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EARTHQUAKE RISK STUDY FOR OREGON'S CRITICAL ENERGY INFRASTRUCTURE HUB

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2013

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NOTICE

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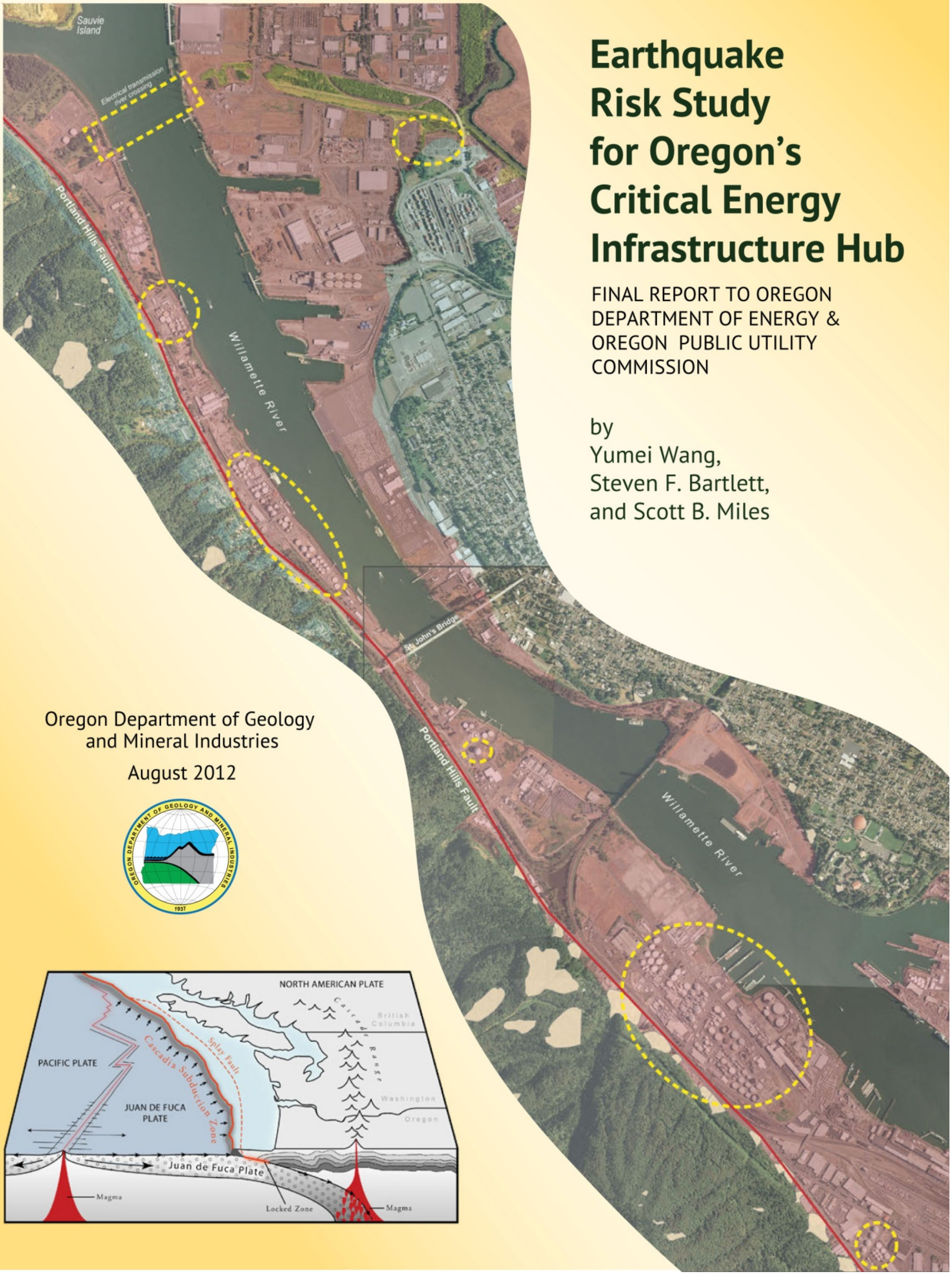

Earthquake Risk Study for Oregon's Critical Energy Infrastructure Hub

FINAL REPORT TO OREGON DEPARTMENT OF ENERGY & OREGON PUBLIC UTILITY COMMISSION

by
Yumei Wang,
Steven F. Bartlett,
and Scott B. Miles

Oregon Department of Geology and Mineral Industries
August 2012

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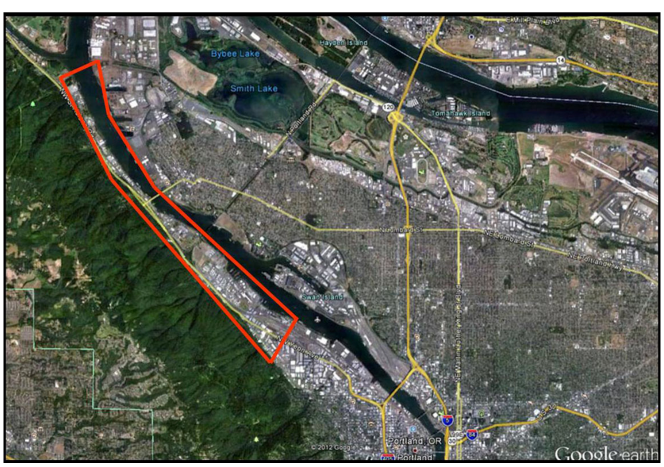
Six magnitude 5 or higher earthquakes have occurred within the Portland metropolitan area in the past 150 years. The Cascadia Subduction Zone has produced more than 40 large magnitude earthquakes in the past 10,000 years. The most recent occurred on January 26, 1700 with an estimated magnitude 9. These occurrences and extensive scientific understanding of seismic processes indicate that it is not a question of *if* Oregon will experience a catastrophic earthquake, but *when* it will occur.

Oregon's critical energy infrastructure (CEI) Hub is located in an area with significant seismic hazard. Significant liquid fuel, natural gas and electrical infrastructure and facilities are situated in this relatively small area in Portland. The CEI Hub covers a six-mile stretch on the lower Willamette River located between the south tip of Sauvie Island and the Fremont Bridge on US Highway 30. The energy sector facilities in the CEI Hub include:

- All of Oregon's major liquid fuel port terminals
- Liquid fuel transmission pipelines and transfer stations
- Natural gas transmission pipelines
- Liquefied natural gas storage facility
- High voltage electric substations and transmission lines
- Electrical substations for local distribution

More than 90 percent of Oregon's refined petroleum products come from the Puget Sound area of Washington State. Oregon imports the product by pipeline and marine vessels to the CEI Hub before it is distributed throughout Oregon to the end user. One large consumer is the Portland International Airport. In addition, much of NW Natural's natural gas passes through the CEI Hub. A high voltage electrical transmission corridor crosses the area as well as supplies distribution for this area.



Site map of the Critical Energy Infrastructure (CEI) Hub on the western bank of the Lower Willamette River area in NW Portland, Oregon. The CEI Hub, outlined in red, stretches for six miles. (Google Earth)

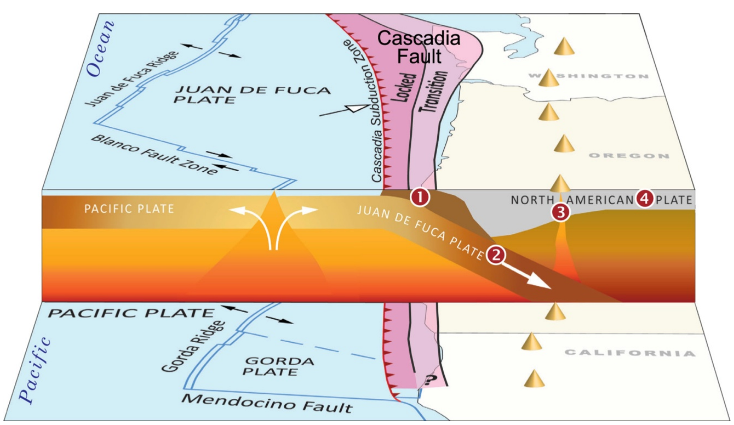
Oil terminals in the CEI Hub. (DOGAMI photo)

Earthquake Risk Study for Critical Energy Infrastructure Hub

The Oregon Department of Geology and Mineral Industries (DOGAMI) conducted an earthquake risk study on Oregon's CEI Hub as part of the Oregon Energy Assurance Project (EAP) with Oregon Department of Energy (ODOE) and Public Utility Commission of Oregon (OPUC). The study focuses on a large-magnitude Cascadia earthquake which because of widespread shaking and vulnerable infrastructure poses a high risk to the health and safety of Oregonians and the region's economy. The study identifies and defines the CEI Hub area, assesses the seismic hazards and identifies the vulnerabilities of the petroleum (liquid fuel), natural gas, and electric energy facilities in the CEI Hub.

Oregon's Natural Hazards

Oregon has numerous natural hazards. These range from high probability (fires) to low probability (volcanic eruptions). Earthquakes are considered to have a moderate probability because earthquakes in Oregon are rare. The earthquake vulnerability score for Oregon, however, is very high because a vast majority of Oregon's existing infrastructure has been designed and constructed without seismic resistance considerations. The earthquake consequence score is also very high because damage will likely be widespread and, in many places, severe. Finally, the earthquake overall risk score is very high because when a major earthquake occurs, it will likely result in a high loss of life, economic damages and long-term impacts.



Cascadia seismic source is Oregon's most threatening fault and can produce a magnitude 9 earthquake and accompanying coastal tsunami waves. (DOGAMI)

Energy Facilities in the CEI Hub

A significant portion of Oregon's electricity, natural gas, and fuel oil infrastructure is concentrated in the CEI Hub (a six-mile stretch in the lower Willamette River located between the south tip of Sauvie Island and the Fremont Bridge on US Highway 30). A magnitude 8 or 9 Cascadia Subduction Zone earthquake would impact the CEI Hub with:

- Ground shaking
- Liquefaction (soil behavior phenomenon in which a saturated sand softens and loses strength during strong earthquake ground shaking)
- Lateral spreading (where surficial soil permanently moves laterally due to earthquake shaking)
- Landslides
- Co-seismic settlement (where the ground surface is permanently lowered due to seismic shaking)
- Bearing capacity failures (when the foundation soil cannot support the structure it is intended to support)

In addition, secondary seismic hazards could be initiated and include:

- Seiches (waves that oscillate in water bodies often initiated by ground shaking)
- Fire
- Hazardous material releases, including by sloshing of liquid agitated by ground shaking

Liquefaction and lateral spreading hazards are of primary concern to the oil terminals that handle Oregon's fuel supply. The CEI Hub is adjacent to the Willamette River and has extensive deposits of highly liquefiable soils. These soils (made of sands, silts, gravels and clays) have been naturally deposited by river activity as well as been created from man-made activities, such as hydraulically placed material from river dredging or debris placed as landfill. For this reason, DOGAMI performed ground deformation analyses to better understand the nature of the hazard and the possible mitigation needs. A section on the deformation analyses is included in this study. Tsunamis are expected to damage the coastal areas, including ports along the coast and Columbia River mouth, but are not expected to cause significant damage in the Portland waterways.

DOGAMI staff and others visited all relevant energy companies with facilities in the CEI Hub. DOGAMI and ODOE staff conducted site visits at these petroleum facilities: BP, Chevron, ConocoPhillips, KinderMorgan (KM) fuel terminals and KM pipeline, McCall Oil, Nustar, and Shell. The fuel facilities often include: transmission and distribution pipelines, piers or wharves, tank farms, loading racks, control buildings, electric distribution equipment, and many other components. The liquid fuel transmission system includes gate stations, and transmission and distribution pipes at the Columbia and Willamette river crossings. DOGAMI and OPUC staff also conducted site visits of natural gas and electrical facilities owned by NW Natural, Portland General Electric, and the Bonneville Power Administration (BPA).

General Findings

The CEI Hub facilities have infrastructure that ranges from about 100 years old built to no or very antiquated standards to new infrastructure built to the current state-of-practice standards. Because of the wide range of ages and associated construction practices, the seismic vulnerability of the facilities also spans a wide range. Based on visual observations, engineering judgment and limited information from the facility operators, major seismic vulnerabilities exist in the CEI Hub. The vast majority of the facilities are constructed on soils susceptible to liquefaction. Some critically important structures appear to be susceptible to significant damage in a major earthquake. In addition, DOGAMI discovered that older building codes and practices did not adequately address many non-building structures that exist in the CEI Hub, such as tanks, pipes, and piers. One explanation is because non-building structures typically hold few, if any, people and the focus of the building code has traditionally been on life safety. Current building codes do not adequately address the seismic deficiencies in existing CEI Hub facilities. The expected length of time to resume services after a Cascadia earthquake has not been evaluated by any company except BPA.

Sector Specific Findings

Liquid Fuel

Liquid fuel pipeline: The CEI Hub petroleum facilities receive liquid fuel via two methods: 1) the liquid fuel transmission pipeline, and 2) marine vessels. The transportation method and amounts vary due to product need, transportation costs, weather and other conditions. The liquid fuel pipeline was largely constructed in the 1960s when the regional seismic hazards were unknown and state-of-practice construction techniques at that time did not include any reference to seismic standards. The regional seismic hazards are now known to be significant and the soils at the river crossings are susceptible to liquefaction and lateral spreading. The 1960s vintage pipeline design did not consider ground movements from lateral spreading at river crossings or the stresses to the pipelines induced by earthquakes that may cause pipe damage and multiple breaks. A pipe break would have a significant impact on all of the petrochemical facilities in the CEI Hub and could result in a statewide fuel shortage.

Shipping channel: The navigational channel from the Columbia River mouth to the lower Willamette River is used to transport fuel by marine vessels. The Columbia River mouth is expected to have tsunami damage and the channel is expected to experience slope failure, which would close the channel to traffic. It is possible that bridges and other river crossings, such as buried gas pipelines and electrical crossings, would be damaged and temporarily block the waterway. Closure of the shipping channel would prevent marine vessels from delivering liquid fuel as well as emergency response and recovery equipment from being delivered.

Marine terminals: All of the port facilities in the CEI Hub have significant seismic risks due to liquefaction, lateral spreading, and seiches. Some older piers were constructed without any seismic protection, have deteriorated, and are likely to fail in even a moderate earthquake. If oil products are released and contaminant the navigable waterway, the waterway may be closed to river traffic thus impeding emergency response activities as well as the supply chain. The local capacity to fight fires and clean hazardous material spills is limited.

Fuel supply: Only three existing tanks are known to have addressed liquefaction vulnerabilities. The fuel terminals in the CEI Hub on average have a three to five day supply in the tank farms for regular unleaded gasoline and diesel fuel. Premium gasoline is subject to the daily delivery and heavily dependent on whether the intercompany pipeline on Front Avenue is operational. If the supply chain is disrupted by pipe breaks north of the CEI Hub and closure of the shipping channel to the west, fuel would quickly become scarce. Options to transport fuel from the east and south and by air are very limited.

Portland International Airport (PDX): PDX airport receives 100 percent of their liquid fuels from a terminal in the CEI Hub. PDX has a limited on-site fuel supply. If the pipeline between the CEI Hub and PDX fails, then PDX would likely experience a shortfall and operations would be impacted.


Left: Lateral timber bracing for steel plumb piles in the CEI Hub is considered inadequate by California's MOTEMS standards. (DOGAMI photo) Right: An example of a damaged pier in the 2010 Chile earthquake (Technical Council on Lifeline Earthquake Engineering – TCLEE, 2010)


This under-designed oil terminal pier foundation (left) in area with high susceptibility for liquefaction and lateral spreading in the CEI Hub and the poor timber-to-concrete oil terminal pier connection and exposed rebar foundation (right) in the CEI Hub are considered inadequate. (DOGAMI photo)

The connection on this pier in the CEI Hub appears to have deteriorated due to a split in the timber beam. This type of damage suggests that the condition of the structure may not be routinely monitored and maintained and that the overall pier is seismically vulnerable. (DOGAMI photo)

The approach (foreground) to the 1966 Astoria-Megler Bridge that spans the Columbia River has major structural deficiencies that could lead to a collapse following an earthquake. Damaged bridge sections could block waterway access to the CEI Hub. (DOGAMI photo)

Natural Gas

Natural gas: Oregon's largest natural gas service provider receives the majority of their natural gas from pipelines that cross under the Columbia River both near Sauvie Island and also between Washougal, Washington and Troutdale, Oregon. One of the natural gas pipelines crosses under the Willamette River at Multnomah Channel near their gate station at the southern end of Sauvie Island. The soils at these river crossings are subject to liquefaction and lateral spreading, the pipes are 1960s vintage and constructed without seismic design provisions, and the consequences of potential pipe failures could be major for natural gas service territories and Oregon. The natural gas company's storage capacity is limited and pipe breaks could lead to a natural gas shortfall in the state as well as explosions or fires.

Electricity

Electrical facilities: Electrical facilities and systems have significant seismic risk due to ground shaking and ground failure, including liquefaction and lateral spreading. Seismically vulnerable facilities include substations and transmission in the CEI Hub as well as facilities outside of the CEI Hub, including power plants, substations and transmission lines, all which are important for distribution.

Major vulnerabilities in the CEI Hub include the control buildings, transformers and other electrical equipment in yards at the substations, and transmission towers near the Willamette River. Damage is likely to occur to both the transmission system and the distribution system in the CEI Hub. Damage to the electrical grid will likely result in a blackout in the CEI Hub and elsewhere.

BPA: Bonneville Power Administration (BPA) has conducted a comprehensive seismic vulnerability study of their system and has had a long-term seismic mitigation program in place since 1993. BPA’s long-term seismic mitigation program includes 1) investment protection (e.g. anchoring transformers), and 2) power system recovery of critical paths (e.g. hardening of equipment at one of multiple bays within a major substation). The first phase of BPA's mitigation program includes bracing and restraining critical equipment and seismically upgrading critical building facilities west of the Cascade Range. Seismic strengthening in the substation yard would typically include: anchoring high-voltage power transformers; bracing transformer conservators and radiators; replacing seismically vulnerable live tank circuit breakers with more robust dead tank circuit breakers; adding damping systems to existing live tank circuit breakers; hardening transformer bushing storage facilities; replacing rigid bus connections with flexible bus. These mitigation techniques will improve the reliability of seismic performance. Additional phases of the seismic mitigation program will include facilities east of the Cascade Range.

BPA has a critical 115 kV and 230 kV high voltage transmission river crossing in the CEI Hub as well as a substation. At the substation in the CEI Hub, some of the high-voltage equipment had been anchored and braced to withstand earthquake motions. BPA is in the process of conducting seismic strengthening of the control building and equipment inside the control building (e.g., brace computer floors, control cabinets, battery racks, ceiling, pipes, etc) and additional mitigation in the yard. BPA has conducted subsurface, liquefaction and lateral spreading analyses at one of the transmission tower sites at the Willamette River crossing and concluded severe ground movement up to 25 feet towards the river channel is possible. Until mitigated, it is likely that at least two transmission towers would experience extensive damage, be inoperable, require repair or replacement, and power lines could temporarily block river traffic, including the pathway to the oil terminals. The BPA transmission towers at the Willamette River crossing are scheduled to be seismically analyzed, have a seismic mitigation design completed in 2013, and be mitigated by 2014.

Recent unpublished BPA Cascadia earthquake scenario studies of the existing transmission line system indicate that their main grid would require between 7 and 51 days to make emergency damage repairs to the transmission line system (Oregon and Washington) from a magnitude 9 Cascadia earthquake. This scenario assumes many ideal conditions (BPA employees and contractor resources are immediately available, all roads and bridges are passable, available fuel, etc), which is optimistic.

Left: These high voltage electrical transmission towers are built on a river bank in the CEI Hub susceptible to lateral spreading. (DOGAMI photo) Right: Structural damage to a high voltage transmission tower located at a river crossing in 2010 Chile earthquake (Technical Council on Lifeline Earthquake Engineering – TCLEE)

Impacts to Oregon

Based on visual observations, engineering judgment, limited analyses, and limited information from the facility operators, city records, and available literature, significant seismic risk exists in the CEI Hub. Some critically important structures appear to be susceptible to significant damage in a major earthquake with catastrophic consequences. Multiple liquid fuel transmission pipe breaks and natural gas transmission pipe breaks are possible. Damage to liquid fuel, natural gas, and electrical facilities in the CEI Hub is likely. The waterway would likely be closed and require clean up.

Due to a combination of the existing seismic hazards, vulnerability of the exposed infrastructure and potential consequences, Cascadia earthquakes pose substantial risk to the CEI Hub and to Oregon. Not only are the energy sector facilities in the CEI Hub dependent on other sectors and systems in Oregon, including transportation and communication, they are interdependent upon each other. A major Cascadia earthquake and tsunami would likely produce an unprecedented catastrophe much larger than any disaster the state has faced.

Western Oregon will likely face an electrical blackout, extended natural gas service outages, liquid fuel shortage, as well as damage and losses in the tens of billions of dollars in a future major Cascadia earthquake. Preparing for a catastrophic disaster to become more resilient is needed to improve personal safety and security, and safeguard communities and businesses.

Recommendations

The most critical call-to-action that DOGAMI has concluded from this study of the CEI Hub is this: Energy sector companies must **pro-actively integrate seismic mitigation** into their business practices for Oregon's energy sector to adequately recover from a magnitude 8.5 to 9 Cascadia earthquake in a reasonable time period.

Although energy sector companies have made efforts to prepare for seismic events, such as through emergency planning and complying with the current building codes, these efforts are limited and a timely restoration of energy sector services is questionable. As discussed in the Summary of Findings section, only one company has completed comprehensive seismic vulnerability assessments and instituted seismic mitigation plans. Energy sector companies must make earthquake mitigation an integral part of their overall business plan. This is not only prudent for the impact a large magnitude Cascadia earthquake would have on Oregonians and the environment; it is good business continuity management. Oregon homes, businesses and industries depend upon reliable energy sources. Liquid fuel, natural gas and electricity are critical to our economy, environment and everyday existence, and the energy sector must do more in order to assure those services and products in the event of a large earthquake.

In order for the energy sector to pro-actively integrate seismic mitigation into their operations, DOGAMI makes these four recommendations to both private and public energy sector stakeholders:

1. Energy sector companies should conduct ***Seismic Vulnerability Assessments*** on all of their systems or facilities, and should work with the appropriate local, state, tribal and federal government agencies and stakeholders to achieve timely completion of the assessments to understand existing vulnerabilities.
2. Energy sector companies should institutionalize long-term ***seismic mitigation programs;*** and should work with the appropriate local, state, tribal and federal government agencies and stakeholders to achieve timely and effective mitigation to ensure facility resilience and operational reliability.
3. The State of Oregon's ***Homeland Security Council*** should review the vulnerability and resilience of the energy sector to earthquakes and other natural disasters within the scope of their mission. This could involve the EAP partners (ODOE, OPUC, and DOGAMI) as well as ODOT, Building Codes Division, and the Oregon Seismic Safety Policy Advisory Commission (OSSPAC).
4. Energy sector companies and the State of Oregon should ***build Oregon's seismic resilience*** to a Cascadia earthquake. Adopting pro-active practices and a risk management approach will help achieve seismic resilience. Encouraging a culture of awareness and preparedness concerning the seismic vulnerability of the energy sector including long range energy planning should be conducted.

