks could significantly impact a community's ability to respond to day-to-day events, let alone the crisis in the first days after a CZE.

5.2.5. Material and logistics—equipment, communications, and fuel supplies

Interviewees reported the following concerns about materials and logistics in a CZE:

- **Equipment.** Interviewees told us about firehouses that have had to operate on constrained budgets for several years. We heard that resource constraints can occur for a range of reasons, including the failure of local tax levies, inadequate Medicaid reimbursement for services rendered, or the creation of special districts that defer tax payments that pay for critical public services like emergency response in order to stimulate an area's economic base. In areas where funding has been especially constrained, interviewees said it can be difficult, if not impossible, to replace old and

[34] National information about this downturn can be found here: https://www.firerescue1.com/volunteer/articles /volunteerism-recruitment-and-retention-efforts-professionalism-and-future-members-ODsxrSlCD0Er6HaV/.

[35] Available online at https://www.firerescue1.com/volunteer/articles/6-key-questions-about-being-a-volunteer-firefighter-J03ynVu7QORaVHPI/.

antiquated equipment like emergency response vehicles and communications equipment.

One interviewee shared another concern about emergency response equipment being stored at locations vulnerable to damage in the event of a CZE (e.g., under vulnerable bridges) potentially rendering the equipment unusable. Finally, one interviewee said that, in reality, one of the main challenges in preparing for a CZE is that no one alive today in the United States knows what it will be like given that they haven't experienced one. Consequently, all who are engaged in emergency response will have to be creative, think outside the box, and use all of their skills, training, resources, and connections to the best of their ability to save lives.

- **Communications.** Communications equipment and the lack of interoperability troubled a few interviewees. We heard that many first responders in similar regions are still not on interoperable communications systems. One interviewee said that interoperability is often more important regionally, and that geographic barriers, like mountains, still mean that not all systems need to be the same. But interoperability within responding regions was seen as important. Interoperability "is more than just radio frequencies … [it is] the ability to work together across jurisdictions and agencies … fire, police, EMS, and dispatch on the same page, working toward the same goal, using the same format."[36] But according to *The Atlantic*, as of 2015, "roughly 65,000 public-safety agencies still rely on a patchwork of radio systems that are often incompatible with each other."[37]

- **Fuel supplies.** We heard from many interviewees that their organization does not have adequate stores of fuel to last through a severe event. Several spoke about the critical role backup generators play during such events. Hospitals, firehouses, emergency response centers, airports, or other critical facilities rely on them to provide electricity so technology and computer systems run, ensuring water pumps operate, and communications networks for essential emergency responders are sustained. But to operate, they require fuel. Absent fuel, food and water might not get distributed, hospitals may not be able to maintain basic operations or sanitation, airports would not have fuel for airplanes, and heavy equipment needed to remove debris from roads would be inoperable.

  Some interviewees felt they could stretch their current supplies for five to seven days, maybe longer. Others noted that, through regional interagency training, they are aware where a cache of fuel and other supplies are stored. But if the hub goes down or pipelines break, the competition for and preservation of those supplies will pose serious challenges.

[36] Available online at https://psc.apcointl.org/2011/09/06/911-10-years-later/.
[37] Available online at: https://www.theatlantic.com/politics/archive/2015/09/why-police-and-firefighters-struggle-to-communicate-in-crises/457443/.

5.2.6. Lack of understanding of hub issues

Finally, more than one interviewee was unsettled by the belief that too many individuals from too many sectors still have little to no understanding of the importance of the hub and the impact its failure would have for most of Oregon. One interviewee lamented that "countries like Argentina are better prepared," for severe earthquakes, while "the 'people in Salem' [and by extension, most Oregonians] don't realize they will have no fuel," when the earthquake happens.

5.2.7. Other responses regarding preparedness

Not all of the relevant response we heard from interviewees fit well into the categories listed above. Therefore, we are including them in the table below.

Needed to respond to a CZE today	**Needed for response if CEI hub is severely damaged**
Hub Specific ● Minimize tank failures: retrofit older tanks where feasible to mitigate against spills and releases, seismic shut off valves, etc. ● Spill containment ● Invest in CEI hub to withstand a CZE: decommission tanks, build new seismically stable tanks, etc. ● Situational awareness: early warning, use of drones, etc. ● Protection from fire at the CEI hub	**Hub Specific** ● Coordinated hub-wide worst case scenario plan ● CEI hub rapid recovery ● Ensure first responders have equipment and training to respond to oil fires ● CEI hub-specific fire response infrastructure ● Resources to respond to fires in the surrounding area: Forest Park and others ● Understand how long pipeline will be down in case of damage from CZE and timeframe for getting it back online ● Revisit fuel storage and capacity moratorium in context of market demand and earthquake risk
Fuel Diversification ● More fuel storage capacity ● Redundant fuel supply ● Invest in alternative fuel sources (green energy and others) and run pilot projects to test for reliability ● Diverse fuel storage locations around the city and tied to key facilities	**Fuel Diversification** ● Make sure counties are clear on primary sites to access and deliver fuel if communications are disrupted ● Statewide fuel distribution plan coordinated with counties and the fuel industry ● Leverage partnerships on fuel sharing between airports (who have to discard aged fuel) and critical services (hospitals and others) for their storage and use in generators

Needed to respond to a CZE today	Needed for response if CEI hub is severely damaged
First Responders ● Stabilization of communications equipment ● Diversify locations where emergency response equipment is stored around the city as well as in other states ● Ensure local equipment caches are in seismically reinforced locations ● Mutual aid agreements with other states	**First Responders** ● Work with FEMA to operate from a federal incidents support base ● Prevent "islanding" in emergency communications systems ● Establish a "reverse 911" communication system that gives vital information to different sectors on the emergency response ● Increase training with other agencies (federal, state, tribal) to increase efficiencies ● HazMat team available to address immediate hazards around chemical or fuel spills
Healthcare ● Acute field medical teams ● Engage hospitals and medical providers (public and private) on medical based CZE preparedness and response ● Larger capacity fuel storage at hospital sites	**Healthcare** ● Technical assistance for hospitals, especially the ten coastal hospitals, to extend their ninety-six-hour period of shelter in place: food, water, sanitation, electricity, seismically sound fuel tanks, other engineering solutions, regulations ● Establish enough search and rescue to set up a good APOE (Aerial Point of Embarkation) for a couple weeks ● Install flexible piping at Oregon Health Sciences University, harden the Jackson pumping station, and build infrastructure at the top of the hill by Oregon Health Sciences University for water storage.