Emergency batteries, as well as other components such as generators and communication devices, should be braced or anchored to a withstand Cascadia earthquake. (DOGAMI photo)

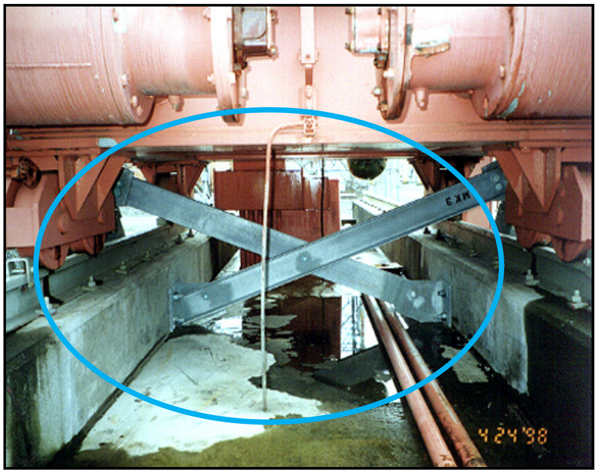


Photo shows the front view of an existing transformer with seismic anchorage including steel cross bracing as mitigation. (Photo: Leon Kempner)

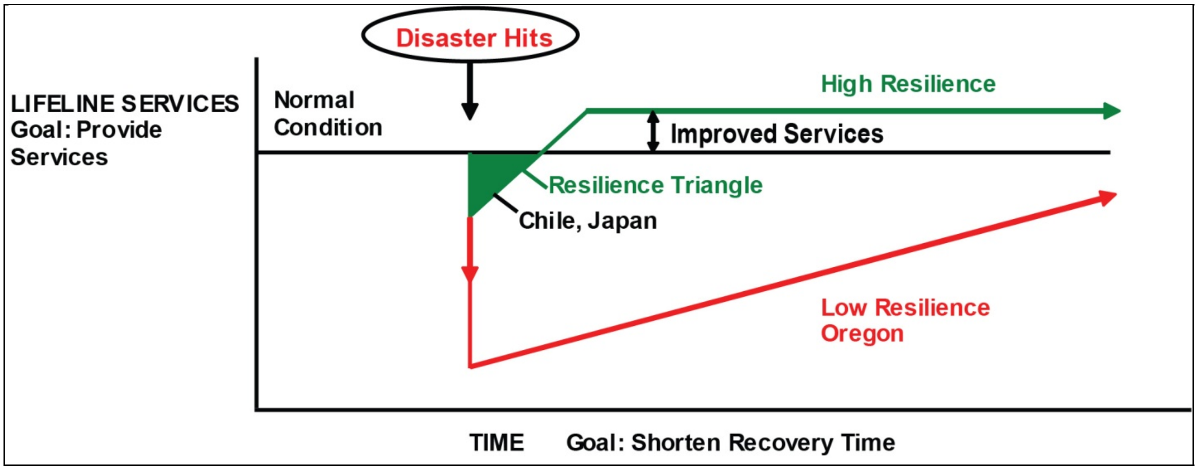
The length of time to resume services after a Cascadia earthquake should be evaluated by each energy company to establish a baseline understanding, and improvements to achieve a satisfactory service level should be made. Improvements, for example, can involve adding stone columns to strengthen the ground against liquefaction-related damage and anchoring power transformers to prevent sliding-related damage.

For the EAP, DOGAMI developed the resilience triangle graph with the resilience triangle shown in green. (*See figure)* The basic principle of the resilience triangle is that the smaller the triangle, the higher the resilience. Higher resilience requires minimal reductions in critical lifeline services after a disaster, speedy recovery of those services, and an overall improved service level as a result of rebuilding damaged systems and implementing better systems. The resilience triangle diagram indicates that Chile and Japan have high levels of earthquake resilience on the basis of their performance after the 2010 magnitude 8.8 earthquake in Chile and 2011 magnitude 9.0 earthquake in Japan (notwithstanding the nuclear energy issues). At the current stage, Oregon's energy sector has low resilience and is expected to have significant loss of energy sector services and a slow recovery time.

Funding is essential to increase Oregon's seismic resilience in the energy sector, and to:

- Pay for assistance and oversight to compel private sector companies into action to conduct Seismic Vulnerability Assessments and implement seismic mitigation programs
- Support an effective Homeland Security Council on energy security preparedness
- Build the State of Oregon's energy resilience
- Increase Oregonians' awareness of the effect of a Cascadia earthquake on energy availability

As part of this project, DOGAMI and EAP partners promoted seismic awareness of Oregon's critical energy infrastructure. We developed productive relationships with other state agencies, federal agencies, energy sector companies, associations, emergency response organizations and other major stakeholders regarding seismic preparedness. We conducted table-top exercises and outreach and have more planned with energy companies and associations. The EAP partners have made more than 60 presentations to various stakeholders during the duration of this study.



Resilience Triangle (modified from MCEER)

These efforts were minimal, however, considering the task at hand. In order to build resilience in Oregon's energy sector, it is necessary to increase awareness on the risk to the energy sector and Oregonians from a Cascadia earthquake. There needs to be a cultural shift by Oregonians to become an earthquake-prepared culture. The energy sector must demonstrate transparency and accountability concerning Cascadia earthquake preparedness activity.

This study has demonstrated that Oregon's CEI Hub is vulnerable to a Cascadia earthquake, and that such an earthquake will impact our supply and sources of liquid fuel, natural gas and electricity throughout Oregon.

Oregonians should heed this study's findings, that:

- A Cascadia earthquake will occur.
- Oregon's CEI Hub – where critical energy infrastructure is located in a six-mile stretch of land – is vulnerable to a Cascadia earthquake.
- Oregon's resilience to a Cascadia earthquake is low.
- Energy sector companies must adopt best practices and pro-actively integrate seismic mitigation efforts into their business operations to prepare their facilities and systems to absorb and recover from a Cascadia earthquake and to sufficiently restore critical electric, natural gas and liquid fuel services to Oregon homes, businesses and industries in a reasonable time period. This has not happened to date, as this study has shown.
- More stringent oversight authority on seismic preparedness in the energy sector (liquid fuel, electricity and natural gas) may be needed.

Section 1
Introduction

The Oregon Department of Geology and Mineral Industries (DOGAMI) conducted an earthquake risk study of Oregon's Critical Energy Infrastructure (CEI) Hub in Portland, Oregon. This study was conducted as part of a larger U.S. Department of Energy (DOE)-funded Energy Assurance Project (EAP) conducted by the Oregon Department of Energy (ODOE), Public Utility Commission of Oregon (OPUC) and DOGAMI. More information on the EAP project is at http://www.oregon.gov/ENERGY/Recovery/Funding.shtml#Energy_Assurance_Planning, including the Oregon Energy Assurance Plan http://www.oregon.gov/ENERGY/docs/OregonStateEnergyAssurancePlan.pdf.

Background

Oregon is exposed to many natural hazards, including earthquakes, volcanoes, floods, landslides, and more. These hazards have varying characteristics, including frequency of occurrence and severity of possible damage and impact. For example, severe winter storms can occur every few years and sometimes as often as several times per year. Because of technological advances in weather forecasting, these storms typically have several days of advance warning. They typically have limited fatalities (e.g., tens of fatalities or fewer) and can result in flooding, landslides, and downed trees that impact communities, roads, and electrical service to a limited portion of the state. The economic impact can reach hundreds of millions of dollars.

In contrast, major earthquakes rarely occur, but there are no systems that allow for days or hours of advance warning of earthquakes. Major earthquakes in urban areas would likely result in more damage than winter storms because the existing building inventory has many seismically deficient buildings that were constructed before modern seismic building codes.

The most likely major earthquake to occur in Oregon is on the Cascadia Subduction Zone, which is an earthquake fault at the boundary of the Juan de Fuca and North American plates. The next Cascadia earthquake could be as large as a magnitude 9.2, which would shake a substantial portion of the Pacific Northwest and create a tsunami that would flood low-lying coastal areas. Although a magnitude 8 or higher Cascadia earthquake is an infrequent event, it would likely result in thousands of fatalities and widespread, devastating damage throughout western Oregon. The consequences from a major Cascadia earthquake would be much greater and farther reaching than any other natural hazard in Oregon. DOGAMI focused its study on a Cascadia earthquake of magnitude 8 or higher because of the potential consequences to the state of Oregon. Specific information on Oregon's hazards is included in Section 2: Characterization of Oregon's Natural Hazards and Section 4: Seismic Hazards in the CEI Hub.

Oregon's energy sector will be among many severely impacted industries after a major Cascadia earthquake. The energy sector involves the petroleum, natural gas and electricity industries. Each energy industry is a network. The petroleum supply chain involves oil resource development, oil refineries and distribution systems that include fuel terminals with products as well as multiple modes of transportation. Likewise, the natural gas supply chain involves resource development, processing and distribution systems. The electricity supply chain involves generation, transmission and distribution. For Oregon to have a secure and stable energy supply, energy sector industries must ensure a resilient supply chain during normal operations as well as during extreme conditions, including a Cascadia earthquake.

This study evaluates seismic hazard, vulnerability, risk and resilience in the CEI Hub. These concepts have varying meanings among earth scientists, engineeres and social scientists, so for the purposes of this report, we define them as follows:

- Seismic Hazard: The combination of the severity of damaging seismic effects (shaking, liquefaction, landslides) at a particular location with the frequency with which those effects occur at that location. A very large earthquake that is very rare poses a small seismic hazard, as do very frequent but very small earthquakes. High levels of seismic hazard result from the combination of relatively frequent and relatively large earthquakes. Sesimic hazard is a function of the size and frequency of the earthquake, its location relative to the site in question, and geologic conditions at the site.
- Seismic Vulnerability: The degree to which a particular structure or system is likely to sustain damage when exposed to a particular level of damaging seismic effects like shaking, liquefaction or landsliding. Seismic vulnerability is an intrinsic characteristic of the structure or system.
- Seismic risk: The combination of seismic hazard affecting an area, the vulnerability of the structures and systems in that area, and the consequences of failure of those structures and systems.
- Seismic Resilience: The ability of a structure, system or community to recover from a damaging earthquake. Resilience includes not only the resistance of the system to initial damage, but also the ease and speed with which it can be brought back into service after the event.

Objective

This purpose of this study is to better understand the vulnerabilities of the energy sector when it is confronted with a magnitude 8 or larger Cascadia earthquake. This risk study focuses on Cascadia earthquakes because a large magnitude Cascadia earthquake poses the highest risk of all natural hazards to the state of Oregon (Wang, 2008).

Study goals were to:

- Characterize Oregon's natural hazards by developing qualitatively-derived risk scores to estimate the scale of potential disasters,
- Better understand CEI facility operations and learn about site conditions, structures, and components as well as the systems and interdependencies,
- Describe some of the potential critical seismic vulnerabilities in the energy sector, and
- Offer recommendations to improve energy sector resiliency to minimize earthquake impacts.

Use of this Study

This report provides information to help encourage a seismically resilient energy sector and protect Oregonians in the event of a future Cascadia earthquake. It can be used to develop scenarios, demonstrate objectives, and determine extent-of-play for table-top exercises. The findings in this report can be applied to the development of mitigation, response, and recovery strategies in the Oregon State Energy Assurance Plan and Energy Sector-Specific Emergency Response Plans. The findings can also be used in Oregon resilience planning efforts directed by the Oregon Seismic Safety Policy Advisory Commission (OSSPAC).

Scope of Work

DOGAMI was tasked to determine seismic hazard and risk information of critical energy facilities in Oregon in an intra-governmental agreement with OPUC. DOGAMI did not perform detailed seismic vulnerability assessments of any specific facility, system or asset.

Although DOGAMI had conducted previous studies on Oregon earthquake resilience, including Wang 1999, Wang 2008, and Wang 2010a, these studies did not focus on the energy sector. Because there were many unknowns involving the energy sector, DOGAMI's approach was to: 1) gather information and learn about the state's energy systems; 2) characterize Oregon's natural hazards and its impacts on the energy sector; 3) conduct scoping studies; 4) perform document reviews; 5) collect input and expert opinions from a wide range of professionals (see Section 8: Acknowledgements); 6) conduct visual screening assessments; and 7) perform our own state-of-practice engineering studies. The goal was to evaluate the overall vulnerability of the energy sector to damage at the CEI Hub from a magnitude 8 or larger Cascadia earthquake.

From these activities, DOGAMI created a natural hazard risk matrix based on the natural hazards recognized by the State of Oregon's Natural Hazard Mitigation Plan. DOGAMI also defined the CEI Hub project study area as the six-mile stretch of the lower Willamette River located between the south tip of Sauvie Island and the Fremont Bridge on US Highway 30. (*Figure 1*) The project entailed assessing the seismic hazards of the CEI Hub, identifying the major energy sector facilities in the CEI Hub, and surveying their seismic vulnerabilities.

DOGAMI staff conducted a review of building codes to help assess the vulnerability of the structures in the CEI Hub. DOGAMI conducted site visits to all major energy sector facilities in the CEI Hub (*Figure 1*) as well as several facilities outside of the CEI Hub. In each case, the facility's operator accompanied DOGAMI to visually survey their facilities, which is discussed in the following section: Study Methods.

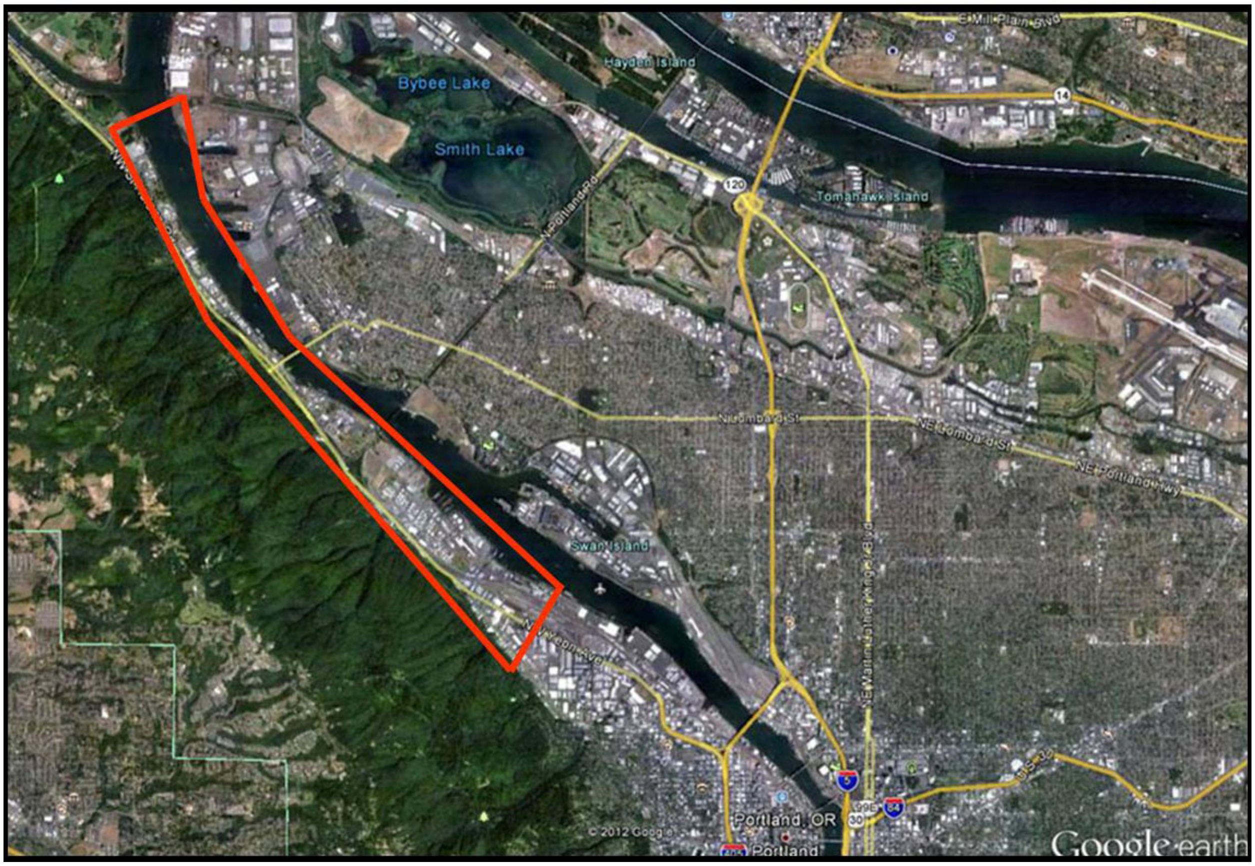


Figure 1: Site map of the Critical Energy Infrastructure (CEI) Hub on the western bank of the Lower Willamette River area in NW Portland, Oregon. The CEI Hub, outlined in red, stretches for six miles. (base map: Google Earth)

DOGAMI also partnered with academic earthquake professionals to co-conduct a statewide economic study focusing on energy sector interdependencies (*Appendix A*) as well as a ground deformation analysis for this project *(Appendix B).* These studies provide specialized technical information that is useful towards meeting the study objective.

As a result, this earthquake risk study provides generalized information on the seismic hazard, the exposed facilities, consequences of the seismic hazards to the exposed facilities, and key findings and recommendations to make the energy systems more resilient to earthquake impacts. The term "risk" is defined herein as a function of the threat of seismic hazard, the vulnerability of the exposed parts, and the severity of the consequences. Sections 4 and 5 of this report address the seismic hazards and seismic vulnerability of the exposed facilities in the CEI Hub. Section 6 starts with a discussion of consequences to help illustrate the concept, then addresses the conditions involving seismic risk in the CEI Hub, and ends with discussing impacts to Oregon. This information will allow the energy industry and decision-makers from all levels of government to collaborate on strategies to rapidly recover from a major disaster, and to protect public health and safety, the environment, and the region's economy.

Study Methods

The project method involved assessing the seismic hazard in the CEI hub area posed by a Cascadia earthquake (Section 4 of this study). Although local crustal faults exist in the CEI Hub, only the Cascadia fault was evaluated based on its higher probability of occurrence, many seismic hazards and high risk (Sections 2 and 4 of this study). Many seismic hazards were considered, which included ground shaking, soil susceptibility to earthquake-induced liquefaction, lateral spreading, landslides, and co-seismic settlement. Since liquefaction and lateral spreading hazards are the primary concerns, especially to the waterfront facilities, we co-conducted a ground deformation analyses to better understand the nature of the hazards and the possible mitigation needs.

DOGAMI reviewed the building code environment for facilities in the CEI Hub to determine the design conditions of the facilities. Building codes set forth minimum standards on new construction and for certain major changes. Building codes are frequently upgraded to reflect new design knowledge including seismic hazards. These codes play a vital role in the seismic robustness of structures. If the code requires a high level of seismic design, then the new structure is designed and built to resist seismic forces. In contrast, if past codes call for seismic design levels that are significantly lower than the levels in the current code, then those structures may be seismically deficient.

The EAP partners, which include staff from DOGAMI, ODOE, and OPUC, assessed the seismic vulnerability of CEI Hub facilities through a series of site visits and meetings. Key individuals are listed in Table 1 and contributors are listed in the acknowledgements (Section 8). The EAP assessments included on-site facility visits in the CEI Hub to meet with the operators and tour their facilities, as well as viewing facilities by boat and aerial reconnaissance. A few site assessments were conducted at facilities outside of the CEI Hub. DOGAMI co-organized two boat tours with the City of Portland and invited key stakeholders including Oregon leadership (director of Oregon Emergency Management, representative from Senate President's office), FEMA and EAP partners. DOGAMI, OPUC and Oregon Department of Transportation (ODOT) also conducted aerial reconnaissance with the Civil Air Patrol covering the CEI Hub to the Columbia River mouth to consider emergency response options using the Columbia River waterway.

Table 1: List of Key Individuals: EAP Partners and Stakeholders

EAP partners
Oregon Department of Energy Deanna Henry Emergency Preparedness Manager Nuclear Safety & Energy Emergency Preparedness Division
Oregon Department of Energy Rebecca O'Neil EAP Project Manager Senior Policy Analyst, Energy Technology Division

Table 1: List of Key Individuals: EAP Partners and Stakeholders (cont)

Public Utility Commission of Oregon
J. R. Gonzalez, P.E. (former)
Administrator
Safety, Reliability and Security Division

Public Utility Commission of Oregon
Rick Carter
Senior Utility Analyst
Emergency Management-Disaster Response and Recovery
Safety, Reliability and Security Division

Public Utility Commission of Oregon
Immanuel Runnels (former)
Utility Analyst, Intern

EAP stakeholders
Bonneville Power Administration
Leon Kempner
Structural Engineer

BP
Jim Swatman
Portland terminal manager
US Pipelines and Logistics

Chevron
Jerry Henderson
Willbridge terminal manager

ConocoPhillips
Tom Lyons
Portland terminal manager
Scott Edwards
Division Engineer, West Coast Terminals, Transportation Pipelines and Terminals
Rafael Rengifo
Tank Integrity Initiatives Lead

Kinder Morgan
Greg Westling, Area manager- Willbridge/Linnton Terminals
Ron Lown, Eugene Terminal, Lead Operator

McCall Oil
Ted McCall, Portland terminal owner

Table 1: List of Key Individuals: EAP Partners and Stakeholders (cont)

NuStar Energy LP
Ricky Hudiburgh
Portland terminal manager

NW Natural
Grant M. Yoshihara
Vice President, Utility Operations & Chief Engineer
Jon Huddleston
Director, Deliver Gas Process
Kerry Shampine,
Manager, Engineering Services
Robbie Roberts
Security Specialist, Business Continuity & Corporate Security

Olympic PipeLine Company
Kurt Hayashida
Lead Engineer
Jim Fraley Jr.
Damage Prevention Team Lead

Pacificorp
Jack Vranish
Director, Asset Risk and Strategy
Debbie Guerra
Director, T&D Dispatch, Emergency Management

Portland General Electric (PGE)
Bill Nicholson
Vice President Distribution
Dave Ford
Director, Business Continuity and Emergency Management
Dave VanBossuyt (retired)
General Manager Southern Region
Todd Jones
Civil Engineer, Substation Engineering

Shell
Mario Berrios
Operations Supervisor Portland - Tumwater Terminals
Billy Powell
Regional Response Manager, HSE Emergency Management

Table 1: List of Key Individuals: EAP Partners and Stakeholders (cont)

Williams Northwest Pipeline
George Angerbauer
Manager of Public Outreach
Troy Robey
Assistant District Manager, Battle Ground District

Assessment of the energy sector facilities in the CEI Hub included:

- All of Oregon's major liquid fuel port terminals
- Liquid fuel transmission pipelines and transfer points
- Liquefied natural gas (LNG) facility
- High voltage electric substation and transmission lines

Assessment of energy facilities outside the CEI Hub included:

- Four electrical substations
- Two power plants (Port Westward and Beavers in Western Oregon (Columbia County)
- A natural gas gate station on Sauvie Island
- A liquid fuel terminal in Eugene

ODOE organized site visits at these petroleum facilities: BP, Chevron, ConocoPhillips, KinderMorgan (KM) fuel terminals and KM pipeline, McCall Oil, Nustar, and Shell. Site visits were also conducted at Bonneville Power Administration (BPA), NW Natural, Portland General Electric (PGE), and Williams Northwest Pipeline. We did not visit any PacifiCorp facilities as all are located outside the CEI Hub.

DOGAMI reviewed US Coast Guard (USCG) inspection protocols for port facilities with petroleum terminals. Because USCG inspections of the Portland fuel terminals do not include a seismic component, the EAP partners worked with the California State Lands Commission to look at how California addresses seismic issues at port facilities with fuel terminals. With help from Martin Eskijian, Supervisor, Engineering Branch Marine Facilities Division from the California State Lands Commission (retired in 2011) and his staff, the EAP partners reviewed parts of the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS), which is implemented and enforced by California State Lands Commission that incorporates seismic safety http://www.slc.ca.gov/Division_Pages/MFD/MOTEMS/MOTEMS_Home_Page.html.

The EAP partners joined MOTEMS staff on two oil refinery inspections in Richmond and Benecia, California, as well as observed a MOTEMS regulatory review meeting with a petroleum company at the MOTEMS office in Hercules, California. DOGAMI and ODOE, with the assistance of MOTEMS staff engineer Kendra Oliver at four of the Portland fuel terminals, conducted site visits to inspect the piers and the wharves used for transporting liquid fuel in the CEI Hub.

A significant part of the project involved identifying key stakeholders for all the energy sectors as well as government agencies and other stakeholders. These are listed in *Table 2.* Many other individuals provided their expertise upon request. These individuals are listed in Section 8: Acknowledgments. The EAP partners provided EAP information to the energy sector, as well as the public, at many meetings and through a variety of media in order to build awareness. For this report, the names of the companies have often not been identified, and in places, replaced with "*unnamed*". Furthermore, the location of their facilities in the CEI Hub have not been pinpointed. This action was taken to promote participation from privately-owned energy sector operators while respecting their privacy when obtaining seismic vulnerability data associated with their facilities.

Table 2: List of stakeholders in this Earthquake Risk Study for Critical Energy Infrastructure Hub.

Private sector fuel stakeholders	Private sector electricity natural gas stakeholders	Government Agency stakeholders	Non-profit stakeholders	Academic stakeholders
BP	NW Natural	Bonneville Power Administration (BPA)	American Society of Civil Engineers	University of British Columbia
Chevron	PacifiCorp	City of Portland	Western Energy Institute	University of Utah
ConocoPhillips	Portland General Electric (PGE)	City of Salem		Western Washington University
Kinder Morgan (KM) fuel terminals and pipeline	Williams Northwest Pipeline	Federal Emergency Management Agency (FEMA)		
McCall Oil		Oregon Dept. of Transportation		
NuStar Energy LP		Oregon Emergency Management		
Olympic Pipe Line Company (operated by BP Pipelines, North America)		Oregon Seismic Safety Policy Advisory Commission		
Shell		Port of Portland		
		US Coast Guard		
		US Dept. of Energy		
		US Geological Survey		

Limitations

This study did not entail site-specific vulnerability and risk studies, including studies of any particular facility or system, and provides only estimates of seismic vulnerability based on reconnaissance visual inspections, site-independent analyses and studies and existing site specific information conducted by CEI Hub facilities. The study is only an exploratory seismic risk study of the CEI Hub. Additional studies are required to obtain site specific conditions, and accurate and comprehensive vulnerability and risk data.

While tsunami damage is expected to impact coastal areas, including maritime fuel transport through Columbia River mouth, DOGAMI did not assess damages from tsunami impacts in the CEI Hub because it was outside the scope of this project. Models of likely tsunami inundation from Cascadia earthquakes suggest that tsunami effects in the Columbia River diminish rapidly east of Astoria, and the possibility of tsunami inundation in Portland is remote. (Priest et al, 1999). DOGAMI did not assess dam failure impacts to the CEI Hub because it was outside the scope of this project.

Report Organization

The report is organized into these sections:

Summary of Report
Section 1. Introduction
Section 2. Characterization of Oregon's Natural Hazards
Section 3. Oregon's Energy Sector
Section 4. Seismic Hazards in the CEI Hub
Section 5. Energy Facilities and Vulnerabilities in the CEI Hub
Section 6. Summary of Findings
Section 7. Recommendations
Section 8. Acknowledgments
Section 9. References
Section 10. Appendices

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Section 2
Characterization of Oregon's Natural Hazards

The section discusses the natural hazards and risks in Oregon and summarizes key results from previous statewide earthquake and tsunami studies.

Natural Hazards and Risk

Oregon is exposed to a wide range of natural hazards, each with its own characteristic frequency and severity. Floods, wind and winter storms are expected to occur frequently in limited geographic area, and are, therefore, considered to be high-probability, low-consequence events. In contrast, large Cascadia Subduction Zone earthquakes and tsunamis rarely occur, but would results with significant, widespread damage. Cascadia earthquakes are considered to be low-probability, high-consequence events.

The earthquake hazard in Oregon varies depending on the location. The likelihood of an earthquake occurring in western Oregon is higher than in eastern Oregon, thus the earthquake hazard is considered to be higher in western Oregon (Figure 2). Considering the entire state of Oregon as a whole, the overall earthquake hazard can be considered as high to moderate. The earthquake risk, however, may be considered as very high. The terms hazard and risk may be defined differently by engineers, business continuity specialists, social scientists, emergency managers, and others and may also vary depending on the specific context. In risk studies performed by engineers, the risk level is often determined as a function of the hazard (the probability of the earthquake occurring), the vulnerability of the exposure, and the consequences. Additional information on probability and risk concepts in engineering are covered in Ang and Tang (2007) and Garvey (2008).

The State of Oregon's Natural Hazards Mitigation Plan, produced by the Oregon Emergency Management with the assistance of many state agencies, is state government's plan to address natural hazards. This plan, available on http://opdr.uoregon.edu/stateplan, is in a continual process of being updated. Oregon's Governor last approved and adopted the plan in 2009. The major hazards identified for Oregon in this plan include: climate change, coastal erosion, drought, dust storm, earthquake, fire (wildland-urban interface), flood, landslide and debris flow, tsunamis, volcanic, windstorm and winter storm.

Development of Risk Matrix

In the early stages of this EAP, DOGAMI assessed how different natural hazards compare with each other with respect to the hazard, vulnerability and consequence to rank how Cascadia earthquakes compare with other hazards. DOGAMI used the identified hazards identified in the State of Oregon's Natural Hazards Mitigation Plan and created a qualitative statewide risk matrix for natural hazards. (See *Table 3)* The table was developed to provide a better understanding of the state's natural hazards and the risk to estimate the scale of potential future disasters. The risk scores include low, moderate, high and very high. The risk scores were subjectively determined by expert opinion and are based on the probability of the <u>hazard</u>, the <u>vulnerability</u> of the exposure, and the <u>consequence</u> of likely damage for the state as a whole. These scores do not specifically consider energy infrastructure.

Table 3: Statewide Risk Matrix for Natural Hazards (Oregon Emergency Management identified the hazards list; EAP partners created the risk matrix)

Description of Hazard	Hazard	Vulnerability	Consequence	Risk Score
Climate Change	NE	NE	NE	NE
Coastal Erosion	H	M	M	M
Drought	M	M	H	M
Dust Storm	L	L	M	L
Earthquake	**M**	**VH**	**VH**	**VH**
Fire (Wildland-Urban Interface)	H	M	M	M
Flood	VH	M	M	H
Landslides and Debris Flow	VH	M	M	H
Tsunamis	M	H	VH	H
Volcanic	L	M	M	M
Windstorm	M	M	H	M
Winter Storm	VH	H	H	H

Explanation: VH=very high; H=high; M=moderate; L=Low; NE=not estimated

The earthquake hazard is only moderate because earthquakes are rare. For example, a magnitude 8 or so Cascadia earthquake has a recurrence interval of about 250 years, and a magnitude 9 Cascadia earthquake has a recurrence interval of about 500 years. The earthquake vulnerability score is very high because the vast majority of Oregon's existing infrastructure has been designed and constructed without seismic resistance considerations. The consequence score is also very high because damage will likely be widespread and, in many places, severe. Finally, the earthquake risk score is very high because when a major earthquake occurs, it will likely result in a high loss of life, economic damages, and long-term impacts.

Method to Develop Risk Score

In developing the risk scores, DOGAMI gave broad consideration to numerous factors that would have a statewide significance. Factors include the hazard’s: onset pattern (ie. earthquakes do not have forewarning, but tsunamis have at least minutes of warning); frequency (ie. earthquakes are rare, but storms are frequent); geographic location and spatial extent (ie. Cascadia earthquakes can suddenly impact all of western Oregon, whereas fires are localized); severity of impact resulting in many fatalities and/or high economic losses (ie. earthquakes can cause widespread physical damage to critical energy infrastructure, transportation, emergency response facilities and other essential facilities). As specific examples, coastal erosion and tsunamis are limited to the coastal areas, whereas winter storms and fires can occur anywhere in the state.

The risk matrix can be used to help determine and prioritize risk management strategies. For each hazard, a single ranking of low, moderate, high or very high was subjectively selected for the probability of the hazard, vulnerability, and consequence. Low, moderate, high and very high were assigned values of 1, 2, 3 and 4, respectively. The risk score was calculated by taking the square root of the sum of the squares, and assigned as low, moderate, high or very high for values less than 3, 3 to less than 4.5, 4.5 to less than 6, and 6 or greater, respectively.

Previous Statewide Earthquake Studies

For most of Oregon's history, the seismic potential was considered to be minimal. Even as late as 1980 during the Mt. St. Helens volcanic eruption, geologists were generally unaware of Oregon's major faults and their earthquake potential. During the 1980s, geologists learned about the Cascadia Subduction Zone and that it could produce large earthquakes. By the late 1980s, there was general consensus among earthquake scientists that the Cascadia fault could unleash a magnitude 8 or higher earthquake and accompanying tsunami (Wang, 1998a). Since that time, scientific research has continued to improve our understanding of the Cascadia fault and numerous earthquake and tsunami studies have been performed.

Figure 2 shows a current scientific model of the location of the Cascadia Subduction Zone. The potential rupture surface of the Cascadia fault extends from the western edge (white line with triangles) to the eastern edge (dashed black line). The eastern edge of the fault is important because, in general, the shaking levels are closer to the fault.

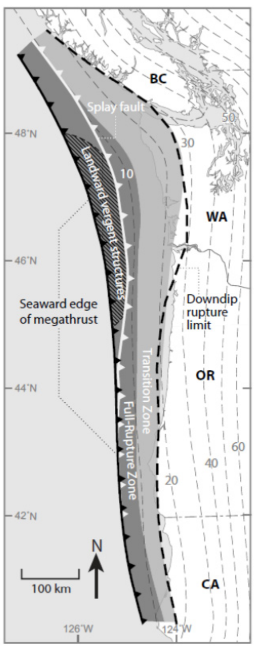


Figure 2: Cascadia Subduction Zone between the black dashed line and the white line with triangles. (Witter et al, 2011).

Statewide Damage and Loss Estimates

In 1998, Oregon was the first state in the nation to conduct a statewide earthquake damage and loss study (Wang, 1998b, Wang and Clark, 1999). Using HAZUS97, a damage and loss estimation software package from FEMA, DOGAMI produced a technical report that included evaluations of damage and losses for the entire state for 1) a magnitude 8.5 Cascadia earthquake and 2) a 500-year return interval probabilistic ground motions. In the second evaluation, the ground motions expected to be met or exceeded in a 500-year period are used in the building code to design for earthquake shaking.

As part of that study, DOGAMI developed a statewide soils map. Next, DOGAMI developed a suite of ground motions that integrated the soils map. The ground motions were used to estimate damage to infrastructure from shaking. *Figure 3* illustrates how layers of information are used to determine damage where the uppermost layer depicts highest damage in red (Wang, 1998b). *Figure 4* shows a spectral velocity map of Oregon at 0.3 seconds, which was one of the ground motion maps used to estimate damage (Wang, 1998c). The statewide damage and loss assessment was conducted in two parts, both indicating severe losses. Building damage from a hypothetical magnitude 8.5 Cascadia earthquake was estimated using FEMA's HAZUS97 software and indicated almost 1,000,000 buildings with some level of damage from earthquake shaking (Wang and Clark, 1999). Fatalities were estimated using crude methodologies and indicated more than 3,000 fatalities from tsunamis, 2,000 fatalities from severe building damage, and many more casualties. (Wang, 1999)

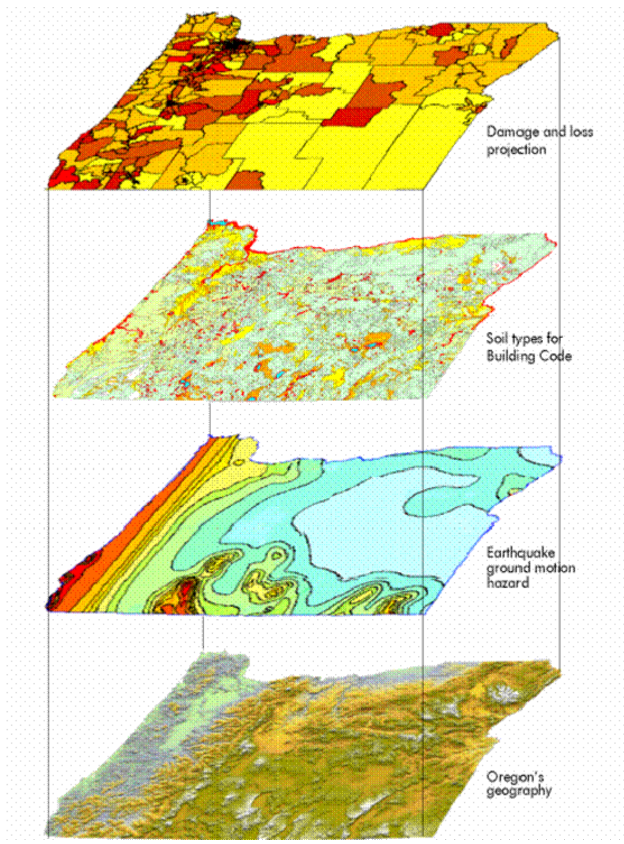


Figure 3: Schematic showing a statewide GIS-based (HAZUS97) study damage and loss assessment using probabilistic ground motions that represent equal seismic hazards throughout Oregon. (Wang, 1998b)

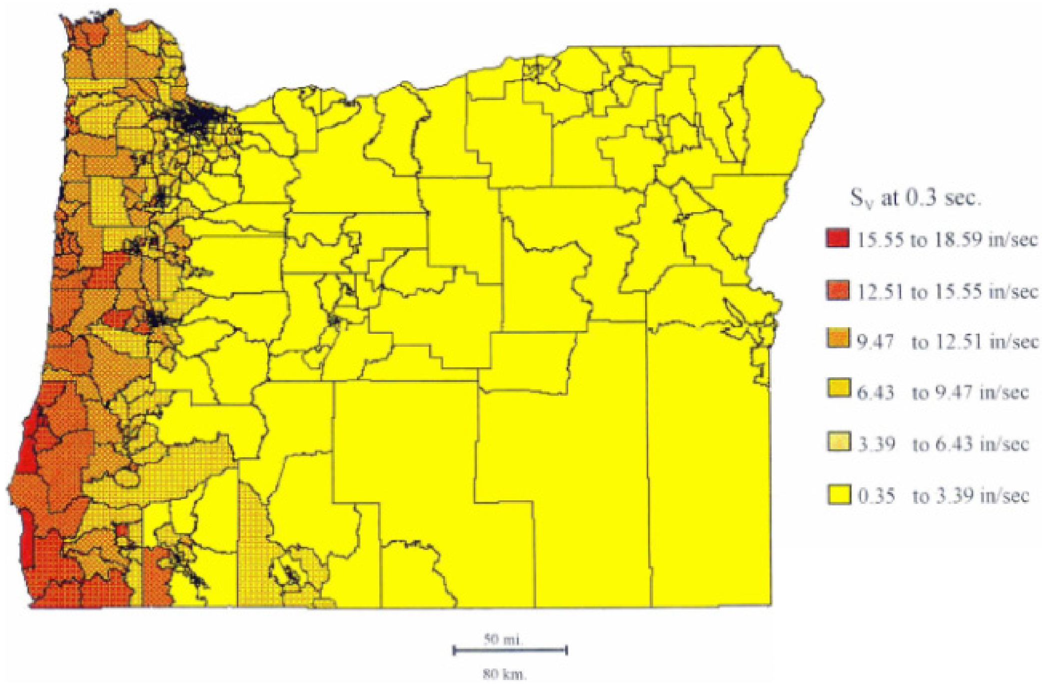


Figure 4: Spectral Velocity Map of Oregon at 0.3 seconds (Wang, 1998c)

Today, earthquake scientists have gained a better understanding of the Cascadia fault, the soils in Oregon, and expected ground motions. Researcher Chris Goldfinger and his colleagues have examined the offshore geologic record of large Cascadia earthquakes in the past 10,000 years. (Goldfinger et al, 2012) *Figure 5* shows a simplified timeline of Goldfinger's findings, which indicate over 40 earthquakes (DOGAMI, 2010). Seismic hazards are further discussed in Section 4.

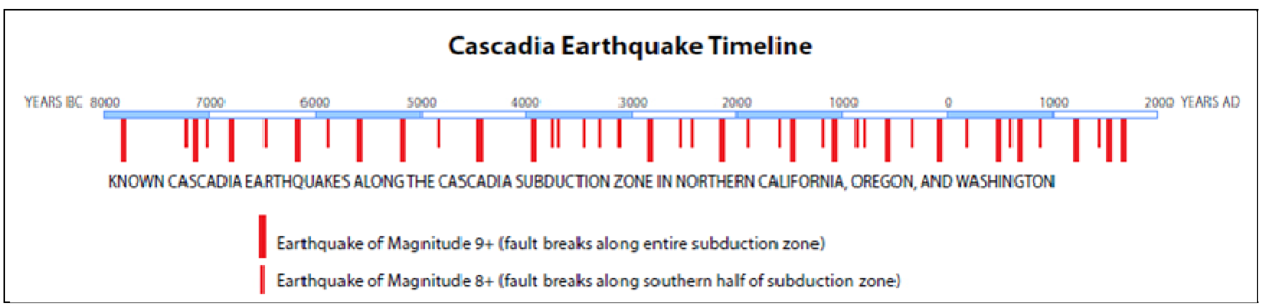


Figure 5: 10,000 year record of past large magnitude earthquakes on the Cascadia Subduction Zone. (DOGAMI, Cascadia Winter 2010)

Lessons from Recent Subduction Zone Earthquakes

In recent years, three significant earthquakes have occurred in subduction zones around the world. These include:

- 2004 magnitude 9.1 Sumatra earthquake
- 2010 magnitude 8.8 Chile earthquake
- 2011 magnitude 9.0 East Japan earthquake

Each time a major subduction zone earthquake occurs, earthquake professionals working in the Cascadia region gather important earthquake information and learn a great deal more about the Cascadia Subduction Zone.

In the Sumatra earthquake, one big lesson learned was that tsunamis can kill over 200,000 people from one side of the ocean to the other side. The tsunami hit and killed people in Sumatra, but also traveled across the Indian Ocean and killed people in 12 other countries including Thailand, India, and Sri Lanka. In 2009, stakeholders from the Pacific Northwest discussed tsunami vertical evacuation refuges as a new mitigation option. (Wang, 2010a)

In the 2010 Chile earthquake, moderate shaking damaged an oil refinery that was rendered inoperable for months. Earthquake professionals working in the Cascadia region learned lessons on the importance of critical infrastructure. (Wang, 2010b)

In the 2011 Japan disaster, the electrical sector was impacted not only by damaged nuclear and thermal power plants, but also by undamaged nuclear power plants, which were shut down due to the public's concern about their safety. Also, one electric company experienced damage to 85 of its high voltage transformers. The Oregon Seismic Safety Policy Advisory Commission adopted policy recommendations to address the issue of critical infrastructure (including fuel and electric) following the Japan earthquake. (http://www.oregon.gov/OMD/OEM/osspac/docs/lessons_recomm_7-11.pdf). They are reprinted in the Winter 2012 Cascadia (DOGAMI).

Based on observations from historical earthquakes, scientists have determined that 1) large earthquakes release more energy and produce stronger ground shaking than small earthquakes, 2) the level of ground shaking lowers with distance away from epicenter of the earthquake, and 3) damage is typically concentrated nearer the epicenter of the earthquake as well as in farther locations with soft soil deposits, such as old lake bed soils. Based on post-earthquake field visits after the 2004, 2010 and 2011 subduction zone earthquakes, co-author Yumei Wang, observed that the damage in those subduction zone earthquakes was concentrated in three areas:

1. Tsunami inundation zones,
2. Areas of permanent ground deformation, such as landslides and liquefaction zones, and
3. Seismically weak buildings and infrastructure.

Section 3: Oregon's Energy Sector

This section provides an overview of Oregon's energy sector, the CEI Hub project study area, and Oregon's economic interdependencies with the energy sector.

Overview of Energy Sector

Three energy sources are considered—electricity, natural gas and fuel oil. The energy sectors have separate systems for supplying their products and/or services. Not surprisingly, each has sector-specific seismic vulnerabilities.

The crude oil used in Oregon originates in the Alaska North Slope oil fields. The Trans Alaska Pipeline transports crude oil from these oil fields to the Valdez terminal in southern Alaska. From there, barges, tankers and pipelines carry the crude oil to four refineries located in the Puget Sound area of Washington State, which provide more than 90 percent of Oregon's refined petroleum product. About 75 percent of the product is transported via the Olympic Pipeline to seven petroleum distribution terminals located within close proximity of one another in the CEI Hub project study area, further described in the next section. The remaining fuel coming to Oregon from the Washington State refineries is transported by tanker vessels to the Portland facilities. (ODOE, 2011)

In 2010, Oregon's electrical power mix from a variety of power plants was 0.77% biomass, 35.46% coal, 0.12% geothermal, 38.74% hydroelectric, 0.04% landfill gases, 16.24% natural gas, 3.66% nuclear, 0.14% other, 0.17% petroleum, 0.34% waste, and 4.31% wind (ODOE Power Mix Fact Sheet, 4/4/12). The electrical grid that serves the state of Oregon is coordinated and highly interconnected with similar systems in the 13 western U.S. states, parts of northern Mexico and western Canada. Critical grid functions, in relation to Oregon, are most predominately the responsibility of the Bonneville Power Administration (BPA), Western Electricity Coordinating Council (WECC), PacifiCorp and PGE. On a local level, the electric distribution systems, as well as some transmission and generation, are also the responsibility of Oregon's numerous municipal and public power agencies. Being integrated, Oregon's generation and transmission systems are exposed to adverse events that may be caused over a thousand miles away. In theory, Oregon's electric resiliency (e.g., reliability) can be significantly impacted by transmission or generation related events that could occur anywhere in the entire interconnected region. Conversely, events emanating within Oregon could also significantly impact other states. The prudent management, operations, planning and maintenance of bulk power transmission and generation grids play a fundamental role in Oregon's electric resiliency (RW Beck, 2011).