Needed to respond to a CZE today	**Needed for response if CEI hub is severely damaged**
Neighborhood Specific ● Evacuation plans and pathways for local communities (e.g., evacuation trail system in Forest Park for communities along the park) ● Local fire station for communities near the CEI hub ● Neighborhood-specific food, water, and medical supplies ● Neighborhood-specific community member medical teams	**Neighborhood Specific** ● Clarity about who is responsible for responding (e.g., firehouses) and assessment of their capacity to actually reach the hub in the case of a CZE ● Coordinate with emergency responders about hazards to response efforts (and likely areas for hazards) and plan for mitigating or removing those hazards ● Reignite natural gas pilots after gas lines are restored

Additional responses related to preparedness included the following:

Transportation
- Clear on and off ramps for bridges that are still intact and safe
- Transportation corridors need to be available and open—linkages between Washington State and Multnomah County are limited
- Remove debris from important emergency routes, waterways, and ports
- Clarify crane operations at Port 6 (designated main port of entry for emergency supplies)
- Create physical access to the Metro waste facility

Strategic Approach
- Establish a "resilience mindset" to make sure we don't need a big response
- Minimize talking about "response" and maximize talking about "mitigation"
- Acknowledge that some damage is acceptable, but resilience is minimizing damage and improving the situation to a stronger status after a CZE
- Focus on speed of recovery
- Need to address safety and societal issues related to a catastrophic failure of the CEI hub
- Do modeling of the different potential aspects of a CZE
- Look at customer demand as a benchmark for mitigation

5.3. The View of Oregon's Fuel Infrastructure

5.3.1. About its structure

Experts we interviewed who looked at Oregon's liquid fuel supply infrastructure commented about how unusual it is when compared to other states. Differences include the long distance from refineries for the state's fuel supply; the lack of redundant piping infrastructure; and the existence of a single primary storage facility that supports the fuel needs not only for such an expansive geographic area, but also for nearly all of the state's population. Other states may have one or two of these elements, but these experts reported that it is uncommon for a state to have all three.

These same experts also reported that the development of fuel infrastructure often reflects how populations settled and grew. Case in point: the CEI hub tank farm has served most of the state's population for 100 years. Its growth and development reflect the patterns of population growth over time. As population grew in other parts of the state, so did the extension of Oregon's energy infrastructure, with construction of a new petroleum pipeline in 1962 from Portland to Eugene to support a small tank farm and a growing population in southern Oregon.[38] This pipeline and tank farm are served by fuel coming into the CEI hub. Other areas are also served by fuel coming in by truck.

5.3.2. About its location

Over the last decade, public discussion and awareness about liquid fuel, its transport, and storage have grown significantly. This same is true for our interviewees. Most interviewees demonstrated awareness that fuel coming to Oregon moves at volume via pipe and barge or tanker, and to a lesser extent, by train and truck, with trucks being especially important to the delivery of fuel and oil to its final destination. We heard a growing belief from interviewees that it is unlikely the hub would be moved. Many felt the cost to do so would be too high, and some were uncertain of a better stretch of river to locate a new hub. Others felt that "not in my backyard" issues would be too formidable to make any such move possible.

This sentiment about the hub's location, however, was not universal. One interviewee who was deeply concerned that the hub is located on liquefiable soils said it was "insane" to have "all this hazardous material…within close proximity to residents, industry workers, important infrastructure, and nature." A couple of other interviewees felt Oregon should not have its "eggs in one basket," with one major fuel hub serving the majority of the state's population. Even so, these interviewees felt most people had moved on from any consideration that the hub would be moved or that there could be a diversification of hub-like infrastructure elsewhere.

[38] Available online at https://www.gazettetimes.com/the-hidden-river/article_048d3abe-1a2c-5008-b8b1-60547a3a17b4.html.

5.3.3. The dynamics of fuel movement

A few interviewees felt that even with a strong CZE, the liquid fuel industry should be able to adequately respond to the region's emergency needs because the industry, as a whole, is already robust, dynamic, and diverse and is constantly evolving in response to a range of market, safety, cost, and other infrastructure challenges today. One interviewee said, in short, there is always a way. We were told that if the hub was severely damaged, the industry would pivot to a series of other storage facilities and transload facilities to move fuel into needed areas. Other smaller tank farms, like the ones in Eugene or Vancouver-Marathon (if not damaged) could be used to move fuel by truck, if need be. If those terminals were out, other terminals could be accessed, including Seattle or Tacoma (if not damaged), or even Umatilla, Pasco, Moses Lake, Spokane, and Boise. Each could serve damaged communities farther west to provide emergency access to fuel. Some fuel could move via railroad at transload facilities, even though we were told this would be slower. And more would likely be moved by truck until damage to pipelines was fixed. Barges also could be used both to store fuel for transload and to supply fuel tanks as they came back online. Finally, the coast might even be served by fuel supply barges that are able to land on beaches if local area ports are temporarily inaccessible due to quake and tsunami damage.

However, another interview remarked that OSSPAC came to a different conclusion. In their 2019 report, *CEI Hub Mitigation Strategies: Increasing Fuel Resilience to Survive Cascadia*, OSSPAC wrote that a CZE "would devastate the Pacific Northwest's petroleum supply and distribution system,"[39] and it could "take months if not longer" to restore the region's petroleum infrastructure. Moreover, given anticipated damage to the state's transportation infrastructure, including roads, bridges, railroads, waterways, and even communication systems, it would be difficult to deliver fuel into impacted communities. They note that this too could take months to get fuel delivered to some areas if access were severely limited.[40]We note that the same finding appears in the *Oregon Fuel Action Plan*[41] developed by the Oregon Department of Energy.

5.3.4. Continue effort defining regulatory authorities

We heard strong interest in having the "regulatory rules of the road" outlined as they relate to liquid fuel hubs in Oregon. At the time, there was a lack of clarity about what oversight existed for the safety of those types of facilities. We understood the primary concern to be related to safety of the hub, and there was growing concern about the risk of catastrophic failure of the hub in the event of a CZE.

Since our last report, the Oregon Governor's Office directed the OSSPAC to analyze state and federal guidance on the regulatory authority for seismic upgrades to structures and pipelines. The analysis was to include land mitigation. The purpose was to determine whether "a current state agency has statutory authority to develop long-term mitigation

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[39] Available online at https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf.

[40] Ibid.