Oregon receives natural gas from British Columbia, Alberta, Wyoming, Colorado and New Mexico. Two connected interstate pipelines currently serve Oregon customers. The Williams Company pipeline and the Gas Transmission Northwest (GTN) pipeline owned by the TransCanada Corporation bring product from the Rocky Mountains and Canada. The Ruby Pipeline transports domestic natural gas 675 miles across four states from Opal, Wyoming to the existing Gas Transmission Northwest (GTN) pipeline near Malin, Oregon. According to the Northwest Gas Association (NGWA), the Pacific Northwest is home to more than 48,000 miles of natural gas transmission and distribution pipelines (ODOE, 2011).

More information on the energy assurance project, including the Oregon Energy Assurance Plan is at http://www.oregon.gov/ENERGY/docs/OregonStateEnergyAssurancePlan.pdf.

Critical Energy Infrastructure (CEI) Hub: Project Study Area

The study region for this project was determined based on the location and importance of Oregon's liquid fuel oil terminals. Oregon's liquid fuel terminals are located along a six-mile stretch along the lower Willamette River in Portland. As part of this study, we identified and termed these six miles as the "critical energy infrastructure Hub" or CEI Hub. The CEI Hub is located in a region of high seismicity (*Figure 6*, FEMA 2002).

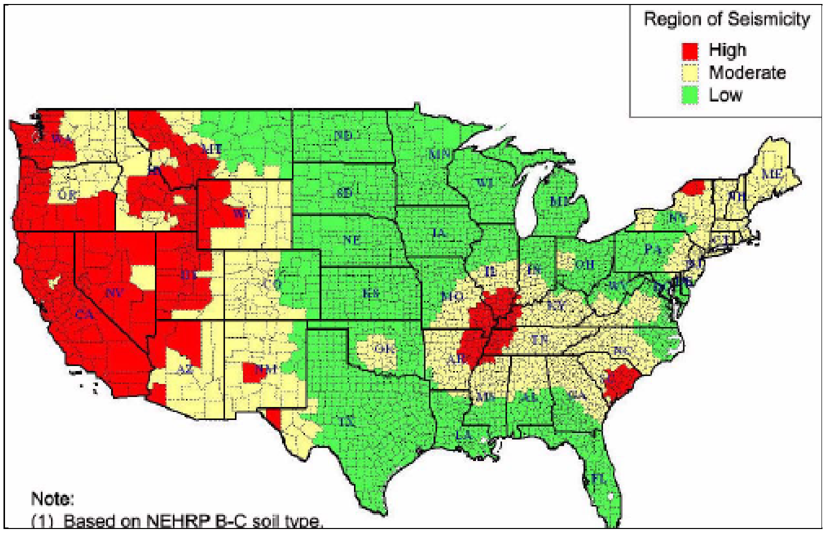


Figure 6: Map showing regions of high, moderate and low seismicity. The CEI Hub is in the high region (FEMA, 2002).

The CEI Hub covers a six-mile stretch of the lower Willamette River located between the south tip of Sauvie Island and the Fremont Bridge on US Highway 30. The energy sector facilities in the CEI Hub include:

- All of Oregon's major liquid fuel port terminals (see *Figures 7, 8 and 9*)
- Liquid fuel transmission pipelines and transfer terminals
- Natural gas transmission and distribution pipelines
- Liquefied natural gas (LNG) storage facility
- High voltage electric substations and transmission lines
- Electrical substations for local distribution

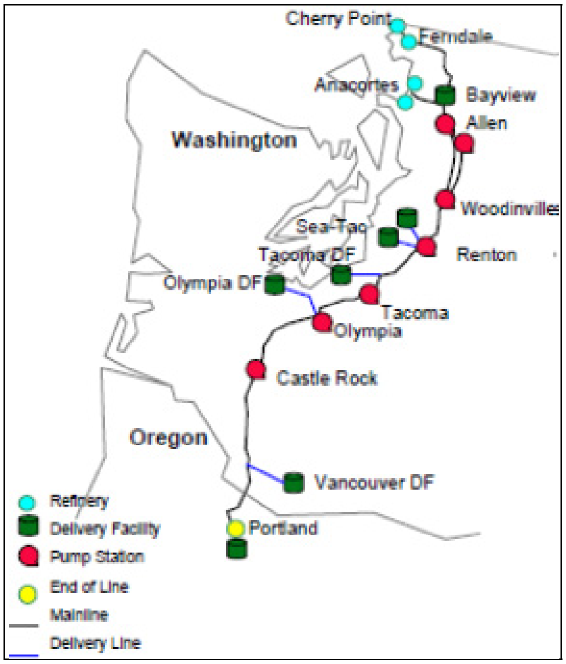


Figure 7: The liquid fuel oil terminals for more than 90 percent of Oregon's supply are located at the end of the line (yellow dot) in Portland, Oregon. (http://www.bppipelines.com/cartoon-maps/olympic.pdf)

Figure 8: Oil terminals in the southern portion of the CEI Hub. (DOGAMI photo)

Figure 9: Oil terminals in the northern portion of the CEI Hub (foreground of photo). (DOGAMI photo)

Petroleum enters the state by pipeline and marine vessels and is transferred to terminals at the CEI Hub before it is distributed throughout Oregon to the end user. Once the product reaches the CEI Hub, tanker trucks deliver fuel to customers in the Portland metro area, barges deliver fuel farther east on the Columbia River, and a pipeline continues south to a terminal in Eugene. Fuel is distributed throughout Oregon, including to the Portland International Airport and many other major consumers.

Oregon's oil terminals are located along the western bank of the Willamette River (*Figures 8 and 9*). The Portland fuel terminals are on a six-day delivery cycle. On average, terminals have a three to five day supply in the tank farm for regular unleaded gasoline and diesel fuel. Premium gasoline is subject to the daily delivery and heavily dependent on whether an inter-company pipeline on Front Avenue is operational. All seven terminals have the capability to receive product by vessel. However, only Chevron and Kinder Morgan terminals have the marine vapor recovery systems required to load unleaded fuel onto vessels for transport up the Columbia River to Pasco, Washington. Diesel can be loaded on vessels without the vapor recovery systems. Vessel deliveries vary. Chevron reports on average, its terminal receives a shipment by barge every three or four days and by ship every seven or eight days. (Portland PBEM, Earthquake Response Appendix, January 2012, http://www.portlandonline.com/oem/index.cfm?c=53895&a=382005)

A significant portion of Oregon’s natural gas passes through the CEI Hub. Also, three high voltage (115 kV and 230 kV) electrical transmission lines cross the area as well as feed the distribution network for the local area.

Economic Interdependencies with the Energy Sector

In August 2003, Americans got a dramatic "wake up call" concerning the vulnerability of electrical systems and the resultant regional and national consequences as a result of the Northeast Blackout. The blackout affected five states, 50 million people, and caused an estimated $4 to $10 billion in business interruption losses in the central and eastern US. The power outage caused "cascading" failures to water systems, transportation systems, hospitals, and numerous other critical infrastructures (National Research Council, 2011).

Oregon's economy, like all other states, has complex interdependencies. The reliability of energy lifelines is vital to ensure the protection of public health and safety. Any prolonged or severe disruption of one or more energy system could put many lives at risk as well as strain the state's economy. To better understand the economic interdependencies with the energy sector, co-author Miles conducted a statewide economic study to evaluate the economic interdependencies of Oregon's energy sector by comparing the interdependencies of electricity, natural gas and liquid fuel as well as critical infrastructure with the rest of Oregon's economy. This work is part of a National Science Foundation-funded research project (Grant #0927356) entitled *"Repeat Disaster Impact to Infrastructure Networks and Their Effects on Economic Agent Recovery."* This part of the study was peer reviewed and is included as Appendix A.

The findings show that if available electricity, natural gas and liquid fuels were significantly reduced, the direct and non-direct dollar losses would have major socio-economic consequences to Oregon. In a scenario where all energy sectors are disrupted, there would be $0.39 of economy-wide impact for every $1.00 of lost output by the energy sector. The sectors with the largest financial impact are Services, followed by Wholesale/Retail, Construction, Non-Durable Goods, Electricity, Communications, Mining, Durable Goods, Petroleum, and Transport by Rail. The impact to Services is about an order of magnitude greater than the other sectors. For employment impacts, a minimum of 2.42 jobs would be expected to be lost for every direct job lost in the energy sector. Electric companies have the greatest monetary and employment impact potential of the three energy sources. In summary, the study concludes that the total impact from a Cascadia earthquake on the energy sector would include the direct damage to energy facilities, the loss of sales, losses from secondary effects, including job losses, and a multitude of cascading functional impacts which would potentially have economic impacts of their own.

Comparison with Other Economic Studies

After the 1994 Northridge, California earthquake, Tierney (1997) found that the second most common reason for business closure, behind having to clean up debris, was a loss of electricity. The most significant impacts were seen in the finance, insurance, and real estate and construction industries. Finance, insurance and real estate services were also impacted the most in the WWU study on Oregon energy disruption. A study by Tierney and Nigg (1995) compared the dependency of businesses to five types of infrastructure between Memphis, Tennessee and Des Moines, Iowa with respect to potential (Memphis; earthquake disruption) and actual (Des Moines; 1993 Midwest floods) disruption. *Table 4* (Memphis) shows the results of that study. In both cases, businesses depend most on electricity, while depending on natural gas third most. In the study of the business impacts from the 1993 Midwest floods, Tierney (1994) wrote the following, which provides further insight into the importance of energy infrastructure:

> "Overall, electricity was rated as the most critical lifeline service by both large and small businesses, with the former considering electric service more important than the latter. Large manufacturing and construction firms and both large and small companies in the finance, insurance, and real estate sectors were more likely than other businesses to rate electricity as critical to their operations. While small businesses generally considered

telephone service to be the second most critical lifeline, large businesses appeared to view telephones, water, sewer service, and natural gas as equally critical."

Table 4. Results of surveys to businesses in Memphis, Tennessee asking the degree of importance on five types of infrastructure (Tierney and Nigg, 1995).

IMPORTANCE	LIFELINE SERVICES				
	Electric	Water	Natural Gas	Water Treatment	Telephone
Very Imp	82%	27%	18%	23%	78%
Important	14	34	29	32	17
Not Very Important	3	31	39	33	3
Not Imp at all	1	8	13	13	2
Total	100%	100%	99%*	101%*	100%

*Does not total 100% due to rounding

A study by Rose et al. (2007) on the economic impacts of electricity outage due to a terrorist attack on Los Angeles, California found that the services sector was most impacted by a significant margin. This is not surprising as the input-output analysis found that services and manufacturing are the two main business users of electricity.

None of the studies included direct dependence on liquid fuel. Nonetheless, the studies have confirmed the general validity of our findings and the importance of resilient infrastructure, as well as the significant economic impact that would arise due to energy disruption from a Cascadia earthquake in Oregon.

Section 4
Seismic Hazards at the CEI Hub

For this study, DOGAMI used earthquake parameters that reflect magnitudes ranging from 8 to 9. A hypothetical magnitude 8 or 9 earthquake would be located about 63 miles (100 km) west of the CEI Hub in Portland, Oregon just offshore from the city of Tillamook. Both earthquakes assume the distance is from the down-dip rupture limit of the Cascadia Subduction Zone, which is the eastern-most edge of the fault, to the CEI Hub (Witter et al, 2011). The hypothetical magnitude 9 earthquake would stretch from coastal Cape Mendocino, California to Vancouver Island, British Columbia (*Figure 10*).

Figure 10: Cascadia Subduction Zone showing the fault's western boundary (red dashed line), which is closest to the ground surface, and the easterly dipping fault plane (yellow) (DOGAMI, 2012).

Seismic Hazards in the CEI Hub Area

The primary seismic hazards that would impact the CEI Hub area are:

- Ground shaking
- Liquefaction (soil behavior phenomenon in which a saturated sand softens and loses strength during strong earthquake ground shaking)
- Lateral spreading (where surficial soil permanently moves laterally due to earthquake shaking)
- Landslides

- Co-seismic settlement (where the ground surface is permanently lowered due to seismic shaking)
- Bearing capacity failures (when the foundation soil cannot support the structure it is intended to support)

In addition, secondary seismic hazards can be initiated and include:

- Seiches (waves that oscillate in water bodies often initiated by ground shaking)
- Fire
- Hazardous material releases, such as fuel overtopping tanks by sloshing (occurs when liquid becomes agitated by ground shaking)

Liquefaction and lateral spreading hazards are of primary concern to the fuel supply waterfront facilities. For this reason, DOGAMI performed ground deformation analyses to better understand the nature of the hazard and the possible mitigation needs. A section on the deformation analyses is included in this study. Tsunamis are expected to damage the coastal areas, including ports along the coast and Columbia River mouth, but are not expected to cause significant damage in the Portland waterways. Following is a summary of these seismic hazards:

Active Fault Sources

Many earthquake faults capable of producing damaging earthquakes exist in the area of the CEI Hub. The most threatening fault is the Cascadia Subduction Zone fault (Cascadia fault) which lies just offshore of the Oregon coast (see *Figures 10 and 11*). The Cascadia fault has produced over 40 large magnitude earthquakes during this past 10,000 years, with the last major earthquake occurring on January 26, 1700. The 1700 Cascadia earthquake likely caused extensive ground shaking that extended from the Cape Mendocino area in Northern California to British Columbia, Canada, as well as a large tsunami. This tsunami first hit the low lying areas along the Pacific Northwest coast, then traveled across the Pacific Ocean to cause damage to Japan's coast.

Based on the 10,000 year record of past Cascadia earthquakes (Goldfinger, 2012), Oregon will certainly experience another magnitude 8-9 earthquake in its future. This future earthquake, which has the same type of subduction zone process as the March 11, 2011 East Japan magnitude 9 earthquake, will be accompanied by a coastal tsunami.

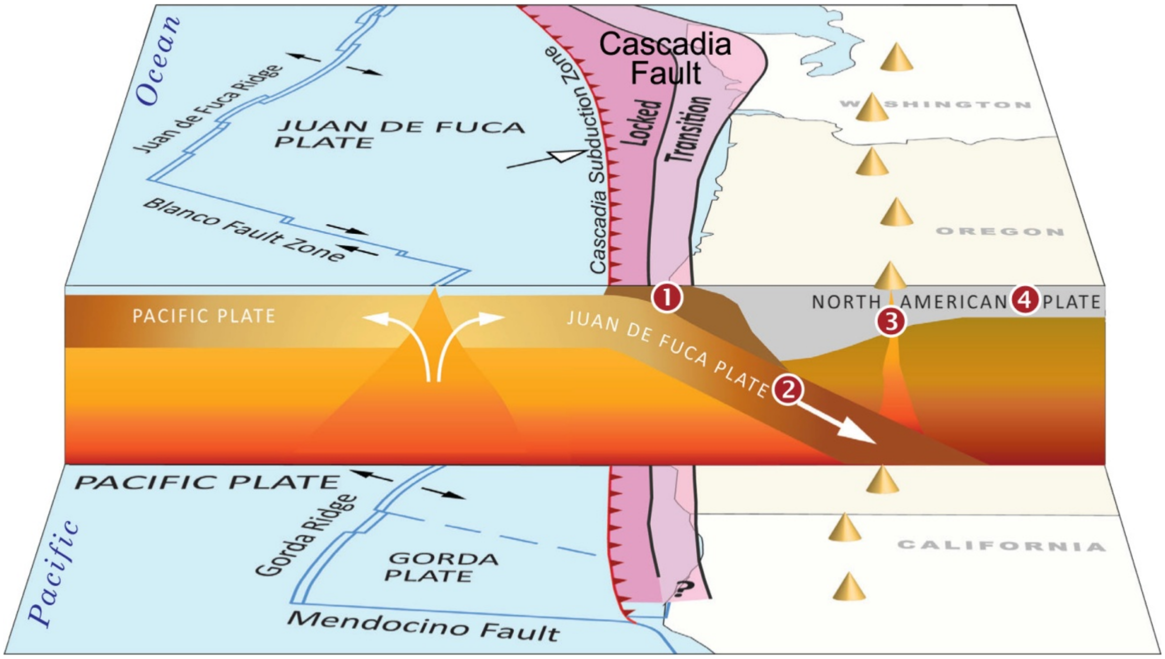


Figure 11:The Cascadia Fault is Oregon's most threatening fault and can produce a magnitude 9 earthquake and accompanying coastal tsunami waves. (modified from DOGAMI, 2010)

Based on data that was used to develop the U.S. Geological Survey's (USGS) probabilistic ground motion maps, the Portland Hills fault is located in the CEI Hub area and can produce a magnitude 7 earthquake (USGS, 2008). In addition, the likelihood of this earthquake occurring is approximately 1% in the next 50 years (USGS National Seismic Hazard Mapping Program: https://geohazards.usgs.gov/eqprob/2009/index.php) whereas a magnitude 9 Cascadia earthquake has a likelihood as high as 14% in the next 50 years (USGS, 2008).

Ground Shaking Characteristics

The USGS has determined the ground shaking characteristics caused by faults. The State of Oregon has adopted building codes that incorporate this information. All of Oregon is exposed to seismic hazards. Higher levels of ground shaking are expected for western Oregon due to the Cascadia fault on the Cascadia Subduction Zone. *Figure 12* shows Oregon's ground shaking seismic hazards with higher expected shaking levels represented by "hotter" (or red) colors. This is the 2008 USGS national seismic hazard maps for 0.2 second spectral acceleration for 2 percent probability of exceedence in 50 years with shaking expressed in percent gravity. This type of information is used by engineers for design purposes. The duration of shaking is not indicated by this map. Additional technical information on ground shaking characteristics is provided below. For a non-technical description of ground shaking, we suggest that you skip to the next section, earthquake intensity.

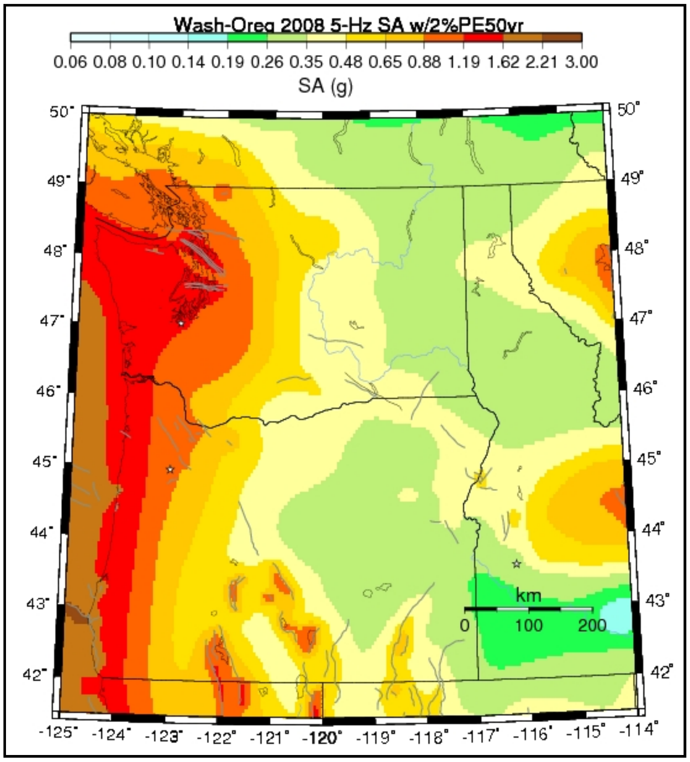


Figure 12: Ground shaking map of Oregon and Washington for rock conditions used in building codes. Red, orange, yellow areas indicate more shaking than beige, green areas.This map shows the shaking level from all possible earthquake sources, based on a probability of exceedance of 2% in the next 50 years.
http://earthquake.usgs.gov/hazards/products/conterminous/2008/maps/wus/pacnw/3hzSA.OrWa.jpg

For the CEI Hub, the ground motions induced by a magnitude 8 to 9 Cascadia earthquake are expected to produce significant damage, particularly in areas of weak soils and weak infrastructure. More specifically for a hypothetical magnitude 9 earthquake, the peak ground accelerations (PGA) in the CEI Hub at the ground surface would be expected to be on the order of 0.18 g (Clark and Roddey, 2005). This 0.18 g value was developed by the USGS national seismic hazard mapping project group as part of the Cascadia Region Earthquake Workgroup Cascadia earthquake scenario (http://earthquake.usgs.gov/hazards/). Earlier studies by Wong et. al (2000) provided a range between 0.15 and 0.20g at the ground surface. Based on past subduction zone earthquakes and on numerical modeling, strong shaking from a magnitude 8 earthquake is expected to last on the order of 80 seconds on firm rock sites (such as the Portland Hills) and about 120 seconds on soil sites (such as by the Willamette River (personal communication, Art Frankel, USGS). For a magnitude 9 earthquake, the duration of the shaking may be slightly longer than a magnitude 8 because about 32 times more energy is released.

The PGA values used for design purposes in the proximity of the CEI Hub are on the order of 0.36 g at the ground surface for sites with soils that commonly exist in the CEI Hub. This is based on a PGA value of 0.3 g on sites underlain by soft rock (defined as having a shear wave velocity of 760 m/s by the USGS). This value was determined using the USGS's web tools for a 975 year mean return time (https://geohazards.usgs.gov/deaggint/2008). The USGS method considers many fault sources. In this case, these fault sources are considered to be principal sources: Cascadia megathrust, Cascadia intraplate, Western US crustal faults on a grid, crustal faults in Oregon and Washington, and the Portland Hills fault. For more information on the USGS method and the fault sources, please refer to the USGS national seismic hazard mapping project (http://earthquake.usgs.gov/hazards) and USGS Open-File Report 2008–1128, Documentation for the 2008 Update of the United States National Seismic Hazard Maps (USGS, 2008). For sites underlain by soil type Se, which is defined by the building code as soils that soil transmit shear waves at a velocity of 200 m/s or less for the upper 30m, shaking is expected to be stronger due to the site amplification effect in these types of soils. Soil type Se has been identified in geotechnical reports in the many parts of the CEI Hub. Using an amplification factor of 1.2, the PGA at the ground surface is expected to be about 0.36 g. The amplification factor is from the "Guide Specifications for LRFD Seismic Bridge Design", provided in Table 3.4.2.3.1 - Values of Fpga and Fa as a Function of Site Class and Mapped Peak Ground Acceleration or Short-Period Spectral Acceleration Coefficient (AASHTO, 2009).

Earthquake Intensity

The effects of an earthquake on people and objects is measured by the intensity scale, which in contrast to engineering ground motion characteristics used for design, is a scale designed for use by the general public. The intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and finally - total destruction. The Modified Mercalli Intensity (MMI) scale, shown in *Figure 13*, comprises 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, and is designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. The MMI value assigned to a specific site after an earthquake is a more meaningful measure of severity for the non-scientist than the magnitude, which expresses the energy released by the earthquake on a logarithmic scale, because intensity refers to the effects actually experienced at that place. In general, lower MMI values relate to the manner in which the earthquake is felt by people. Higher MMI values are based on observed structural damage. (http://earthquake.usgs.gov/learn/topics/mercalli.php) (Wald et al, 1999)

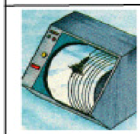
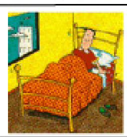
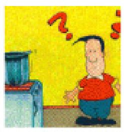
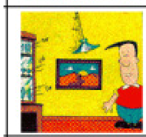
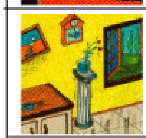
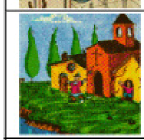
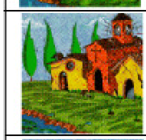
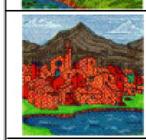
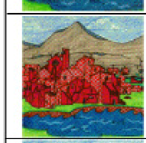
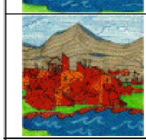
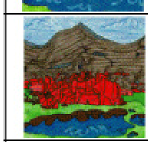
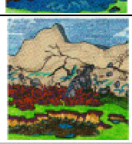
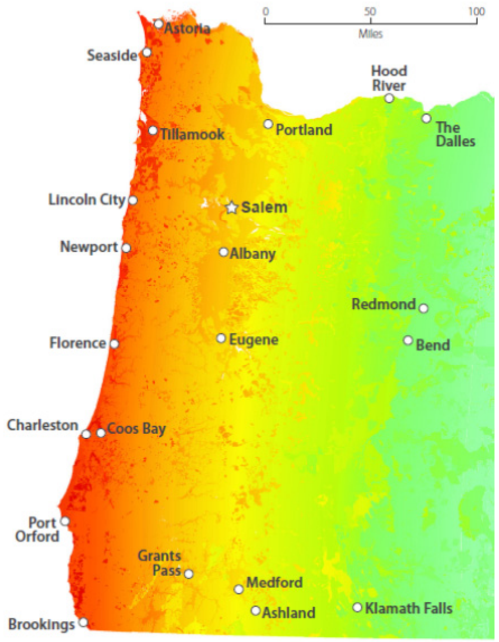
	MMI value	Summary description used on maps	Description of shaking severity	Full description shortened From Elementary Seismology
	I	Not mapped	Not mapped	Not felt
	II	Not mapped	Not mapped	Felt by people sitting or on upper floors of buildings
	III	Not mapped	Not mapped	Felt by almost all indoors. Hanging objects swing. Vibrations like passing of lights trucks. May not be recognized as an earthquake.
	IV	Not mapped	Not mapped	Vibration felt like passing of heavy trucks. Stopped cars rock. Hanging objects swing. Windows, dishes, doors rattle. Glasses clink. In the upper range of IV, wooden walls and frames creak.
	V	Light	Pictures move	Felt outdoors. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing. Pictures move. Pendulum clocks stop.
	VI	Moderate	Objects fall	Felt by all. People walk unsteadily. Many frightened. Windows crack. Dishes, glassware, knickknacks and books fall off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster, adobe buildings, and some poorly built masonry buildings cracked. Trees and bushes shake visibly.
	VII	Strong	Nonstructural damage	Difficult to stand or walk. Noticed by drivers of cars. Furniture broken. Damage to poorly built masonry buildings. Weak chimneys broken at roof line. Fall of plaster, loose bricks, tiles, cornices, unbraced parapets and porches. Some cracks in better masonry buildings. Waves on ponds.
	VIII	Very Strong	Moderate damage	Steering of cars affected. Extensive damage to unreinforced masonry buildings, including partial collapse. Fall of come masonry walls. Twisting, falling of chimneys and monuments. Wood-frame houses moved on foundations if not bolted, loose partition walls thrown out. Tree branches broken.
	IX	Violent	Heavy damage	General panic. Damage to masonry buildings ranges from collapse to serious damage unless modern design. Wood-frame structures rock, and if not bolted, shifted off foundations. Underground pipes broken.
	X	Very Violent	Extreme damage	Poorly built structures destroyed with their foundations. Even some well-built wooden structures and bridges heavily damaged and needing replacement. Water thrown on banks of canals, rivers, lakes, etc.
	XI	Not mapped because these intensities are typically limited to areas with ground failure		Rails bent greatly. Underground pipelines completely out of service.
	XII	Not mapped because these intensities are typically limited to areas with ground failure		Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Figure 13: Earthquake Intensity Scale (http://quake.abag.ca.gov/shaking/mmi/)

A magnitude 9 Cascadia earthquake (Figure 14) would likely produce MMI values of VIII and IX along the coast in most locations except for areas with tsunami flooding and areas of unstable soils. Most areas with coastal tsunami flooding would experience major destruction with damage levels equivalent to MMI X to MMI XII values. Areas of unstable soils in western Oregon could experience major destruction reaching MMI IX to X, with very limited areas seeing even greater damage. The MMI values would decrease towards the east. The Willamette Valley would likely experience MMI VI and MMI VII with localized areas of MMI VIII associated with unstable soils. East of the valley would likely experience MMI V and lower.

Local earthquakes in 1877 and 1962 produced ground shaking levels as high as MMI VII in portions of Portland. (Bott and Wong, 1993)



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
WHAT HAPPENS AT EACH INTENSITY? *Text descriptions from http://quake.abag.ca.gov/shaking/mmi/*	Not felt.	II. Felt by people sitting or on upper floors of buildings. III. Felt by almost all indoors. Hanging objects swing. Vibration like passing of light trucks. May not be recognized as an earthquake.	Vibration felt like passing of heavy trucks. Stopped cars rock. Hanging objects swing. Windows, dishes, doors rattle. Glasses clink. In the upper range of IV, wooden walls and frames creak.	Felt outdoors. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing. Pictures move. Pendulum clocks stop.	Felt by all. People walk unsteadily. Windows crack. Dishes, glassware, knickknacks, and books fall off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster, adobe buildings, and some poorly built masonry buildings cracked. Trees and bushes shake visibly.	Difficult to stand or walk. Noticed by drivers of cars. Furniture broken. Damage to poorly built masonry buildings. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets and porches. Some cracks in better masonry buildings. Waves on ponds.	Steering of cars affected. Extensive damage to unreinforced masonry buildings, including partial collapse. Fall of some masonry walls. Twisting, falling of chimneys and monuments. Wood-frame houses moved on foundations if not bolted; loose partition walls thrown out. Tree branches broken.	General panic. Damage to masonry buildings ranges from collapse to serious damage unless modern design. Wood-frame structures rack, and, if not bolted, shifted off foundations. Underground pipes broken.	Poorly built structures destroyed with their foundations. Even some well-built wooden structures and bridges heavily damaged and needing replacement. Water thrown on banks of canals, rivers, lakes, etc. Pipelines may be completely out of service.

Figure 14: Expected ground shaking from a Cascadia Subduction Zone earthquake with red as areas of highest shaking levels, which would result with the highest damage. (DOGAMI, Cascadia Winter 2012) (DOGAMI, 2012, http://www.oregongeology.com/pubs/cascadia/CascadiaWinter2012.pdf)

Potentially Unstable Soils

Near-surface soil deposits, those within the top 100 feet of the ground surface, can have a variety of ground responses when subjected to earthquake shaking. Soils with specific engineering properties, such as slow shear wave velocity, can increase or decrease the shaking levels depending on specific ground motion characteristics (e.g., frequency). The shear wave velocity of soil, which is related to the density of the soil, is the velocity at which specific seismic waves travel through the soil deposit. Some soils with slower shear wave velocity can also liquefy in a process called liquefaction. (See Section 5) Soils with shear wave velocity of 1,200 feet per second (360 meters/second) or generally slower are typically found in valleys and near water bodies. (Wang et al, 1998) *Figure 15* is a statewide National Earthquake Hazard Reduction Program (NEHRP) soils map shows areas with potentially unstable soils with respect to earthquake shaking. Areas shown in red (Sf), orange (Se) and bold yellow (Sd) have the potential to amplify earthquake ground shaking. In addition, areas shown in red in western Oregon have the highest potential for liquefaction and lateral spreading. Areas shown in orange and dark bold yellow (often adjacent to areas in orange) in western Oregon have the potential for liquefaction. Eastern Oregon will not have significant liquefaction in a Cascadia earthquake because shaking will be much weaker there.

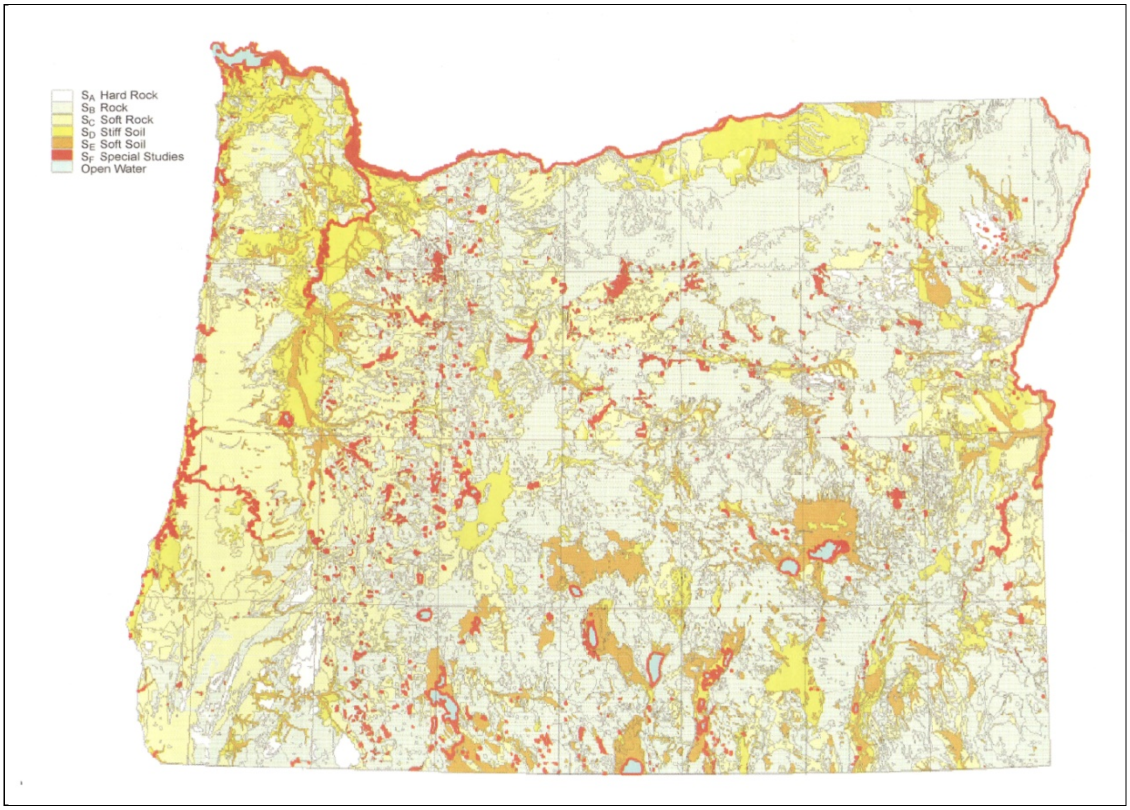


Figure 15: Statewide National Earthquake Hazard Reduction Program (NEHRP) soils map. Areas in red, orange and yellow have potentially unstable soils with respect to earthquake shaking. These areas can experience amplified ground shaking, liquefaction, and lateral spreading (Wang et al, 1998)

Figure 16 shows a portion of a relative earthquake hazard map of Portland area indicating areas with liquefaction, amplification of ground shaking, and landslide susceptibilities (Mabey et al, 1997). Areas in red and orange have a higher relative susceptibility to at least two of the hazards. In general, the areas by the rivers are susceptible to liquefaction and lateral spreading.

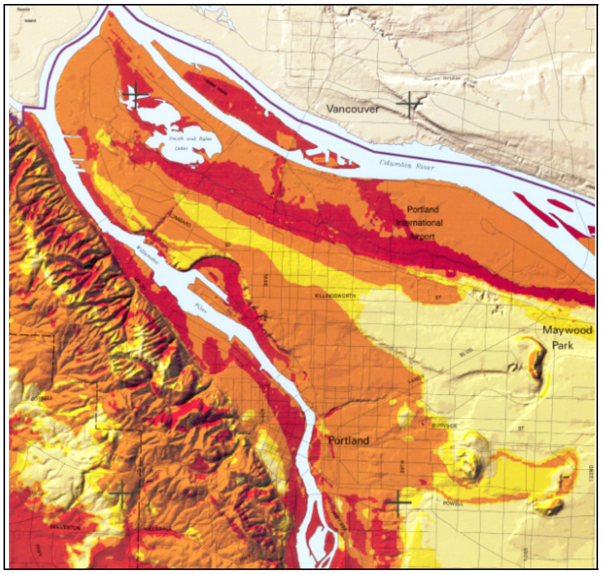


Figure 16: A portion of a relative earthquake hazard map of Portland area indicating areas with liquefaction, amplification, and landslide susceptibilities (in red, orange and yellow). (Mabey et al, 1997)

Liquefaction

Liquefaction can be triggered by earthquakes and occurs in loose, water-saturated, sandy soils and will result in liquefied soils with low strength (See *Figure 17*). Structures founded on or buried within liquefied soils can experience significant damage due to the reduction in soil strength. Buildings can sink several feet into the ground and buried pipes and tanks can float to the ground surface. (See *Figure 18*) The CEI Hub is adjacent to the Willamette River and has extensive deposits of highly liquefiable soils (See *Figures 19 and 20*, Mabey et al, 1996 and Mabey et al, 1993).. These soils (made of sand, silt, gravel and clay) have been naturally deposited by river activity or have been created from man-made activities, such as hydraulically placed material from river dredging (See *Figure 21*) or debris placed as landfill.

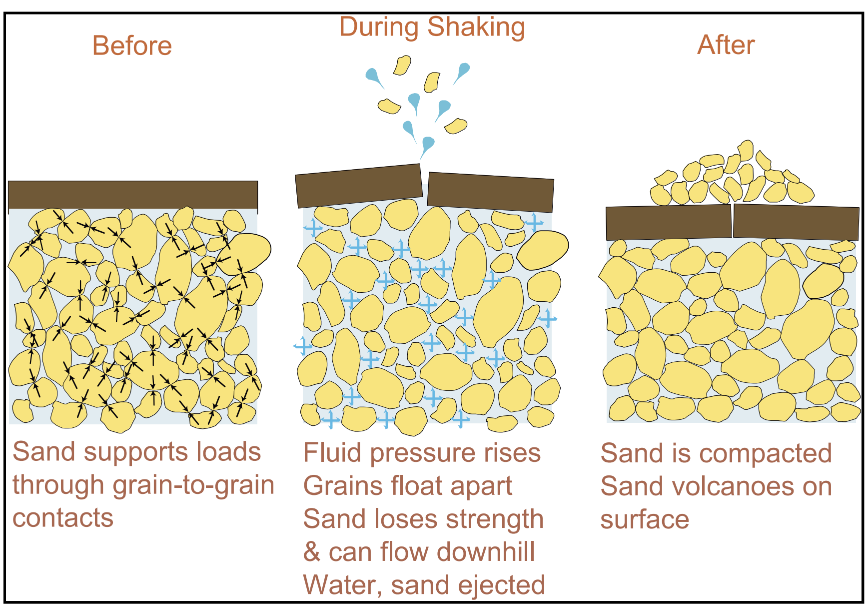


Figure 17: Liquefaction process explanation (US Geological Survey)

Figure 18: Buried tank in liquefied soil that was uplifted due to buoyancy forces in the 1993 Hokkaido-Nansei-Oki Earthquake and Tsunami in Japan (Photo permission on 1/9/12 from Youd; Youd, T.L. et al 1995, Photo taken by R. Chung)

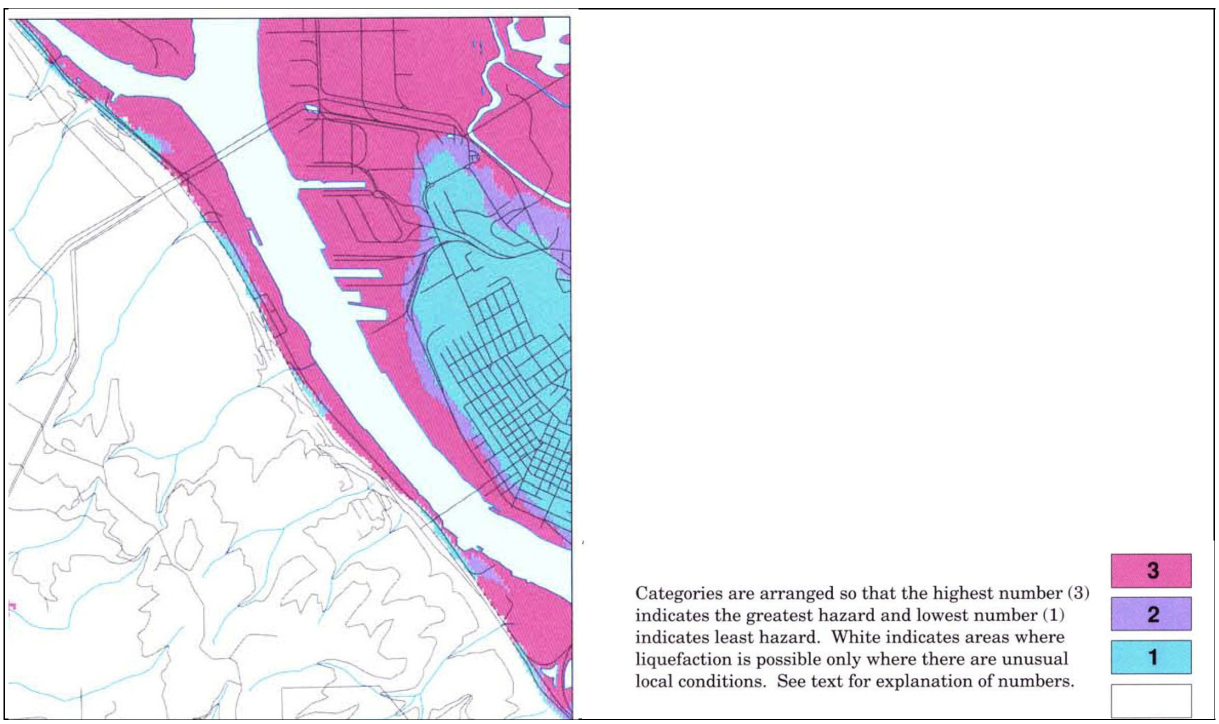


Figure 19: Map showing liquefaction potential in the northern part of the CEI Hub (Mabey et al, 1996)

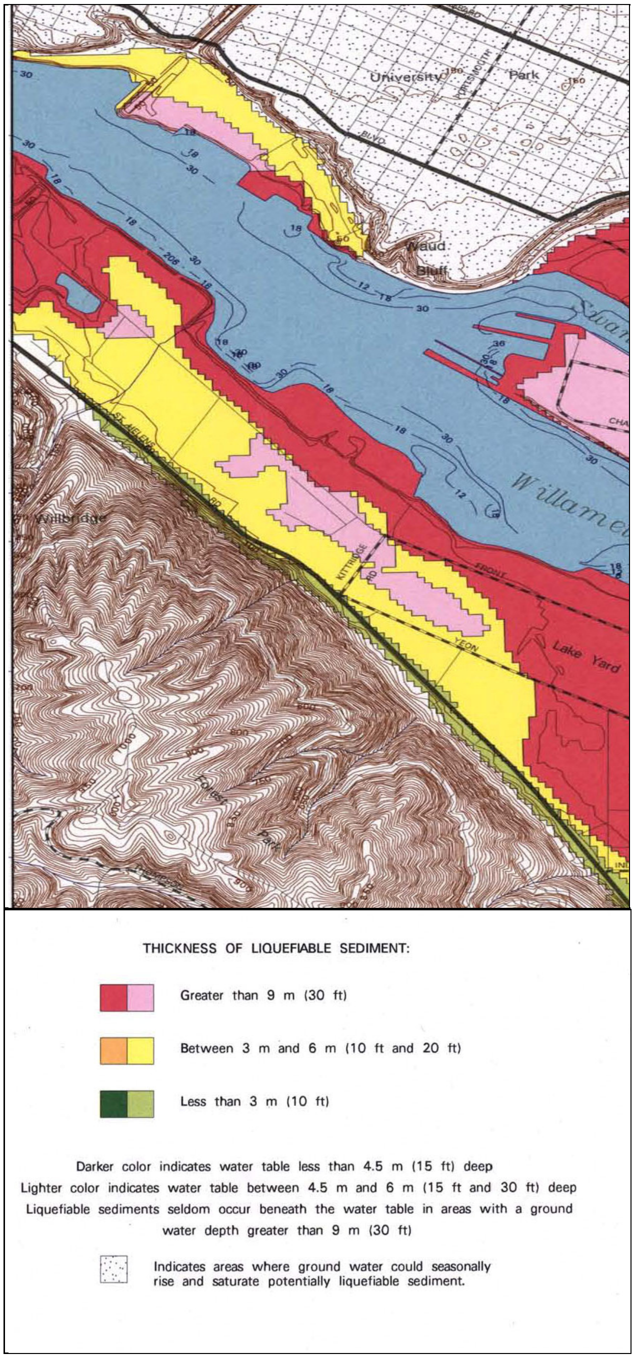


Figure 20: Map showing thickness of liquefiable sediment in the southern part of the CEI Hub (Mabey et al, 1993)

Figure 21: This photo was taken in the early 1900s and shows river dredging activity in the Guild's Lake area south and adjacent to the CEI Hub. Dredged material can be comprised of highly liquefiable soil. (Oregon Historical Society photo)

Lateral Spreading

Lateral spreading occurs when the ground permanently moves laterally due to earthquake shaking. (See *Figure 22*) Lateral spreading is common along river fronts because river deposited soils are often weak and water saturated, conditions that can increase susceptibility. Lateral spreading can occur on gentle slopes (e.g., less than 1 percent), on flat ground with a distant slope face, and by waterfront retaining structures. Lateral spreading often occurs in liquefied soils, but is not restricted to liquefied soils. The magnitude of lateral spreading can range from inches to several feet, and in extreme cases as in flow slides, hundreds of feet. Lateral spreading features include fissures and slumping. *Figures 23 and 24* are examples of lateral spreading from the 2010 magnitude 8.8 Chile earthquake.

The CEI Hub is adjacent to the Willamette River and has extensive deposits of soils highly susceptible to lateral spreads (*Figure 25*, Mabey et al, 1993). Due to the significant concerns about lateral spreading hazards in this area, DOGAMI performed dynamic analyses to model possible ground deformations. Results from a ground deformation analysis are located at the end of this section.