[41] Available online at https://www.oregon.gov/energy/safety-resiliency/Documents/Oregon-Fuel-Action-Plan.pdf.

efforts, and if not, to recommend which state agency would be best suited for this new authority,"[42] among other things. They published their report on December 19, 2019, and recommended legislation to "assign regulatory oversight of liquid fuel facilities at the CEI hub to the Oregon Department of Environmental Quality."[43] Even with this direct recommendation, some interviewees for this assessment still felt ongoing work was advisable to further the key parties' understanding of existing regulatory authority and any outstanding regulations that could be in place. We heard from interviewees with expertise that ongoing work could further refine recommendations and better clarify concerns and worries about "who is the lead," or "who is in charge," when it comes to safety of the hub.

5.3.5. Include focus on community safety and cultural preservation

For those interviewees who have knowledge of the surrounding neighborhoods or historic cultural resources, we heard strong concerns about what is seen as gaps in emergency plans that put their physical well-being and the well-being of culturally significant resources at risk. A few interviewees told us there is a lack of available emergency routes for area residents to escape in the event of fire, which left an impression that community members feel vulnerable and isolated. We did find the neighborhood near the hub has an active and engaged neighborhood emergency team that has been working to secure and organize emergency response supplies. We heard that the neighborhood emergency team has also been building emergency route trails toward Forest Park to allow people to get away from the hub in an emergency. It is unclear if this effort, to date, is sufficient. Interviewees with knowledge of the surrounding neighborhoods also noted it could take several days for emergency responders to reach the area with basic supplies or medical aid given the lack of a nearby fire station.

Some interviewees expressed deep concern about potential long-term damage that could be done to the Columbia River and the ecological system that supports culturally important resources such as salmon, lamprey eels, sturgeon, other wildlife, and plants. This area is an important archeology site with Forest Park, Linnton, St Johns, and Sauvie Island, among others, identified as historic gathering or village sites. A few interviewees thought that both damage and oil spills and the resulting clean-up efforts could result in the invocation of treaty rights. There was also worry that an oil spill would cause major setbacks to the Portland Harbor Superfund clean-up effort.

5.3.6. Cross-sector collaboration valued to build trust and relationships

A majority of interviewees felt that a cross-sector collaborative effort would be valuable, and nearly all said they would likely participate. Most interviewees said that a collaborative effort like this would help with much needed trust and relationship building and would clarify discrete issues and needs. Interviewees also said that a collaborative effort focused on cross-sector education on the emergency response system in place today and how each stakeholder group fits into it would be a crucial and novel approach. Some felt that

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[42] Available online at https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf.
[43] Ibid.

alternatives to a collaborative effort (e.g., legislative, legal, etc.) were unpalatable and likely ineffective. Also, one interviewee was notably skeptical about the establishment of a collaborative effort focused on education because they felt that "some chose to stay willfully ignorant" about the vulnerabilities of the hub.

We heard several issues that could be worked through as part of a cross-sector educational effort:

- **Vision and purpose of the hub today.** Some interviewees expressed confusion about the role of the hub as an energy asset given its private ownership yet status as a public good like water or electricity. Some were also unclear how important of an asset it is to government entities, especially the state. These interviewees wanted a clearer articulation of its public benefit and understanding of how it fits into our current and near-term energy picture.

- **Antitrust.** As noted earlier, the industry's antitrust constraints are not well understood to many of those we interviewed. We often heard interviewees thinking it may be related to trade-sector information about a company's particular product, but they could not say for certain. Many interviewees are aware that antitrust issues are a concern for the industry, and might limit what information they could share or how they would participate in a collaborative effort focused on education, trust building, and cross sector education. Even so, they told us they want to better understand these constraints in order to ensure that all parties could meaningfully engage in mitigation activities at the hub. One interviewee described it as needing to share best practices without sharing the cake recipe.

- **Hub infrastructure use in the future.** Some interviewees were unclear how the hub will be used, if at all, fifty to seventy-five years from now if there is a transition away from fossil fuels. These interviewees are aware that experts often speak of a transition beyond fossil fuels and that it will take decades. But they want to better understand what is next. Would the hub and pipeline infrastructure have any value after that? They question if there is an intention to phase out the hub, or whether it can be used for alternative fuels in the future. Others wondered whether, absent a detailed cost-benefit analysis, there was any way to know the value of the hub.

- **Primer on the fuel industry and first responders—**Several interviewees expressed genuine interest in better understanding the liquid fuel industry, how it works, what work it does to focus on safety, and what it does to integrate into a larger regional fabric. There is a limited understanding about the dynamism of the liquid fuel industry, and how ownership of assets at the hub often changes hands. There is a better understanding of the inner-workings of first response; however, there is a desire to learn more.

Finally, in the spirit of "no one can do it alone" and "no one entity owns this issue," interviewees said that, in order for a collaborative effort to succeed, the following elements would be essential: shared goals and principles; concurrence that a CZE is potentially imminent and creates urgency; commitment that mitigation work should come from all parties; a strong effort to balance regulations and incentives; and a focus on making the needs of the community and public safety a priority. Many also hope a collaborative process would serve to educate the public, stakeholders, and subject matter experts alike, would be capable of balancing different interests (e.g, environmental, public safety, cultural resources), would help avoid "analysis paralysis," and would provide enough transparency to generate effective solutions. Lastly, we heard interest in doing collaborative work on what can be done now and on developing momentum that is innovation-minded and future-oriented to help with complex, long-term issues.

5.4. Challenges to Mitigation Efforts

Interviewees identified a range of barriers to mitigation efforts.

- Some interviewees said that efforts to mitigate CEI hub infrastructure is like a two-sided political coin: on one side there is no political payoff for dealing with the crisis that never comes during one's tenure; on the other side there is total payoff if it does. This dynamic makes it difficult to get important work done and it is easy for political entities and owners to avoid making improvements. They feel that the risks and costs are too high and the timing of rewards is uncertain.
- Several interviewees, across a diverse array of sectors, said that focusing emergency response efforts, as currently required, on single facilities as opposed to hub-wide is very problematic. One interviewee said that trying to do emergency preparedness work at one facility at a time "is not productive." Some even expressed relief that Portland State University has been asked to conduct a hub-wide study focused on mitigation.
- Even for those that expressed overt interest in a hub-wide emergency plan focused on response and infrastructure, there was still acknowledgment that proprietary information within the fuel industry is subject to antitrust regulations and could be a barrier.
- A few interviewees noted that the lack of strong partnerships between different parties is a barrier. One interviewee said that a collaborative effort could have been a really good avenue to work on the parties' perceptions of each other and to reveal each other's needs.
- For some interviewees, the fact that no one in the United States—especially emergency responders and the fuel sector—has lived or worked through an emergency at the scale of a CZE is of real concern. One interviewee described that lack of experience as "a significant threat."