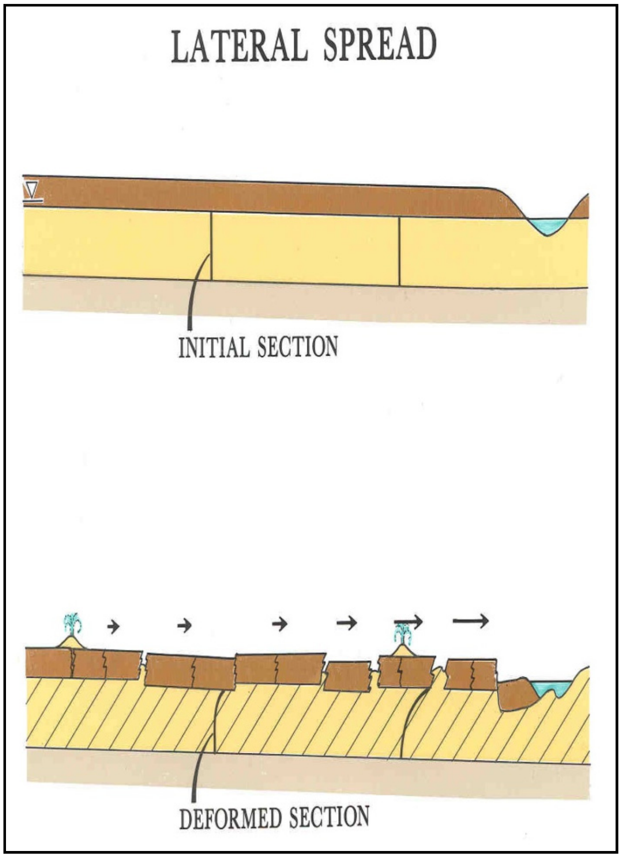


Figure 22: Lateral spreading process illustration (US Geological Survey)

Figure 23: Lateral spreading damage from the 2010 magnitude 8.8 Chile earthquake. (Technical Council on Lifeline Earthquake Engineering - TCLEE)

Figure 24: Lateral spreading damage from the 2010 magnitude 8.8 Chile earthquake. (Technical Council on Lifeline Earthquake Engineering - TCLEE)

Co-Seismic Settlement

Co-seismic settlement is where the ground surface is permanently lowered due to seismic shaking and occurs in certain types of soft, loose soils, such as liquefied soils. The CEI Hub area has soils that are generally susceptible to co-seismic settlement, in some places, on the order of a few inches or more. When soils experience uniform settlement, structures are often unharmed. However, when soils experience differential settlement, structures can incur damage. For example, rigid pipe fittings often break when the surrounding ground shifts.

Bearing Capacity Failures

Bearing capacity failures can occur during shaking when the foundation soil cannot support the structure it is intended to support. This occurs when the sub-grade soils have not been engineered and constructed adequately. The CEI Hub area has soils that are generally susceptible to co-seismic bearing capacity failures, including from liquefied soils. When soils experience differential settlement, structures can tilt and incur damage. For example, tanks can tilt and internal floating roof apparatus can become inoperable.

Landslides

Landslides are land masses that move down slope and result in permanent ground deformation. Many types of landslides exist, including fast moving and slow moving types and can occur on steep ground to even level ground. Earthquakes can trigger thousands of landslides due to the ground shaking over a wide region and can cause extensive damage. The CEI Hub area has several mapped landslides including debris flows from the West Hills and rock falls and slumps along US Highway 30. These mapped landslides are likely from past rainfall events and not by past earthquake activity.

Seiches

Seiches are waves that oscillate in water bodies and can be initiated by ground shaking. Seiches can vary from minor (e.g., centimeters in height) to over 10 feet and last up to hours. Theoretically, the Willamette River in the CEI Hub area can experience a seismically-induced seiche.

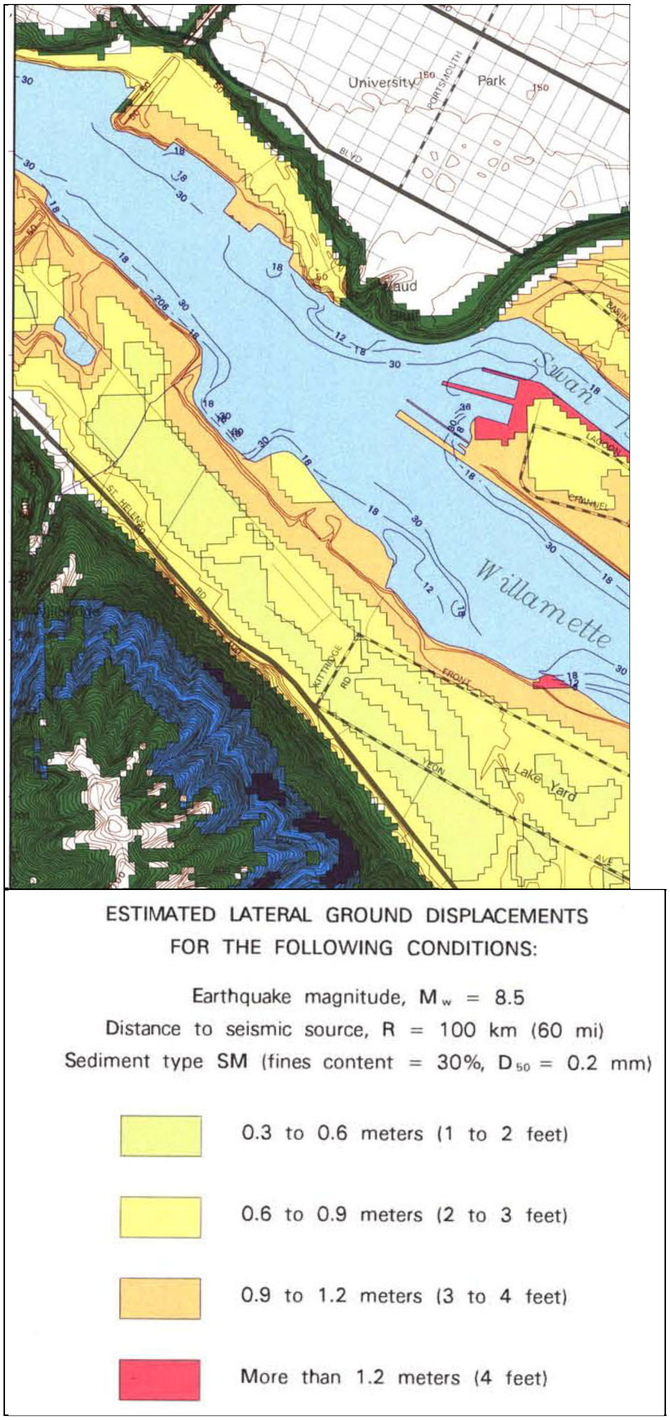


Figure 25: Lateral spreading susceptibility map of southern portion of CEI Hub (Mabey et al, 1993)

Figure 26: Welded steel water tank damaged in 1992 Landers, California earthquake. (Photo - Curt Edwards, Technical Council on Lifeline Earthquake Engineering - TCLEE)

Fires

Fires are often triggered as secondary effects from earthquakes. Numerous potential ignition sources are available in the CEI Hub area. Certain types of fires, such as fires with predominately petroleum fuel or transformer PCBs, require advanced fire specialists to contain. Water storage tanks may be damaged and the water supply system may be inoperable. (*Figure 26*)

Hazardous Material Releases

Hazardous materials are often released during earthquakes. Numerous potential sources for possible uncontrolled hazardous material releases exist in the proximity of the CEI Hub, both at and nearby the energy facilities. These materials can pose different types of hazards, such as being corrosive, explosive, combustible, poisonous, and/or toxic. A few examples are: petrochemicals, liquefied natural gas (LNG), chlorine gas, and anhydrous ammonia. Sloshing of hazardous materials in tanks can occur in earthquakes. Sloshing occurs when liquid becomes agitated by ground shaking. The CEI Hub has numerous tanks with liquid fuel and other products that are susceptible to sloshing. Waves and splashing of liquids can overtop tanks and/or damage tanks. (*Figure 27*)

Figure 27: Sloshing of crude oil during the 2010 Chile earthquake. Note the black oil stains on the outside of the fuel tank. (Wang photo)

Ground Deformation Analyses in the CEI Hub

The susceptibility for liquefaction and lateral spreading in the CEI Hub area has been evaluated in a number of past studies, including the development of liquefaction and lateral spreading susceptibility maps by DOGAMI (Mabey et al, 1993, Mabey et al, 1996). Studies have indicated a high potential for both. Liquefaction and lateral spreading can cause structures to move horizontally and vertically. The amount of potential horizontal movement of the land, termed lateral spreading, and the amount of potential vertical movement, or settlement, can be analyzed. The analyses can be performed on a site-specific basis using sub-surface data from the site or can be conducted using assumed parameters that represent the CEI Hub. Liquefaction and lateral spreading could cause significant damage to local facilities and the potential impact from the damage to certain facilities could be high.

DOGAMI reviewed selected site-specific work conducted by Bonneville Power Administration (BPA). Due to the engineering results from the BPA study indicating that the Willamette River bank soils can move towards the river by 10 to 25 feet in a Cascadia earthquake, DOGAMI contacted and collaborated with Dr. Steven Bartlett from the University of Utah (co-author) for a sensitivity study on lateral spreading to be conducted as part of this project. The sensitivity study incorporated soil properties obtained from the BPA study, and a variety of generic riverbank conditions that approximate the slopes at marine oil terminals in the CEI Hub. The ground deformation analysis is both summarized below and included in Appendix B.

BPA Study

Bonneville Power Administration (BPA) evaluated the liquefaction, liquefaction-induced settlement and lateral spreading potential of selected transmission tower and substation sites in the greater Portland area. The 2008 report, titled "*Liquefaction Assessment, Bonneville Power Administration Facilities, Portland Metropolitan Region*," includes the work conducted from their investigation, provides summary information and includes subsurface data and analyses (BPA, 2008). A portion of their work and findings is summarized herein for two BPA sites. Although the BPA findings are site-specific for their facilities, their findings are generally consistent with findings from previous studies in the CEI Hub. Depending on the soils (underlying geology units and fill materials) and ground water conditions, the liquefaction susceptibility at other sites in the CEI Hub can be higher or lower than found at these BPA sites.

The 2008 BPA work included 11 cone penetration tests (CPT) and Lidar (light detection and ranging) technology which was used in their engineering analyses for liquefaction, liquefaction-induced settlement, and lateral spreading. For all of their sites, they used a ground motion input value of 0.2 g to evaluate for liquefaction.

One of the BPA study sites is the river crossing in the north end of the CEI Hub (*Figure 28*). The study group completed a CPT at the tower site that indicated soft to stiff clay and medium dense sand to silty sand to the maximum depth of exploration at 80 feet; the medium dense sand to silty sand occurs at depths of 7 to 31 feet and 44 to 66 feet, with the remainder of the profile being soft to stiff clay. The study said the depth to the groundwater at the site is expected to range from approximately 17 to 21 feet below the ground surface (BPA, 2008).

The tower site soils were interpreted to be susceptible to liquefaction. Their estimates indicated settlement from liquefaction will be around 12 inches. The results from the analyses of potential lateral spreading indicate that there could be 10 to 25 feet of lateral spreading of the surficial soils towards the Willamette River, depending on the magnitude and duration of strong ground shaking. These large displacements imply that there could be a flow of the liquefied material into the river channel that could result in even larger lateral spreading at the tower site. The potential for lateral spreading was analyzed using the methodology of Youd et al, (2002) (BPA, 2008).

The BPA study also evaluated a nearby substation (*Figure 28; see red pin on the map on right*) located in the Rivergate area between the Willamette and Columbia Rivers about one mile east of the Willamette River transmission crossing. The substation is located on nearly flat ground at an approximate elevation 46 feet. According to the study, the site appears to be fill soils situated on a cut-fill pad along the side of a low sloping hill above the abandoned, partially in-filled slough, which lies at an elevation of about 22 feet. The study indicates that the depth to ground water is approximately 30 feet below the ground surface. The site soils were interpreted to be susceptible to liquefaction at depths of more than about 30 feet. The study stated that the settlement from liquefaction will be around 0 to 2 inches. The results from the analyses of potential lateral spreading indicate that there could be up to 1 foot of lateral spreading of the surficial soils towards the slough to the north. (BPA, 2008)

Figure 28: Two towers in the CEI Hub are owned by BPA (center and right in photo on left, yellow pin in NW corner of map on right) and were analyzed in a BPA study conducted in 2008 to have the potential to move 25 feet towards the river during a magnitude 9 Cascadia earthquake. (The tower in the foreground - left–hand side of photo - is owned by an investor-owned utility.) (DOGAMI photo) (map: Google Earth)

Lateral Spreading Sensitivity Study

A number of geotechnical engineers have performed lateral spreading analyses to evaluate the potential for permanent ground deformation (PGD) for a variety of facilities in the CEI Hub. Many of these studies used a state-of-practice method developed by Youd, Hansen, and Bartlett in 2002 (Youd et al., 2002). This method provides mean (i.e., average) estimates of lateral spread PGD for cases where lateral spread is fully developed and not greatly affected by boundary conditions or lack of continuity in the liquefied zone for earthquakes with moment magnitudes, M_w, between 6 and 8 and ground slopes between 0.1 to 5.0 percent. Youd et al., (2002) have shown that the actual displacement may vary by a factor of 2 (plus or minus) of the mean estimate. In addition, this empirical method may under estimate the amount of PGD for cases where lateral spread is not fully developed due to changes in the subsurface conditions or lack of continuity in the liquefied zone. Further, its application to magnitude 9.0 subduction zone earthquakes has not been verified. Lastly, another limitation of the empirical approach of Youd et al. (2002) is its inability to estimate the effects that ground improvement may have on reducing PGD displacement. To answer this question, mechanistic or numerical modeling methods are required.

To help determine the potential range of PGD in the riverbank soils in the CEI Hub, and better understand the potential to mitigate future ground deformation, we conducted a numerical modeling study. This model is a generic sensitivity study where we vary the earthquake shaking characteristics and site parameters. This specialty study is technical in nature and is summarized herein. Additional information on the input parameters, evaluation and results are presented in Appendix B.

The purpose of this sensitivity study was to determine a likely range of PGD in soils with slope conditions found along the lower Willamette River banks. Structures in areas with significant PGD are likely to incur damage. Depending on the specific structure, the amount of horizontal and vertical movement will affect the severity of the damage. This generic study does not represent any particular site in the CEI Hub. There likely exists sites more vulnerable to PGD in the CEI Hub that have a combination of soils with a higher susceptibility to liquefaction, steeper slopes and higher ground water conditions. For specific locales, site-specific evaluations are needed.

We selected representative acceleration time histories for M_w9.0 and M_w8.0 earthquakes and adjusted these time histories for use in the numerical model. The selected software was a nonlinear time domain analysis called FLAC (Fast Lagrangian Analysis of Continua) (Itasca, 2005). In-situ soil data from the BPA Rivergate South - Willamette River Towers site was used to develop the soil properties for the analyses in conjunction with other generic local data (BPA, 2008; CH2MHill, 2006).

The predicted results from the numerical modeling were also compared and calibrated with the lateral displacements results predicted by the Youd et al. (2002) regression model prior to completing the final runs. After numerous trial runs, we narrowed the earthquake motions input to six subduction zone earthquake time histories for the final computer runs. The estimation of horizontal displacement from liquefaction-induced lateral spread was performed for cases with and without ground improvement.

The modeling results indicate that the amount of PGD varies significantly with the ten different earthquake ground motion inputs and with varying slope conditions of 0.5, 1, 2, and 5 percent. The results from our sensitivity analysis, which models a fixed zone of liquefaction and ground water table at 5 m below the ground surface, are more sensitive to the input ground motions than the slopes. The PGD results range from negligible to extreme. Maximum PGD (on 5% slopes) for most input motions ranged from 0.2 m (8 inches) to 2.6 m (8.5 ft). One ground motion (1msoil, M_w9.0 earthquake) produced an extreme PGD result; the predicted displacements of the untreated soils range from 0.4 meters (1 foot) on a 0.5 percent slope to 17 meters (56 feet) on a 5 percent slope. Summary results of the lateral spread deformation analyses and the average displacement derived from the Youd et. al (2002) relations for both M_w8 and 9 earthquakes are presented in Appendix B for comparative purposes.

Although the results indicate that the soils are likely to move down slope towards the river, it is possible to mitigate the potential movement by strengthening the soil. Based on this deformation analyses, we estimated the amount of ground treatment required to mitigate the lateral spreading for two representative cases. According to our analyses, the required ground improvement to control deformation from lateral spreading could be achieved by increasing the composite undrained shear strength of the soil to about 1,000 psf using a soil mixing or other cementitious injection technologies. For soil densification technologies, the target improvement to achieve minimal lateral spread displacement is to densify the soil to a standard penetration test (SPT)

N_{160} blow count of 15, or greater, in the liquefiable zone. Nonetheless for actual sites, site-specific engineering studies would be required.

In summary, the evaluations in Appendix B verified that the soil in the CEI Hub could be vulnerable to damaging lateral spreading displacement during a Cascadia earthquake on a ground slope as low as 0.5 percent. In addition, for critical structures that cannot tolerate PGD, vulnerable soil conditions can be mitigated against lateral spreading using ground improvement. This is valuable information as we consider the many critical energy facilities located in the area.

Section 5
Energy Facilities and Vulnerabilities in the CEI Hub

Portland's critical energy infrastructure, including high voltage electricity transmission, fuel pipelines, tank farms, ports and facilities, is concentrated along the Willamette River in the critical energy infrastructure (CEI) Hub. Much of the existing infrastructure was constructed prior to current seismic safety specifications and many of the petroleum storage tanks, piers, marine docks and buildings may not be adequately hardened. This area consists primarily of man-made filled land overlying river sediments and is vulnerable to liquefaction and lateral spreading. The concentration of facilities and hazardous materials in this area has the potential to produce damaging cascading effects including fires from ruptured natural gas and fuel lines, hazardous material releases and debris blockage of the Willamette River.

There are a variety of structures at the oil terminals, natural gas facilities, and electrical substations, as well as transmission pipes for liquid fuel and natural gas, and transmission towers and lines for electricity. Most of the facilities include control buildings with control equipment, some with emergency generators and/or batteries. The fuel terminals often include: transmission and distribution pipelines, piers or wharves, tank farms, pipe and loading racks, pumps, electric distribution equipment, and many other components. The liquid fuel transmission system includes gate stations, and transmission and distribution pipes, including at the Columbia and Willamette river crossings. *Figure 29* shows infrastructure, including liquid fuel pipelines (dashed yellow), natural gas pipelines (yellow) and electrical transmission lines (pink) on potentially vulnerable soils in the CEI Hub. In addition to the major energy lines co-located in this area, water, waste-water, rail and a highway are located here. *Figure 29* is a close up of a larger map, which shows that the natural gas system has a loop configuration around the greater Portland area. Similarly, it shows that the electrical system includes a loop around the greater Portland area. The larger mapped can be accessed at:
http://pubs.usgs.gov/sim/3027/sim3027_front.pdf

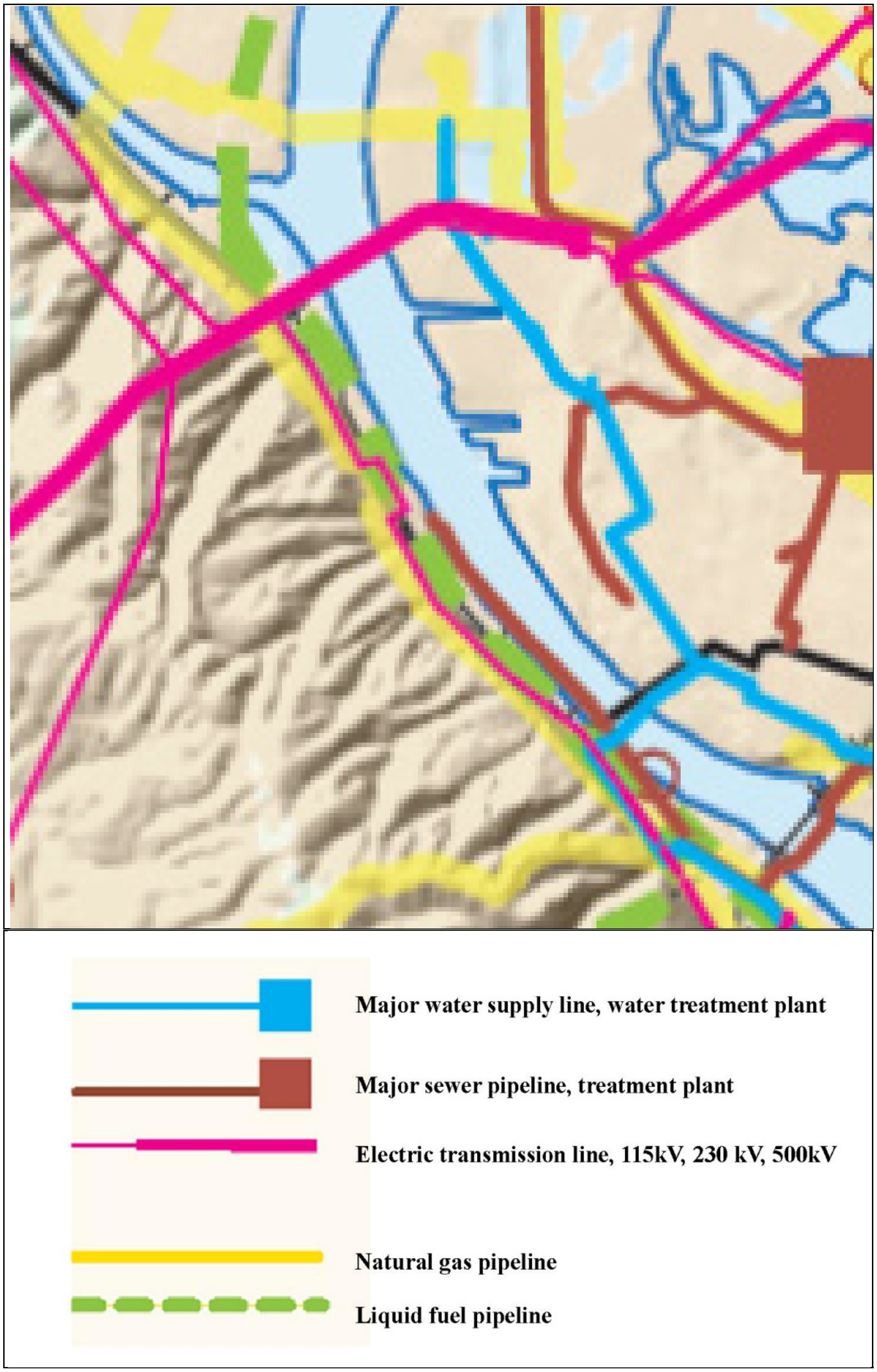


Figure 29: Lifelines in the CEI Hub area, including liquid fuel and natural gas pipelines, and transmission lines. This is a close-up of a greater Portland area map showing co-located critical lifelines on various soil types. (modified from Barnett et al, 2009) *http://pubs.usgs.gov/sim/3027/sim3027_front.pdf*

The electrical facilities include electric substations that feed into the region's power grid. Substations include control buildings with control equipment and back-up batteries, transformers, circuit breakers, and bus structures. The power system also includes transmission lines and transmission towers. The natural gas system includes gate stations, transmission and distribution pipes, and a liquefied natural gas (LNG) terminal, which includes tanks, liquefication and gasification processing equipment, and control equipment.

DOGAMI conducted evaluations of the facilities with varying levels of detail ranging from review of available engineering reports to conducting visual screening-level assessments. DOGAMI was assisted by professional specialists for much of the work (see acknowledgements). For example, DOGAMI worked with the local U.S. Coast Guard (USCG) and engineers from California's program called Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) to perform some of the visual screening level assessments of the piers and wharves in the CEI Hub. William R. Clark, USCG Port Security Specialist was DOGAMI's key point of contact. Martin Eskijian, MOTEMS Engineering Branch Supervisor (retired in 2011), Kendra Oliver, Senior Engineer, Petroleum Structures, and several other staff, provided technical expertise, which is described in Oil Terminal Facilities.

This section reviews the facilities included in the study. It also includes a discussion on building codes. Building codes regulate the seismic design criteria, which in turn, controls seismic vulnerability. This section also includes a more detailed discussion on waterfront dock structures, land-based structures, seismic pipeline vulnerability and co-located facilities in the CEI Hub.

CEI Hub Facilities: Liquid Fuel, Natural Gas and Electricity

All of the facilities in the CEI Hub are exposed to a variety of seismic hazards. The energy sector facilities in the CEI Hub include:

- All of Oregon's major liquid fuel port terminals
- Liquid fuel transmission pipelines and a transfer station
- Natural gas transmission pipelines and a transfer station
- Liquefied natural gas facility
- High voltage electric substation and transmission lines
- Electrical distribution substations

The EAP partners visited all relevant energy companies with facilities in the CEI Hub. DOGAMI and ODOE jointly conducted site visits with the terminal managers at these petroleum facilities: BP, Chevron, ConocoPhillips, KinderMorgan (KM) fuel terminals and KM pipeline, McCall Oil, Nustar, and Shell. MOTEMS senior engineer, Kendra Oliver, participated in the visits to BP, Chevron, McCall and Shell. The fuel facilities often include: transmission and distribution pipelines, piers or wharves, tank farms, loading racks, control buildings, electric distribution equipment, and many other components. The liquid fuel transmission system includes gate stations, and transmission and distribution pipes at the Columbia and Willamette river crossings. It is important to note that more than 90 percent of liquid fuels consumed in Oregon pass through the CEI Hub, as does a significant portion of NW Natural's natural gas. Thus, this area is critically important to Oregon residents, businesses and industrial firms.

Figure 30 show some of the facilities in the CEI Hub which are located near the Willamette River on soils that have been mapped as artificial fill or modified ground (Madin et al, 2008) and which are potentially unstable. Loose fills, such as those placed without compaction, are very likely to be susceptible to liquefaction (Kramer, 1996). (*Figure 31*)

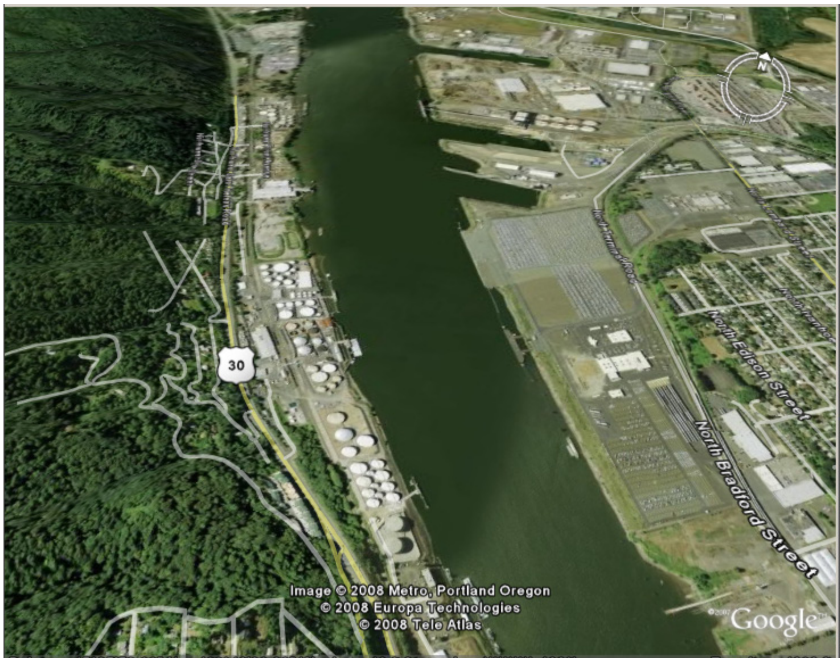


Figure 30: Fuel tank farms and marine terminals along the Willamette River's edge near US Highway 30. For geographic reference to Figures 29 and 31, note the three parallel water inlets. (Basemap: Google Earth)

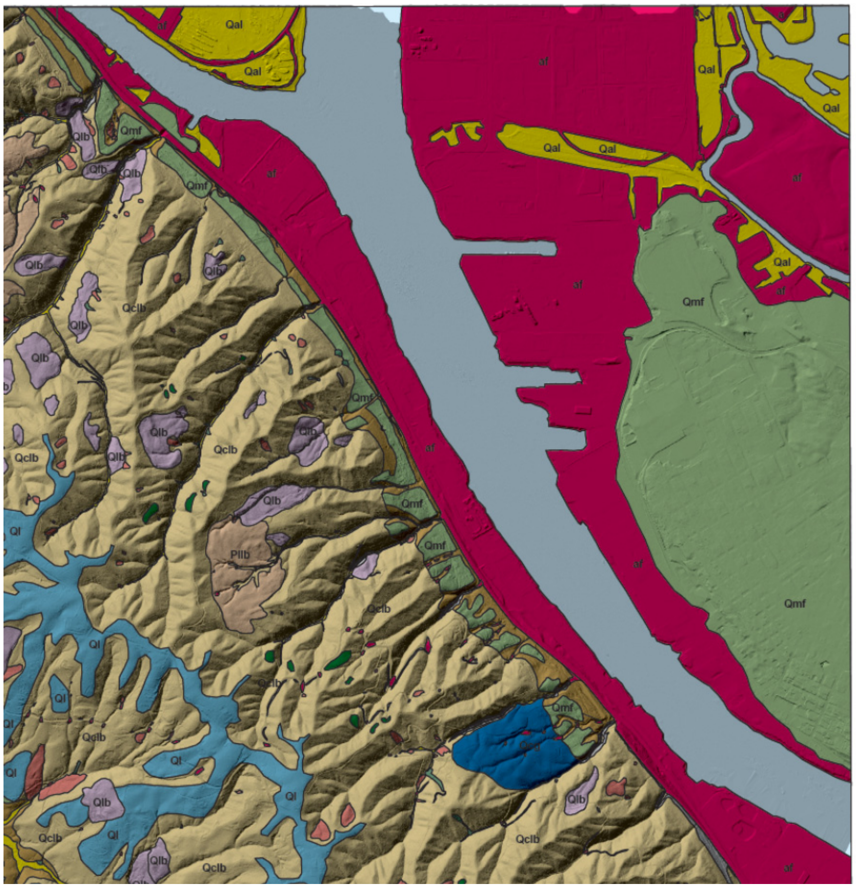


Figure 31: Surface geology map showing areas of fill materials (in pink) adjacent to the river. For geographic reference to Figures 29 and 30, note the three parallel water inlets. (Madin et al, 2008)

DOGAMI and OPUC conducted site visits with utility operators at Bonneville Power Administration, NW Natural, Portland General Electric (PGE), and Williams Northwest Pipeline electrical and natural gas facilities. (No PacifiCorp facilities are located in the CEI Hub.) BPA principal structural engineer, Leon Kempner Jr., provided technical expertise at all of BPA's electrical facilities. The electrical facilities include electric substations that feed into the region's power grid. Substations include control buildings with control equipment and back-up batteries, transformers, circuit breakers, and bus structures. The power system also includes transmission lines and transmission towers. The natural gas system includes gate stations, transmission and distribution pipes, and an LNG terminal, which includes tanks, liquefication and gasification processing equipment, and control equipment.

We also conducted selected site visits to important energy facilities located just outside of the CEI Hub. These included:

- Two large electrical substations on Front Street (*Figure 32*)
- A natural gas gate station on Sauvie Island

- Two Columbia County electric power plants that use natural gas (Port Westward and Beavers) are located next to the Columbia River. Both plants were developed on land susceptible to liquefaction triggered by a Cascadia earthquake; the soil at the newer plant was mitigated before construction.
- A liquid fuel terminal in Eugene that is dependent on the CEI Hub for its fuel and serves as an important distribution facility for Southern Oregon

Figure 32: Two large electric substations just south of the CEI Hub on Front Street that are separated by a railroad track (Basemap: Google Earth)

Some infrastructure in the CEI Hub facilities was built 100 years ago, to very antiquated standards while other infrastructure is new and built to the current state-of-practice standards. Because of the wide range of ages and associated construction practices, the seismic vulnerability of the facilities also spans a wide range. Based on visual observations, engineering judgment and limited information from the facility operators, major seismic vulnerabilities exist in the CEI Hub. Some critically important structures appear to be highly susceptible to significant damage in a major earthquake. In contrast, some structures are expected to have adequate seismic performance, including the new structures because of improved seismic design practices. Some existing structures have been strengthened or upgraded, such as evidenced by the newer dolphin structures used for mooring ships by older piers. No estimate has been made on the percentage of newer or upgraded structures.

Energy companies have operational interdependencies with the transportation and telecommunication sectors. To address seismic resilience for critical energy infrastructure operations and interdependencies, DOGAMI:

- Worked with the Oregon Department of Transportation (ODOT) to prioritize key bridges and highways in the CEI Hub for potential future upgrades to withstand Cascadia earthquake impacts. Highway 30 is essential for vehicular access to many of the CEI Hub energy facilities. Bridges are critical to supporting fuel deliveries from the CEI Hub to other parts of Oregon. In June 2012, ODOT issued its Oregon Seismic Lifeline Route Study, which includes Highway 30 and the I-405 bridge as tier 1 lifeline routes (See *Figure 33*). Co-author Wang was a steering committee member on the project. http://www.oregon.gov/ODOT/TD/TP/Reports/Lifeline%20Selection%20Summary%20Report.pdf
- Worked with ODOE and ODOT to ensure reliable alternate routes are identified and maintained to support distribution should the primary bridges for fuel deliveries become impassable. This included co-author Wang and Tova Peltz (ODOT geotechnical engineer) inspecting the Columbia River waterway in an air reconnaissance, as well as discussions with William Clark (USCG), and bridge engineers Albert Nako (ODOT) and David O'Longaigh (City of Portland Bureau of Transportation).
- Worked with OPUC and the investor-owned telecommunication providers in Oregon that the PUC regulates to promote reliable communications to energy companies located in the CEI Hub. This includes working with telecommunications providers to: 1) identify and resolve vulnerabilities to the system prior to an emergency, and 2) ensuring the rapid recovery of downed communication systems in the CEI Hub in the aftermath of an emergency. OPUC and DOGAMI have suggested to member of the telecommunication industry that they conduct seismic vulnerability assessments of their systems, including at Oregon Utility Safety Committee, OPUC's Energy Emergency Management Team and at invited talks, such as to the Oregon Telecommunications Association.

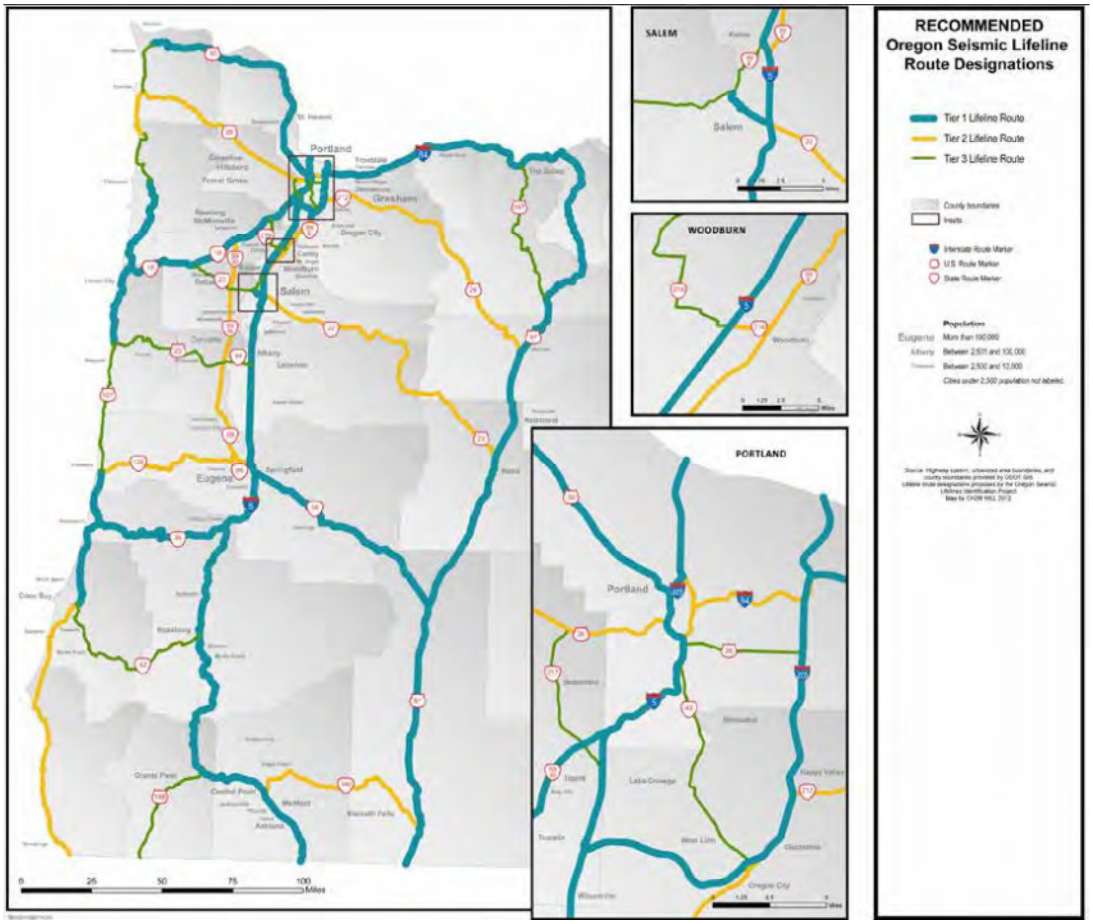


Figure 33 Map from the 2012 ODOT Oregon Seismic Lifeline Route Study, which includes Highway 30 and the I-405 bridge as tier 1 lifeline routes (Source: ODOT, 2012)

Oregon Building Code Influences in the CEI Hub

For the area of the CEI Hub, the City of Portland has responsibilities to enforce the requirements set forth by the building code. Building codes set forth minimum standards on new construction. Building codes are frequently upgraded to reflect new design knowledge including seismic hazards. These codes play a vital role in the seismic robustness of structures. If the code requires a high level of seismic design, then the new structure is designed and built to resist seismic forces. For existing structures, there are few, if any, regulations that require them to be upgraded to meet today's knowledge on seismic hazards. If past codes call for seismic design levels that are significantly lower than the levels in the current code, then those structures may have been designed with serious seismic deficiencies. DOGAMI reviewed the building code environment for facilities in the CEI Hub.

The history of Oregon's building codes is important because the structures in the CEI Hub have been built over the last century and the building codes can have a major influence on the seismic vulnerability of the exposed facilities. For buildings and certain other structures, the seismic design level is typically regulated by the building code. A history of Oregon's seismic building code is available at: http://www.cbs.state.or.us/external/bcd/programs/structural/Seismic_Codes-Oregon_History_020712.pdf (Oregon Building Codes Division, 2012).

Both Oregon and Portland have a complex building code history. The State of Oregon adopted its first building code in 1974. Building codes apply to new buildings, and not retroactively applied to existing buildings except under special conditions. Building codes that account for our basic understanding of the Cascadia fault and modern seismic loading conditions were not adopted until 1993.

Figure 34 illustrates the trend of increasing seismic load requirements in the past half-century. As a technical example, it specifically shows the increase to the seismic base shear for a low-rise shear wall building located in Portland, Oregon for an Occupancy Category III structure. Occupancy Category III as defined on Table 1-1 of the ASCE 7-05 publication includes certain facilities that handle hazardous fuels. Base shear is an important seismic loading parameter on structures. Note that the figure shows the required base shear value drops in 2004. This is because the 2004 Oregon Structural Specialty Code, which adopted the 2003 International Building Code, integrates new knowledge about seismic performance that previously used a more conservative approach. A shear wall building is a building that relies on certain walls designed to resist forces generated by an earthquake that are applied to the building. Ductility relates to the building's ability to be reshaped without breaking. The current construction requirements for “specialty” structures, such as piers, tanks, and loading racks are also contained within the current building code, which is the Oregon Structural Specialty Code (OSSC) adopted by the Oregon Building Code Division and local building departments, such as in the City of Portland.

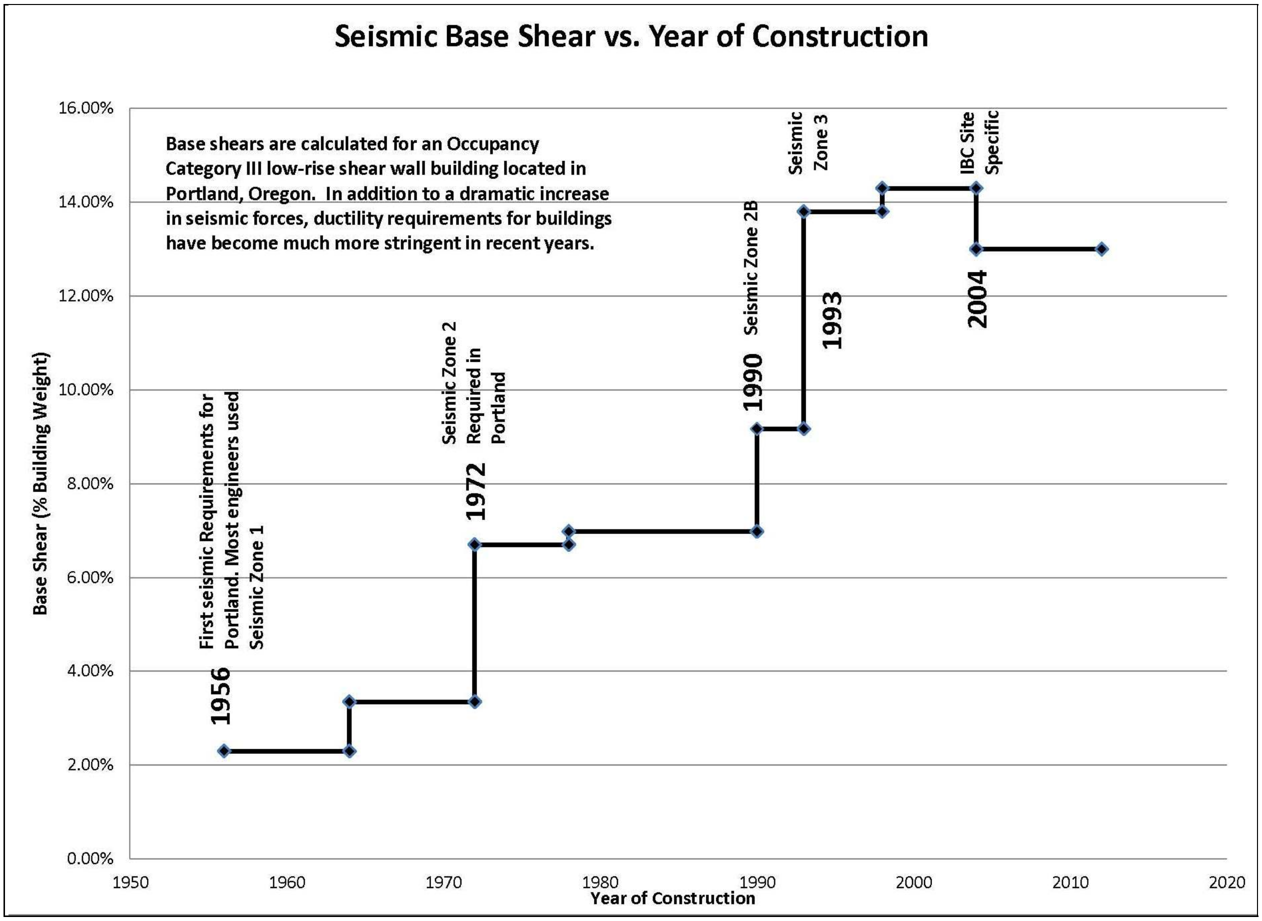


Figure 34: Seismic load requirements have increased over the decades to reflect the increasing understanding of Oregon's earthquake setting. For seismic design, 1993 was a landmark year. (Credit: KPFF consulting engineers)

Based on discussions with Jason Butler-Brown in the City of Portland Development Services department, facilities in the CEI Hub are required to obtain permits for new construction and conform with current building codes. Newly constructed structures are expected to have satisfactory performance in a design-level earthquake, that is, while they may sustain substantial structural damage, they should not collapse. It is possible for a structure to not be usable and still perform in a satisfactory manner that is in accordance with the building code. The level of compliance with past practices was not researched. In recent years, new building codes have been adopted as frequently as every three years. More recent building codes have progressively incorporated seismic design provisions. As an example, in October of 2010, the State adopted the 2010 Oregon Structural Specialty Code (OSSC), which refers to the 2009 International Building Code (IBC).

The first time geotechnical engineering reports were required to evaluate liquefaction potential and soil strength loss was in the 1996 OSSC which was based on the 1994 Uniform Building Code (UBC). At that time, it was widely accepted that silty soils were not prone to liquefaction. By approximately 2004, silty soils became widely recognized as being susceptible to liquefaction (Seed et al, 2003). As a result, the City of Portland began requesting that geotechnical engineering reports evaluate the liquefaction susceptibility of silty soils (pers. comm. with Jason Butler-Brown, city of Portland geotechnical engineer on January 13, 2010). Therefore, structures constructed over soft silty soils that were granted permits by the City of Portland prior to 2004, such as those near the Willamette River, may have liquefaction vulnerabilities.

Although new buildings in the CEI Hub have been regulated by the City of Portland using the OSSC for decades, DOGAMI discovered that older building codes and practices did not adequately address many non-building structures that exist in the CEI Hub, such as tanks, pipes, and piers. This is based on discussions with state, city, and private sector engineers including Steve Judson (Oregon Building Codes Division), Jason Butler-Brown (City of Portland) and Kent Yu (Degenkolb Engineers and Oregon Seismic Safety Policy Advisory Commission). One explanation is because non-building structures typically hold few, if any, people and the focus of the building code has traditionally been on life safety.

In the early 2000s, non-building structures gained more attention in American Society of Civil Engineers (ASCE) 7, an engineering design document referenced by the OSSC and used by engineers. The 2004 OSSC referenced the 2003 International Building Code (IBC) and ASCE 7. For the first time the building code, through ASCE 7, specified more directly the design basis for a variety of non-building structures, including piers and wharves. Furthermore, it specified that the design shall account for the effects of liquefaction along with other marine based-loading criteria. In 2005, the ASCE 7-05 was published. It is considered to be a landmark design document because it specifies the loading criteria, including seismic design for a multitude of structures and structure types. By 2007, with the adoption of the 2007 OSSC and OSSC's reference to ASCE 7-05, ASCE 7-05 has gained significantly more influence among engineers designing non-building structures as a building standard. Design methods other than those in ASCE 7-05 are allowed by building officials.