5.5. Other Preparedness Examples

Several interviewees and other researchers offered us examples of approaches taken in other jurisdictions that could offer useful models for (a) disaster response training and capacity building in disaster response, (b) regional coordination, and (c) collaborative research on soil liquefaction and land damage.[44] We note that Oregon has experience with similar models and we incorporated information we heard (indented) about under each of the following sections. We do not have an Oregon example for each section.

5.5.1. Disaster response training: Texas Taskforce 1
Sponsored by the Texas A&M Engineering Extension Service,[45] Texas Taskforce 1[46] is "one of the twenty-eight federal teams under the Federal Emergency Management Agency's (FEMA) National Urban Search and Rescue (US&R) System and as a statewide urban search and rescue team."[47] It has more than 600 members from sixty organizations throughout Texas, including firefighters, doctors, nurses, structural engineers, canine handlers, professors, police officers, and other professionals. The members of Texas Taskforce 1 participate in over 25,000 hours of disaster preparedness training every year, including two mobilization exercises per year and one operational readiness exercise. Much of the training takes place at Disaster City, a fifty-two-acre training facility designed to simulate various levels of disaster and structural collapse.

> #### *5.5.2. History of Oregon's Taskforce 1*
> In the wake of 9/11, the state of Oregon established a similar urban search and rescue program[48] called Oregon Taskforce 1. It was funded for nine years from grants awarded by the US Department of Homeland Security. These grants paid for specialized technicians and equipment, and focused on structural collapse training for firefighters.
>
> When the funding from Homeland Security ended, and another funding source was not identified, the program was disbanded. Through attrition, staff with this level of training in Oregon has dwindled, and much of the equipment used by Oregon Taskforce 1 has been transferred to community-based fire response units. Instead of having an Oregon-based capability, today the state relies on using the Emergency Management Assistance Compact that allows Oregon to bring in these resources from other states, such as California, Utah, and Washington.
>
> In recent years, Oregon has worked to fill some of the gap left from the loss of Oregon Taskforce 1 through the Oregon Safety Assessment Program. This program was created

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[44] Available online at https://www.eqc.govt.nz/what-we-do/research-programme/ground-improvement-programme#node-detail-1931.

[45] Available online at www.teex.org.

[46] Available online at www.texastaskforce1.org.

[47] Ibid.

[48] Urban search and rescue is a type of technical rescue operation that involves the location, extrication, and initial medical stabilization of victims trapped in an urban area, namely due to structural collapse during natural disasters, war, terrorism, accidents, and collapsed mines and trenches. Urban search and rescue teams bring together, in an integrated response, highly trained personnel from the emergency services along with engineers, medics, search dogs, specialized equipment, effective communications, established methods of command and control, and logistical support procedures to request international assistance if required under an international search and rescue framework. The training that teams receive is an ongoing procedure combining classes from the local fire and rescue services and government agencies.

by the Oregon Legislature through HB 2206 (2019) and under ORS 401.526 and is "administered by the State Fire Marshal to evaluate the condition of buildings after an emergency."[49] Today, the legislature is considering appropriating $300,000 to this program (through HB 2851, 2021).[50] As noted in public testimony in support of HB 2851, those funds would help the legislature "realize its goal in passing HB 2206 to train, certify, and dispatch architects and engineers who volunteer their time to assess building damage following a disaster. It is a partnership that has proven its worth in other states."[51]

5.5.3. Regional coordination: Bay Area initiatives

The Bay Area has taken a number of steps to prepare for the impacts of a major earthquake in the region, including conducting an assessment of the impacts on energy and fuel systems. The Lifelines Council, established in 2009, focuses on post-disaster resilience and recovery. This includes developing and improving collaboration in the city and across the region; understanding intersystem dependencies to enhance planning, restoration, and construction; sharing information about recovery plans, projects, and priorities; and establishing coordination processes for lifeline restoration and recovery following a major disaster event. The council's 2014 *Lifelines Interdependency Report*[52] examined the degree to which each utility provider ("lifeline") depends upon post-disaster functionality of other lifeline systems to respond and restore their services.

In 2014, the region also developed the *Regional Catastrophic Earthquake Logistics Response Plan*[53] that, among other things, looked at impacts on fuel systems. The same year, the Association of Bay Area Governments issued a report, *Cascading Failures: Earthquake Threats to Transportation and Facilities*,[54] examining the impacts of an earthquake on fuel transmission systems. One initiative that emerged from this study was the establishment of an Energy Emergency Management Center[55] to provide a centralized management location for the coordination of energy emergencies.

5.5.4. Metro region's work on lifelines and preparedness

The Portland region previously had a group (including utilities) working on a lifelines approach. A lifelines group brings together the public and private sectors in a highly

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[49] Available online at https://olis.oregonlegislature.gov/liz/2021R1/Downloads/CommitteeMeetingDocument/238879.

[50] Ibid.

[51] Available online at https://olis.oregonlegislature.gov/liz/2021R1/Downloads/PublicTestimonyDocument/23018.

[52]Available online at https://sfgov.org/ccsfgsa/sites/default/files/ORR/documents/Lifelines%20Council%20Interdependency%20Study.pdf.

[53] Available online at http://bayareauasi.org/sites/default/files/resources/Regional%20Logistics%20Response_February%202014.pdf.

[54] Available online at https://abag.ca.gov/sites/default/files/infrastructurereport_2014.pdf.

[55] Example of exercise conducted at center available at https://www.thereporter.com/2020/01/23/earthquake-response-exercise-launches-new-vacaville-emergency-response-center/.

strategic effort "to ensure a rapid recovery from a major disaster." In the California example, they "develop a unified set of post event performance standards, both individually and collectively, for public and private utility providers."[56] This Oregon group had been funded by a US Department of Homeland Security Urban Area Security Initiative grant,[57] and it developed criteria and identified and inventoried critical infrastructure in the region. However, a lack of funding and other challenges made it difficult to keep this group going.

The Portland area does have structures that provide cohesion for much of its preparedness and mitigation work. Since 2012, the greater Portland/Vancouver area has benefitted from the creation of the Regional Disaster Preparedness Organization, whose mission is to help the region be "secure and disaster-resilient." They work with "local agencies, organizations, and communities [to ensure that they] are coordinated and prepared to prevent, protect against, mitigate, respond to, and recover from threats and hazards,"[58] including earthquakes. The area also has a regional government, Metro, which has an emergency manager and assists in resilient transportation planning as it serves as the area's metropolitan planning organization. While these organizations serve as important venues for regional preparedness and coordination work, they do not have the specific resources, infrastructure, or authorities to support a lifelines group similar to the one in the Bay Area.

5.5.5. Collaborative research on soil liquefaction and land damage: Canterbury earthquakes

In the wake of New Zealand's 2010–11 Canterbury earthquakes, which triggered widespread liquefaction and land damage, New Zealand has worked to become a global leader on seismic engineering research focused on techniques to make their earthquake-prone nation more resilient. Their Earthquake Commission, which invests "in natural disaster research [and] education,"[59][60] sponsors collaborative research focused on identifying, developing, and trialing "affordable and practical shallow-ground improvement methods that can be used to strengthen residential land."[61] Through their Ground Improvement Programme, they have "ground piloted" a range of engineering techniques including hard soil mixing, stone columns, driven timber poles, deep gravel raft, cement soil mixing, and rotovated soil mixing with the hope their research and techniques can be applied "throughout New Zealand and globally."[62]

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[56] Available online at https://onesanfrancisco.org/lifelines.
[57] USAI grants fund "risk-driven and capabilities-based planning, organization, equipment, training, and exercise needs of high-threat, high-density Urban Areas," per the US Department of Homeland Security.
[58] Available online at https://rdpo.net/what-we-do.
[59] Available online at https://www.eqc.govt.nz/about-eqc.
[60] It also provides insurance to residential property owners.
[61] Available online at https://www.eqc.govt.nz/what-we-do/research-programme/ground-improvement-programme#node-detail-1930.
[62] Ibid.

The country also holds annual conferences with “the brightest and most experienced engineers from universities and practice”[63] from around the world to share knowledge on how to become more seismically resilient. They hold design competitions to train up the next generation of seismic engineers, and work to share their shared research globally. Their most recent conference was held in April 2021.

5.6. Northwest Planning Actions Currently Underway

In 2016,[64] the first National Level Exercise involving a 9.0 Cascadia subduction zone earthquake and tsunami was conducted. The four-day exercise brought together agencies across federal, state, local, tribal, international, and private sectors in response to the Pacific Northwest’s worst-case disaster scenario. Cascadia Rising 2016 tested the public and private sectors capabilities within zero to ninety-six hours of a CZE to coordinate operational communications, situational assessment, and provide medical and mass care services. Another National Level Exercise is scheduled for 2022, called Cascadia Rising 2022. It will build on Cascadia Rising 2016 and examine new plans and progress made in the intervening years. Cascadia Rising 2022 exercise play begins ninety-six hours into the CZE and focuses on interagency and multi-state public and private sector coordination to restore critical infrastructure and lifeline services.

6. RECOMMENDATIONS

Oregon Solutions wishes to acknowledge the progress made over the last decade to raise awareness about the exposure the hub has to liquefaction in the event of a CZE and the need for better information to guide policymakers, owners, and impacted communities to best mitigate for the impact. Based on our interviews, we have identified the following recommendations we believe will advance the ongoing work of mitigation:

- **Hold a hub-wide worst case scenario exercise at Cascadia 2022.** We are encouraged by the strong cross-sector support for a hub-wide worst case scenario exercise. Most interviewees we spoke with believe training like this is long overdue. Interviewees said the training should include participants from all across Oregon given the statewide significance of the hub and the different types of mitigation approaches that will be needed. We also heard concerns from interviewees in a few sectors that such training should not be siloed and that sectors need to be integrated in order to get the most out of this effort. The soonest potential opportunity for this training is the upcoming Cascadia 2022 training. We understand that an energy sector focus is being considered for this event. If this is the case, we strongly encourage planners to consider an exercise focused on the entire CEI hub given its

[63] Available online at https://www.scoop.co.nz/stories/SC2104/S00008/top-earthquake-engineers-share-decade-of-seismic-progress.htm.

[64] Available online at https://www.fema.gov/press-release/20210318/emergency-managers-announce-improvements-after-cascadia-rising-exercise.

vulnerabilities and significance to such a large population that is geographically dispersed.

- **Conduct an asset review of emergency responders' human capital and infrastructure.** Based on input from interviewees, we find that an asset review of emergency responders' human capital and infrastructure may be beneficial for CZE response. This type of analysis would be best informed following a hub-wide worst case scenario drill and subsequent debrief. The state has good tools to request information from local fire chiefs about resource capacity that exists today. The state also benefits from its regionally based HazMat teams who are composed of "career and volunteer fire-fighters, with some law enforcement and public works employees."[65] However, given concerns raised about the decline in volunteer firefighters, aged equipment, and inadequate funding streams this kind of analysis should be considered.

- **Assess the need and benefits of an urban search and rescue team for Oregon.** Oregon used to be part of FEMA's Urban Search and Rescue System (Oregon Taskforce 1). In lieu of that system of trained responders and equipment, today Oregon relies on support from teams in other states. During a CZE, Oregon would need to know if those teams would have the capacity to respond to Oregon's call for help. We noted that the state has made strides to fill the gap left by the loss of Oregon Taskforce 1 through the Oregon Safety Assessment Program. Even with the Oregon Safety Assessment Program and efforts by state policymakers, we heard in our interviews that Taskforce 1 had great benefit for Oregon. We suggested that any consideration for a revised urban search and rescue system program for Oregon be incorporated into an asset review for first responders to help determine the potential needs and benefits of the program in today's emergency response environment.

- **Cross-sectional collaborative—education and trust building.** We recommended in our previous assessment report on the CEI hub that there be a cross-sector effort to provide education about how each sector works and to help with trust and relationship building. This recommendation was in lieu of a collaborative effort focused on identifying incentives to help with mitigation of the hub. At that time, we did not find that the conditions existed for a collaborative effort focused on incentives. Regardless, today we found stronger support for a collaborative cross-sector effort. Earlier in our findings, we outlined what interviewees told us would be important for a successful collaboration. That information combined with the other offered examples provide a great deal of substance for a meaningful collaboration. Interviewees told us a collaborative effort is the best forum for lasting agreements and relationship building. We agree on this point and stress that for a collaborative effort of this kind to succeed, it will require strong buy-in, ongoing support from key leaders, and mechanisms for the collaborative group to realize its work.

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[65] Available online at https://www.oregon.gov/osp/programs/sfm/Pages/Regional-Response-Teams.aspx.

APPENDIX A: INTERVIEW QUESTIONS

- How familiar are you with resiliency issues related to the critical energy (CEI) hub?

- In broad terms, can you describe how a catastrophic Cascadia Subduction Zone event might impact your industry or region if it were to happen today? (Please elaborate on your thinking for short-, mid-, and longer-term impacts). How would it impact your greater community where you work/reside (if relevant)?

- In your sector/region, are there conversations about the potential for a Cascadia Subduction Zone event (or other related disasters) given we are in the middle of a pandemic? Are you aware if there is planning or other action underway to prepare? Why or why not?

- Can you elaborate on perspectives in your sector/region about what a moderate or severe Cascadia Subduction Zone event would mean if it were to happen today? Is there concern, or is there minor worry? Why?

- What would you (e.g., your sector, your business) need to have in place today in order to adequately survive/respond if the CEI hub were catastrophically or severely damaged? Of these, what is your *highest priority*?

- What *barriers* might there be to mitigate the hub from a CZE?

- What *support* might there be to mitigate the hub from a CZE?

- Both Oregon Solutions and OSSPAC previously recommended there be a table convened for collaborative cross-sector education of critical partners who have a connection to the hub. Do you think this is still important today? Why?

    - If yes, would you (or your industry/sector) be willing to participate in something like this?
    - What would you hope to get out of a process like this?
    - Are there critical issues/challenges/hurdles that might need to be resolved in order to bring people to the table?
    - How would you suggest addressing these challenges/issues/hurdles?

- Who else would you recommend be interviewed for this assessment? For example, who are the *critical* players in relation to this issue (e.g., federal, state, local, private)?

APPENDIX B: KEY PARTIES

Federal Agencies

Pipelines & Hazardous Materials Safety Administration PHMSA (within US Department of Transportation)

Federal Energy Regulatory Commission

US Coast Guard

Bonneville Power Administration

Department of Homeland Security

US Geological Survey

Federal Emergency Management Administration

US Army Corps of Engineers

Environmental Protection Agency (if there is a connection to Portland Harbor Superfund)

State Agencies/Tribes

Oregon Public Utilities Commission

Oregon Department of Environmental Quality

Oregon Department of Energy

Oregon State Fire Marshal

Oregon Department of State Lands (they own riverbeds)

Oregon Department of Geology and Mineral Industries

Oregon Department of Consumer & Business Services—State Building Codes

Oregon Emergency Management

Oregon Department of Transportation

Oregon Health Authority

Oregon Tribes

Oregon Department of Land Conservation & Development

Local/Regional Agencies

City of Portland

City of Salem

City of Eugene

City of Medford

Firefighting divisions

Regional Disaster Preparedness Organizations

Other

Individual oil companies

Conservation groups

Public leaders, including leaders from Eugene, Salem, and Medford (see this as a statewide issue)

Western States Petroleum Association

Oregon Fuel Association

Community groups

Utilities

Port of Portland

APPENDIX C: INTERVIEWEES

Tom Armstrong, Portland Bureau of Planning and Sustainability

Denise Barrett, Regional Disaster Preparedness Organization

Abby Boudouris, Department of Environmental Quality

Tiffany Brown, Clatsop County Emergency Management

Prof. Stephanie E. Chang, University of British Columbia

Lt. Dean Chappell, Code Enforcement/Fire Marshal, Lane County Fire Authority

Alex Crooks, BP

Allen Fore, Kinder Morgan

Sherrie Forsloff, Oregon Health Sciences University

Richard Franklin, US Environmental Protection Agency

Kylie Grunow, BP

David Harrelson , Confederated Tribes of Grand Ronde

Mike Harryman, Oregon Governor's Office

Michael Heffner, Oregon Office of State Fire Marshal

Deanna Henry, Oregon Department of Energy

Jeff Hibner, NuStar Energy

Andrew Holbrook, Kinder Morgan

Bob Houston, Oregon Department of Geology and Mineral Industries

Holli Johnson, Western States Petroleum Association

John Johnson, Oregon Department of Transportation

Ed Jones, Former Chair of the Linnton Neighborhood Association

Gene Juve, City of Vancouver

Ian Keene, Confederated Tribes of Siletz Indians

Leon Kempner, Bonneville Power Administration

Robert Kentta, Confederated Tribes of Siletz Indians

Mark Landauer, Oregon Public Ports Association/Business Oregon

Aaron Lande, City of Vancouver

Mike Lewis, Clark County Emergency Services Agency

David Maydew, Space Age Fuel

Mark McKay, US Army Corps of Engineers, Portland District

Chad Minter, Fire Chief, Coburg Fire District

Mike Myers, Portland Bureau of Emergency Management

Doug Nilsen, BP

Jonna Papaefthimiou, Portland Bureau of Emergency Management

Dan Pippenger, Port of Portland

Jennifer Purcell, Regional Solutions

Holly Robinson, Maritime Fire and Safety Association

Danelle Romain, The Romain Group, LLC, for the Oregon Fuels Association

Nina Rubenstein, Providence Medical Center

Akiko Saito, Oregon Health Authority

Mike Saling, Portland Water Bureau

Danny Santos, Legislative Commission on Indian Services

Paul Slyman, Metro

Scott Smith, Department of Environmental Quality

Robert Taylor, City of Portland

Mariana Ruiz Temple, Oregon State Fire Marshal

Emily Tritsch, Portland Bureau of Transportation

Anthony Vendetti, Clark County Emergency Services Agency

Chris Voss, Multnomah County

Torey Wakeland, Confederated Tribes of Grand Ronde

John Walsh, City of St. Helens

Yumei Wang, Portland State University

John Wasiutynski, Multnomah County

Darise Weller, Linnton Neighborhood Association

John Wheeler, Washington County

Jay Wilson, Clackamas County

APPENDIX D: RELATED STUDIES

The following is a series of studies focused on resiliency and surviving a Cascadia Subduction Zone event (with an emphasis on work specific to the CEI hub).

- In 1999, the Oregon Department of Geology and Mineral Industries (DOGAMI) published a preliminary statewide damage and loss study identifying the dire consequences of a Cascadia earthquake and tsunami for Oregon's infrastructure and for public safety."[66]

- In 2011, the Oregon Legislature passed House Resolution 3 directing the Oregon Seismic Safety Policy Advisory Commission (OSSPAC), "to lead and coordinate preparation of an Oregon Resilience Plan that reviews policy options, summarizes relevant reports and studies by state agencies [in order to make] recommendations on policy direction to protect lives and keep commerce flowing during and after a Cascadia earthquake and tsunami."[67]

- In 2012, DOGAMI released the *Energy Assurance Plan*, which focused on the CEI hub and found it was at significant risk from a seismic event based on "visual observations, engineering judgment, limited analyses, and limited information from the facility operators, city records, and available literature."[68] It further noted that while earthquakes are rare in Oregon, the risk (or 'vulnerability score') to the state is very high given that much of Oregon's existing infrastructure was designed and constructed without consideration of seismic resistance, and due to the "likely result [of] high loss of life, economic damages and long-term impacts."[69]

- In response to HR 3 (2011), OSSPAC issued its *Oregon Resilience Plan* report in 2013. This report explored the likely impacts, acceptable time frames, and changes in practices and policies "that, if implemented during the next 50 years, will allow Oregon to reach the desired resilience targets."[70] It noted that infrastructure at the hub ranged in age from "about 100-years-old" to "new infrastructure built to the current state-of-practice standards." Of the energy sector, they wrote it "recognized the need to prepare its systems for seismic events and other disasters that could have an impact on customers," and there were efforts to update and replace energy infrastructure to current design standards. The resilience plan offered numerous recommendations (pages 175-76) to improve energy resilience, including that "in emergency situations, liquid fuel wholesale and retail operators provide both access to and alternate means of delivering fuels to the end users," and that "energy sector

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[66] Available online at https://www.oregon.gov/lcd/NH/Documents/Apx_9.2.3_OR_Res_Plan_Final_OPT.pdf.

[67] Available online at https://olis.oregonlegislature.gov/liz/2011R1/Downloads /MeasureDocument/HR0003/Enrolled.

[68] Available online at https://www.oregongeology.org/earthquakes/CEI-Hub-report.pdf

[69] Ibid.

[70] Available online at https://www.oregon.gov/lcd/NH/Documents/Apx_9.2.3_OR_Res_Plan_Final_OPT.pdf.

companies should conduct seismic vulnerability assessments … and develop plans to mitigate the seismic risks associated with the identified CEI vulnerabilities."[71]

- In 2014, the Oregon Legislature passed SB 33 creating a task force charged with implementing the recommendations to the Oregon Resilience Plan. The task force, known as the Governor's Task Force on Resilience Plan Implementation,[72] recommended a variety of things, including the creation of a resilience policy advisor to be housed in the Oregon Governor's Office, "capital expenditures toward infrastructure, increased focus on developing community resilience, and structural improvements to critical facilities."[73] Specific to liquid fuels, it recommended that "the State establish a public-private partnership to mitigate and evaluate diversification of locations for storing liquid fuels, and identification of new liquid fuel energy corridors."[74]

- In 2017, the City Club of Portland released a report titled *Big Steps before the Big One: How the Portland Area Can Bounce Back After a Major Earthquake*. The authors of the report argue that while other communities were surprised by recent strong earthquakes, "Portland … has been warned of [the] approaching disaster."[75] Authors noted how many storage tanks were built "long before construction standards took earthquake risks into account," that some "were built more than 100 years ago, and some have been replaced," and that the "risk of tank failure is particularly severe due to the nature of the soil upon which the CEI hub stands."[76] To address these and other concerns, the authors were particularly interested in incentive programs geared toward tank owners to address risk, hardening of soils at the site, designating a state agency to work with tank owners and stakeholders on a plan for crisis response and recovery, and consideration of a stronger regulatory regime for tank farms in Oregon based on similar examples in other states, (e.g, California's MOTEMS program).

- In 2019, the Oregon Seismic Policy Advisory Safety Commission (OSSPAC) issued a report focused on exploring the regulatory authority for seismic upgrades of liquid fuel tank infrastructure, incentives, and consideration of stronger mitigation efforts, among other things.[77] OSSPAC found the hub could be a "major threat to safety, environment, and recovery" on par with Japan's 2011 Fukushima nuclear meltdown after a Cascadia Subduction Zone event; that owners of liquid fuel tanks at the hub "need to be compelled to seismically strengthen their infrastructure;" and, that no state agency was a "perfect fit to be designated as the regulatory authority over [the

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71 Available online at https://www.oregon.gov/lcd/NH/Documents/Apx_9.2.3_OR_Res_Plan_Final_OPT.pdf.
72 Available online at https://www.oregon.gov/oem/Documents/2014_ORTF_report.pdf.
73 Available online at https://www.portlandoregon.gov/pbem/article/504774.
74 Available online at https://www.oregon.gov/oem/Documents/2014_ORTF_report.pdf.
75 Available online at https://drive.google.com/file/d/13KM_9sC1Pg8KAfhYdZyxOWv3tHoJfFx2/view.
76 Ibid.
77 Available online at https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf.

CEI hub] facilities." The report included a series of recommendations, including that the Department of Environmental Quality have regulatory oversight of liquid fuel facilities, the establishment of cross-agency Oregon administrative rules to govern the safety of above-ground liquid fuel tanks, and the full funding of ShakeAlert along with an implementation of a ShakeAlert pilot project at the CEI hub.

APPENDIX E: OIL SPILL RESPONSE GOVERNANCE & FACILITY PLANS

Today's general framework for response and recovery to oil spills in the United States came in the wake of the March 1989 *Exxon Valdez* accident and the public outrage that ensued. The spill highlighted "inadequacies" of the existing coverage of "multiple federal statutes, state statutes, and international conventions that dealt with oil discharges."[78] To address these inadequacies, Congress passed the Oil Pollution Act of 1990, "the first comprehensive law to specifically address oil pollution to waterways and coastlines of the United States."[79]

Within the Oil Pollution Act, "Congress consolidated the existing federal oil spill laws under one program."[80] It changed what was seen as an *overreliance* on the idea that "spillers would perform proper cleanup," and strengthened the federal government's role in oil spill response and cleanup.[81] For example, the federal government provides on-scene coordinators to determine the level of clean up required from a spill and when it can be ended. In the Columbia River, the on-scene coordinator is the US Coast Guard.[82] States can require further work on a spill beyond what the coordinator requires, but that happens without support of federal funding.[83]

Response Planning

The established framework for oil spill response in the United States is the National Oil and Hazardous Substances Pollution Contingency Plan, commonly referred to as the National Contingency Plan. It was established in 1968 in the wake of an oil tanker spill, the *Torrey Canyon*, when President Johnson, "directed the Secretary of the Interior and Secretary of Transportation to investigate preventing other major oil pollution incidents."[84] The plan established, "the procedures for the federal response to oil … spills,"[85] and "has been revised multiple times since."[86] Those procedures can be found in the National Response System, which "establishes the respective roles of federal, state, and local governments in carrying out a federal response, including the party or parties responsible for the incident and other private entities that may wish to contribute resources."[87] Moreover, it is "capable of expanding or contracting to accommodate the response effort required by the size or complexity of the discharge or release."[88]

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[78] Available online at https://fas.org/sgp/crs/misc/RL33705.pdf.
[79] Ibid.
[80] Ibid.
[81] Ibid.
[82] Available online at https://readallaboutitoregon.wordpress.com/2014/07/29/preliminary-statewide-rail-safety-review/.
[83] Available online at https://fas.org/sgp/crs/misc/RL33705.pdf.
[84] Available online at https://guides.loc.gov/oil-and-gas-industry/controversies/oil-spills.
[85] Available online at https://fas.org/sgp/crs/homesec/R43251.pdf.
[86] Ibid.
[87] Ibid.
[88] 40 C.F.R. §300.5.

Role of National and Other Governments in an Oil Spill Response

The National Response System is implemented through National Response Teams, a series of fifteen federal departments and agencies that each have specific roles. State, territorial, local, and tribal governments also participate in the National Response Teams through Regional Response Teams. It is generally acknowledged that "the first government representatives on the [Regional Response Teams] to arrive at the scene of a discharge or release take initial response actions. Consequently, state, territorial, or local officials usually are the first responders who may initiate immediate safety measures to protect the public."[89]

Facility Response Plans

The following is an excerpt from Burns McDonnell.[90]

> If a facility is regulated by the US Environmental Protection Agency (EPA), stores more than one million gallons of oil, and can potentially impact a sensitive environment, a facility response plan (FACILITY RESPONSE PLAN) is required. This document should thoroughly outline response strategies and define roles in the event of an oil spill, including who gets notified, where a release would go, and what could be impacted downstream. Though it is necessary to run through all scenarios, a FACILITY RESPONSE PLAN essentially prepares a facility for a worse-case scenario.
>
> **How Can a Facility Determine if a FACILITY RESPONSE PLAN Is Required?**
>
> If the answer is "yes" to any of the five checklist items below, a FACILITY RESPONSE PLAN is required by law.
>
> 1. Does the facility transfer oil over water to or from vessels AND does that facility have a total oil storage capacity greater than or equal to 42,000 gallons?
> 2. Does the facility have a total oil storage capacity greater than or equal to one million gallons AND within any storage area, does the facility lack secondary containment that is sufficiently large to contain the capacity of the largest aboveground oil storage tank plus sufficient freeboard to allow for precipitation?
> 3. Does the facility have a total oil storage capacity greater than or equal to one million gallons AND is the facility located at a distance such that a discharge from the facility could cause injury to fish and wildlife and sensitive environments?
> 4. Does the facility have a total oil storage capacity greater than or equal to one million gallons AND is the facility located at a distance such that a discharge from the facility would shut down a public drinking water intake?

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[89] Available online at https://fas.org/sgp/crs/homesec/R43251.pdf.

[90] Content from Burns McDonnell Blog available online at https://blog.burnsmcd.com/this-is-not-a-drill-perfecting-spill-response-strategies.

5. Does the facility have a total oil storage capacity greater than or equal to one million gallons AND has the facility experienced a reportable oil spill in an amount greater than or equal to 10,000 gallons within the last five years?

What Should Be Included in a FACILITY RESPONSE PLAN?
Some of the topics to be noted within the document's 10 sections include emergency response information, response equipment, evacuation plans, discharge scenarios, plan implementation, and facility drills and exercises. Additional details are available from the Environmental Protection Agency.[91]

Playing out numerous scenarios helps determine off-site response locations that can be identified using specific mapping techniques to create a spill planning distance. Regulations give guidance for calculating how far the spill will go once it hits a body of water, allowing facilities and environmental specialists to conduct research along that spill planning distance to pinpoint what could be impacted.

Next is documenting what happens if a release gets off-site. For instance, could the spill flow into a drainage ditch where underflow dams might be constructed? Or, if it is headed toward a river, where containment booms could be deployed? Facilities required to have FACILITY RESPONSE PLANs must have access to 1,000 feet of containment boom within an hour. If that's not possible because of limited storage capacity or budget, a facility can rely on its designated oil spill response organization (OSRO), an independent spill contractor, to provide all necessary equipment. Regardless of where the equipment is housed, it still must be delivered within the one-hour time frame.

To know exactly how facility personnel will respond in a time of crisis it is mandatory as part of the FACILITY RESPONSE PLAN requirement to conduct a series of tabletop exercises and drills, as listed within the National Preparedness for Response Exercise Program (PREP) Guidance Document.[92] Release scenarios are key to being prepared, as such scenarios outline all the requirements for properly executing a response plan.

To meet quarterly and semiannual requirements, a facility's OSRO verifies the necessary drills and exercises were performed as expected and within the required time frame. The documentation process includes confirmation

[91] Available online at https://www.epa.gov/oil-spills-prevention-and-preparedness-regulations/key-elements-include-facility-response-plan-frp.
[92] Available online at https://www.bsee.gov/sites/bsee_prod.opengov .ibmcloud.com/files/final_2016_prep_guidelines.pdf.

that the equipment was deployed, or tested, which also is an annual requirement.

What Are the Mandatory Drills and Exercises?
According to the Environmental Protection Agency, the US Department of Transportation, US Coast Guard, and the Bureau of Safety and Environmental Enforcement, the National Preparedness for Response Exercise Program Guidance Document is viewed as the standard for how to execute required drills and exercises as part of a FACILITY RESPONSE PLAN. While some are conducted quarterly and others are conducted semiannually or annually, all require documentation of completion.

Annual Spill Tabletop Exercise: Typically initiated by management, the tabletop exercise brings the facility response team together to discuss spill scenarios and review response actions: what to do, who to call, what equipment to use, what could be affected. The OSRO is required to either participate in the facility's annual tabletop exercise or conduct its own. As this is a conversation-based exercise, no equipment is deployed.

Once every three years, however, this tabletop exercise has to focus on the worst-case discharge scenario.

Semiannual Equipment Deployment Exercise: Environmental Protection Agency-regulated facilities are required to deploy facility-owned equipment two times a year. If a facility doesn't own or maintain its own equipment — some only have spill kits—response team members can still practice what to do on-site and run through the step-by-step procedures that have been put in place for such an event. For a facility that relies on its OSRO to supply equipment, there is a requirement within the National Preparedness for Response Exercise Program guide document that the OSRO deploy spill response equipment at the facility or within a similar environment on an annual basis. Because this can be quite an expense, the government will accept correspondence from the OSRO that certifies the facility has deployed equipment as required.

Facilities that have their own boom on-site should deploy it according to the action plan so the response team knows how to respond in that scenario. The team should be familiar with where the equipment is stored, what shape it is in, and where exactly to deploy it.