Oil Terminal Facilities

The state EAP partners, which consists of ODOE, OPUC and DOGAMI, worked with the US Coast Guard (USCG) on the USCG's routine inspection of the petroleum terminals' port facilities, reviewed California's MOTEMS and conducted site visits with USCG personnel and MOTEMS engineers to better understand the seismic condition of the port structures, primarily the piers and the wharves for transporting liquid fuels.

Port Structures

Beginning in July 2009, EAP partners and USCG leadership and staff developed a working relationship to share information on the earthquake hazards to the port facilities in the CEI Hub that USCG regulates for port security. These include: BP, ConocoPhillips, Chevron, KinderMorgan, McCall Oil, and Nustar Energy. EAP partners arranged boat tours of ports for energy facilities, hosted earthquake table-top scenarios, and organized a meeting with Western Energy Institute and the USCG. The Western Energy Institute is a non-profit organization of energy sector businesses. They help develop memorandum of understandings (MOUs) between petroleum companies that deal with, for example, emergency situations. These MOUs could be helpful to the USCG in fulfilling their responsibilities on port security. In response to concerns raised at the Western Energy Institute meetings, the EAP partners alerted transportation officials about the need to have reliable transportation routes open during a major earthquake disaster.

EAP information was shared with transportation officials at the Oregon Department of Transportation (ODOT) at the Oregon Seismic Safety Policy Advisory Commission, the ODOT bridge section, and at a House Transportation committee legislative hearing held on May 24, 2010.

In December 2009, USCG Port Security Specialist William R. Clark arranged for ODOE and DOGAMI to meet with the USCG Facility Inspections Branch in their Portland office. The goal of the meeting was to determine whether USCG requests any information on the seismic condition of existing facilities and how they would address seismic disasters. At that meeting, it was determined that the USCG inspections did not include seismic information but would be willing to request information by selected port owners to assist the EAP partners. As a result of the meeting, DOGAMI developed two questions for the USCG to request seismic information on port facilities owned by the petroleum companies. The questions listed below were submitted to representatives at these six companies: BP, ConocoPhillips, Chevron, KinderMorgan, McCall Oil, and Nustar Energy.

In March 2010, the USCG provided the ODOE and DOGAMI with the responses from three of the six facilities, which include BP, Chevron, and ConocoPhillips. Terminal managers provided their responses via email, in part written by their engineers They range in detail and completeness and are provided below. No engineering reports were requested nor provided. For this report, very slight modifications to the responses have been made to help with clarity, such as renumbering the answers and correcting misspellings. Also, the names are each facilities have been removed and replaced with "*unnamed*". This action is consistent with the goals of the study, when possible, to respect the privacy of privately-owned energy sector operators when obtaining seismic vulnerability data. In late 2010, the USCG informed ODOE and DOGAMI that they never received responses from Kinder Morgan, Nustar or McCall Oil. Shell's port is not in operation and they were not included in the USCG request for information.

<u>Question 1. What is the original construction date of the docks and waterfront structures (e.g., quay wall, anchored bulkhead, sheet-pile wall)? What level(s) of seismic design was used?</u>

> <u>Response 1</u>. The *unnamed* Portland Terminal Dock was totally re-constructed in 1960 (approx). It should have been designed for seismic forces prescribed in the Uniform Building Code (UBC) at that time. Early (crude) provisions for seismic design were required in the UBC way back in the 1930's.
>
> A dock structural evaluation was completed in 2005. Part of its findings:
>
> Earthquake Load Analysis: A seismic analysis was performed on the existing structure, with the worst load condition being lateral earthquake forces perpendicular to the dock. These lateral forces are resisted by the batter piling at the wide bents (lines 23-58), and by bracing at the narrow bents (lines 1-22), except that the narrow bents at lines 17,18,19 have batter piles also. The methods outlined in IBC 2003 were used for seismic analysis, and this obviously results in higher lateral loads than what the dock was originally designed for. Our calculations indicate that the wide bents (lines 23-58) of the existing structure have adequate resistance for these seismic loads. However, the narrow braced

bents (lines 1-16, and 20-22) would be slightly overstressed due to these seismic loads and the bracing/connections would need to be reinforced. This would likely involve replacing the wood bracing with steel channels and adding some additional bolts. It's important to note that seismic upgrades to existing structures are typically only required when a structure is undergoing a change of occupancy or major design alteration, which is not the case here. So, while it's not legally required, we still recommend adding seismic reinforcing to the narrow dock area. This would increase the structure's resistance to seismic loads and help prevent failures in the product piping/spills into waterway.

Response 2. A comprehensive review of all of the local record drawings for the dock reveal the following:

The earliest drawing for the dock is from *unnamed*, dated June 1936, and it appears that the drawing may not have been an original construction drawing, but a modification. The dock could have been constructed several years earlier. Since the terminal had been in existence since about 1912, it is easy to believe that a wharf structure existed at that time.

In 1972 structural wood piling replacement and firewall improvements were made.

In 1974 major structural improvements were made. The work was performed under city of Portland permit 480690, 12/6/1973. The work added 3 reinforced concrete mooring sections, reconstructed the dock in entirety between bents #3 and #16, added two reinforced concrete dolphins at the head of the dock, and added a 40ft.x80ft.x8" thick reinforced concrete slab at the tanker unloading section. The work was designed and stamped by a licensed PE and work was completed to building codes in force at that time. Any seismic evaluation of the dock required by code would have been completed, however no specific seismic criteria was listed on design drawings.

In 1997 two significant steel-piled fenders were added to the upstream and downstream berths. The work was designed by a PE, Winzler and Kelly.

A new waterfront structure was added in 2007. A 100 ft. long sheet-pile wall was installed and armored with rip rap on the upstream side of the dock. The work was designed in accordance with the latest building codes in force and was permitted by the city or Portland. The downstream side of the dock do not include any significant improvements, e.g., quay wall, anchored bulkhead, or sheet-pile wall.

Response 3. The dock was completed 1993, no idea what level of seismic design was used. The sea wall was completed 2009 and was designed using a computer model to meet current UBC Seismic Zone 3 requirements.

Question 2. What is the post earthquake disaster restoration time for waterfront structures that handle fuel (e.g., operational capacity versus time curves)?

Response 1. The restoration time will depend on the extent of the damage. We'd establish a command post and us the IC system, then assess the damage. Any return to normal operations would take place one component at a time, inspecting all equipment for leaks, etc.

Response 2. My professional opinion on the timing of a repair of a damage dock would rest entirely on the severity and breadth of the damage to critical marine facilities in the Port and the relative rank in priority that the *unnamed* fuel dock holds amongst all damaged facilities.

If damage were isolated to just the *unnamed* dock, I believe that significant damage could be repaired and the dock placed back in operation in 2 to 8 weeks, if emergency repairs were expedited.

Response 3. No idea.

Based on the information contained in the responses received, it was revealed that some CEI Hub ports were originally built around the early 1900s, and, most have had alterations, upgrades and additions over the decades, some recently. This is consistent with our field observations. Based on the above responses as well as discussions with terminal managers, the length of time to restore operations appeared to be difficult to estimate and is not well constrained.

MOTEMS and CEI Hub Ports

MOTEMS is a California program that regulates the state's petroleum companies' facilities (http://www.energy.ca.gov/2009_energypolicy/documents/2009-04-14-15_workshop/presentations/Day-1/03-Eskijian_Martin_MOTEMS.pdf). Earthquake experts consider the program's seismic regulations to meet a high standard (Percher and Bruin, 2009) . MOTEMS is part of the California Code of Regulations, Title 24, Part 2, Volume 2 of 2, 2007 California Building Code, Chapter 31F http://www.slc.ca.gov/Division_Pages/MFD/MOTEMS/MOTEMS_Home_Page.html. The MOTEMS program requires analysis and audits for every marine oil terminal in California. Seismic analyses are required based on the baseline inspection, current condition of the structure and site-specific ground motion input. Selected seismic-related portions include Division 1: Introduction; Division 2: Audit and Inspection; Division 3: Structural Loading Criteria; Division 4: Seismic Analysis and Structural Performance; Division 6: Geotechnical Hazards and Foundations; Division 7: Structural Analysis and Design of Components; Division 8: Fire Prevention, Detection and Suppression; Division 10: Mechanical and Electrical Equipment; and, Division 11: Electrical Systems. Over time, risks of catastrophic failures with environmental contamination, interruption of marine traffic, and serious long-term fuel shortage are being minimized in California.

MOTEMS requires all petroleum companies in the state to provide seismic information regarding their properties. MOTEMS division 2 prescribes the MOTEMS "audit" and requires as-built drawings, and, if not available, reconstructed drawings, along with an above and under-water inspection of facilities in California. If the initial drawings cannot be located, it will be difficult to determine the depth to fixity of the piles. Before any structural assessment can be made, soil conditions, including the presence or absence of potentially liquefiable layers needs to be assessed with geotechnical borings. MOTEMS requires borings to a depth of 100 feet placed in strategic areas around or under the existing wharf/pier. As an example, some of the requirements for the seismic assessment of a marine oil terminal in California include:

- A site-specific seismic hazard study will be required to determine the appropriate response spectrum for the 72 and 475 year return period events. This is mandated for site class “F” and will probably be required with the soft river bottom and potential liquefaction and no shallow bedrock. However, one set of borings may be sufficient for many adjacent facilities to eliminate repetitive borings.

- The MOTEMS criteria (or ASCE u/w standards, Ref. 2) on an above and under-water inspection to the mudline is required. The criteria for the inspection requires that a registered civil or structural engineer to be in the water at least 25 percent of the dive time. As-built or “baseline” drawings may have to be constructed to evaluate the structural integrity of each facility if the original drawings are not available.

Martin Eskijian, MOTEMS Engineering Branch Supervisor (retired in 2011), and his staff provided expertise and assistance to the EAP. Mr. Eskijian provided assistance on one site visit comprised of a boat reconnaissance that included port facilities in Oregon in the CEI Hub. The EAP partners were invited to the MOTEMS northern California office in Hercules, California, where we visited the Chevron refinery in Richmond, California, the Tesero port facility in Vallejo, California, and participated as observers in a MOTEMS meeting with Shell. After that, MOTEMS senior engineer, Kendra Oliver, provided assistance on four terminal visits that included port facilities in Oregon in the CEI Hub.

The following photographs describe and illustrate some of the EAP partners' and MOTEMS engineers’ major concerns about seismic readiness of the port structures operated by oil terminals in the CEI Hub. These issues largely fall under MOTEMS Divisions 3: Structural Loading Criteria, Division 4: Seismic Analysis and Structural Performance, Division 6: Geotechnical Hazards and Foundations, and Division 7: Structural Analysis and Design of Components.

Figure 35 shows steel plumb piles with lateral timber bracing as observed at facilities in the CEI Hub. MOTEMS does not permit the use of timber cross bracing to provide lateral restraint (seismic loading) for vertical piles. This was one of many major shortcomings of the observed facilities in the CEI Hub. With the large variation in water depth, dependent on dam release, tides and storms, the pile heights out of the water look high; buckling forces on the columns may well exceed current design standards and this may become critical for the seismic evaluation.

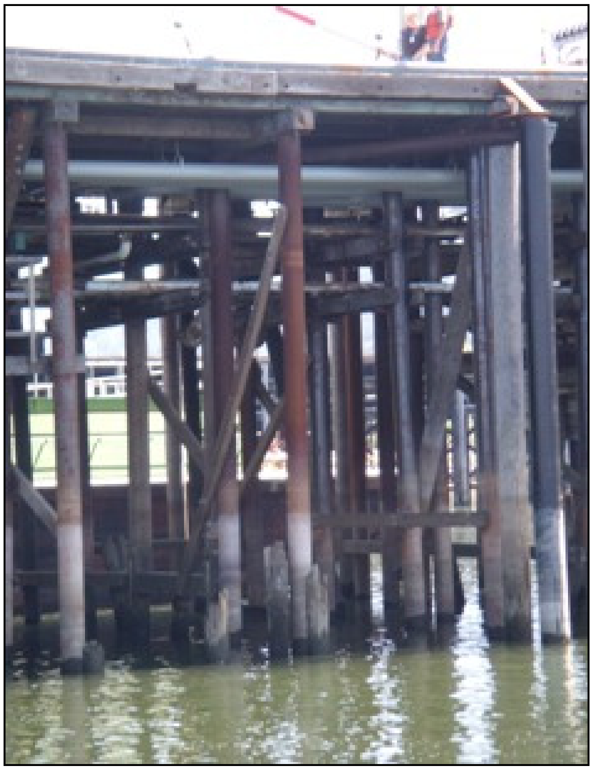


Figure 35: Lateral timber bracing for steel plumb piles in the CEI Hub is considered inadequate by California's MOTEMS standards. (DOGAMI photo)

MOTEMS provides liquefaction screening methodologies that could be used to evaluate whether or not there are slope stability issues, whether lateral spreading along the piers/wharves or trestles is likely, and the possibility of adverse seismic loading of the piles (e.g., out of phase with the inertial loads). It is possible that soil failures may be a significant contributor to compromising the structural integrity. If the seismic demand on the structural system (either above grade or below grade) is higher than the structural capacity and the structural integrity could be compromised, then upgrades would be required. MOTEMS allows for a dialogue between the operator and regulator on the proposed mitigation and schedule of mitigation; the regulator decides whether the time requested to rehabilitate is reasonable or excessive. *Figure 36* shows a foundation for a high traffic pier, shown in *Figure 37*, on highly liquefiable soils in the CEI Hub.

Figure 36: This under-designed foundation in part of an oil terminal pier in the CEI Hub is considered inadequate. Based on previous regional studies, boring logs from an adjacent facility, and on-site visual inspection of the surficial soils, this area has high susceptibility for liquefaction and lateral spreading. (DOGAMI photo)

Figure 37: The area by this pier in the CEI Hub is used to transport liquid fuel. Based on previous regional studies, boring logs from an adjacent facility, and on-site visual inspection of the surficial soils, this area has high susceptibility for liquefaction and lateral spreading. (DOGAMI photo)

Under the MOTEMS system, following on the seismic analyses of the port structure and the ground, a pipeline stress analysis may be required in order to be certain that no leaks will result from the seismic displacements. Facilities in the CEI Hub have flexible timber structures (some with pipelines under the piers) with hard points in locations that would likely indicate failure in a pipeline stress analysis.

During the site visits in the CEI Hub, DOGAMI and MOTEMS engineers observed many structures with pipelines with possible vulnerabilities, some of which were verified by the responses provided by the oil terminal facilities to the USCG. *Figure 38* shows transverse timber beams in seriously degraded condition, with one bolt connecting the beam to the steel plumb pile as observed during visual inspections. Some of the transverse beams support petroleum pipelines. The pile cap beam in the center of the photo, which should be level, has a clockwise rotation. Based on the professional judgment of DOGAMI and MOTEMS engineer Martin Eskijian from post-earthquake investigations, experience with engineering analyses, and from the body of knowledge in the earthquake profession, this configuration would be expected to fail in a moderate earthquake, without even considering lateral spreading or liquefaction.

Figure 38: This photo shows generally poor condition of transverse beams supporting petroleum pipelines and cap beam in the CEI Hub. Notice the clockwise rotation of the pile cap beam in the center of the photo. (DOGAMI photo)

Figures 39, 40, 41 and 42 illustrate some of the poor conditions observed of the oil terminal piers in the CEI Hub. Examples from working piers include: deteriorated concrete foundation, exposed rebar, split timber beams and broken timber piles.

Figures 39 and 40: The close-up photo on the right shows poor timber-to-concrete connection, broken concrete and exposed rebar. Energy sector companies should maintain and upgrade infrastructure to current standards in order to protect assets and limit down-time following an earthquake. (DOGAMI photos)

Figure 41: The connection on this pier in the CEI Hub appears to have deteriorated due to a split in the timber beam. This type of damage suggests that the condition of the structure may not be routinely monitored and maintained and that the overall pier is seismically vulnerable. (DOGAMI photo)

Figure 42: This pier in the CEI Hub appears to be poorly maintained with broken timber piles adjacent to working components of the pier. (DOGAMI photo)

Figure 43 shows a "hard point" (ie, fixed point that could concentrate stresses) for the petroleum pipelines, which may not be desirable due to structural displacement from an earthquake. In accordance to MOTEMS procedures, a pipe stress analysis should be performed, with the input seismic displacement and then the pipeline could be evaluated. In the case illustrated in *Figure 43,* it is unlikely that the ability to tolerate lateral motion was included in the original design.

Figure 43: "Hard point" fixity of petroleum pipeline is located under this pier in the CEI Hub and is considered to be seismically vulnerable. (DOGAMI photo)

It is common for waterfront structures that are under-designed to experience damage in earthquakes as evidenced by worldwide earthquakes. *Figure 44* shows a damaged pier from the 2010 Chile earthquake.

Figure 44: An example of a damaged pier in the 2010 Chile earthquake (Technical Council on Lifeline Earthquake Engineering – TCLEE - 2010)

As part of the EAP, the EAP partners considered possibly using MOTEMS seismic regulation as "best practices" in Oregon as a means to make Oregon petroleum terminals safer. DOGAMI held discussions with MOTEMS personnel, conducted a literature review, accompanied MOTEMS staff on tours of the port facilities in the CEI Hub, and toured California oil terminals to better understand the effectiveness of the program. Based on our findings, it appears that applying the seismic portion of MOTEMS to Oregon facilities and the CEI Hub facilities in particular would provide added safety.

Seismic Pipeline Vulnerability

The overall performance of oil and gas transmission pipeline systems in past worldwide earthquakes has been relatively good. However, failures have occurred in both older pipelines as well as modern pipelines, such as welded steel pipelines. Damage is typically concentrated in areas of unstable soils with permanent ground deformation (PGD) and/or liquefaction, including at river crossings and landslides.

For the EAP, DOGAMI did not obtain any information or reports on seismic vulnerability of existing pipelines in the CEI Hub from the City of Portland, facility owners, or regulators. Seismic vulnerability assessments can be conducted on specific pipelines, both above ground and buried, to address specific pipeline performance. A major liquid fuel transmission pipeline and two natural gas transmission pipelines that have river crossings at the southern tip of Sauvie Island, as shown on Figure 29 Lifelines in the CEI Hub area, as well as Columbia River crossings just north of the CEI Hub (refer to http://pubs.usgs.gov/sim/3027/sim3027_front.pdf) are in need of special attention.

Jason Butler-Brown, engineer at the City of Portland Bureau of Development Services, states that they do not review the structural design of proposed pipelines. Permits are reviewed and issued for the excavation associated with the pipelines (on private property) and where pipelines are supported on structures that cross over private roadways or areas accessible by people (again on private property). Interstate fuel pipeline design is regulated under Title 49 of the Code of Federal Regulation. Part 192 of Title 49 of the Code of Federal Regulations addresses gaseous fuels, Part 193 addresses LNG and Part 195 deals with liquid fuels. These serve as minimum design standards and are applied to interstate pipelines connected to the CEI Hub.

Certain fuel pipelines are regulated for safety by the US Department of Transportation's Office of Pipelines and Hazardous Materials and Safety Administration (PHMSA) (http://www.phmsa.dot.gov/pipeline/regs). As part of this EAP, JR Gonzalez (former) the Administrator of the OPUC Safety, Reliability and Security Division informed Hossein Monfared, Pipeline Engineer, from PHMSA Western Region Office of Pipeline Safety that a liquid fuel transmission pipeline feeds petroleum tank farms situated on potentially liquefiable soils. This was part of a discussion to inquire about the content of PHMSA's audits. As an outcome of that discussion, DOGAMI discovered that, to date, PHMSA has not requested seismic information as part of their audits involving tank farms in Portland.

When soil liquefies, it behaves like a fluid and pipe embedded in it will be subjected to the buoyant force from below. This buoyancy due to liquefaction can occur at river crossings and sandy areas with high ground water tables. *Figure 45* is a schematic showing buoyancy forces (Fb) on a buried pipe with a burial depth of C (IITK, 2007). Pipes can fail due to buoyant forces.

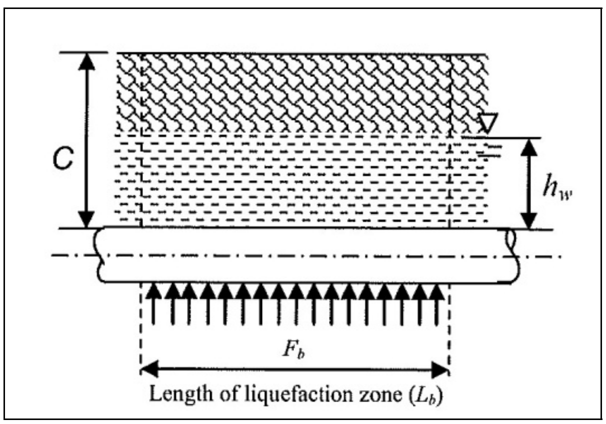


Figure 45: Buoyancy forces on a buried pipeline. (IITK, 2007)

In areas with permanent ground deformation (PGD), such as areas with lateral spreading (without the occurrence of liquefaction) or liquefied soils that have translated down slope towards the river channel (often referred to as a "free face"), the embedded pipe will be subjected to both compression and extensional forces. The total strain on the pipe can exceed the amount of strain the pipe can withstand creating unsafe pipeline conditions and even pipeline rupture. The maximum strain in the pipe both in tension and compression can be evaluated and compared with the allowable strain of the pipe. *Figure 46* is a schematic diagram that shows a pipeline perpendicular to the direction of PGD. *Figure 47* shows a pipeline that is parallel to the direction of PGD. In both figures, the area of unstable soils with PGD are illustrated before (purple zone) and after (gray zone) the ground movement. The actual pattern of PGD will depend on the earthquake ground motions, local soil conditions and the pipeline may cross the zone in any direction. *Figure 48* shows areas of tension and compression due to longitudinal PGD (IITK, 2007).

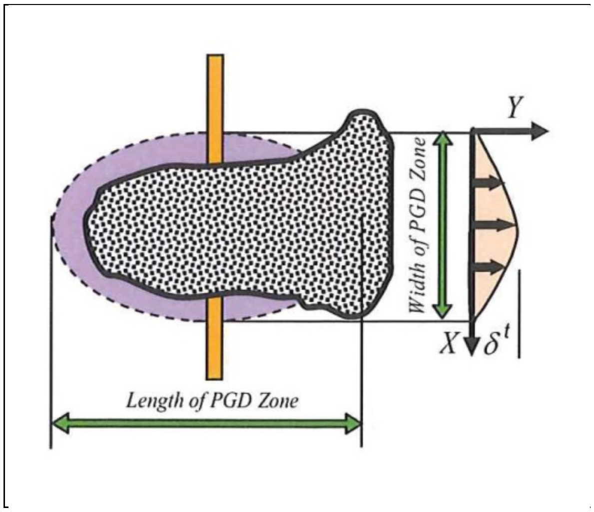


Figure 46: Transverse PGD schematic (IITK, 2007)

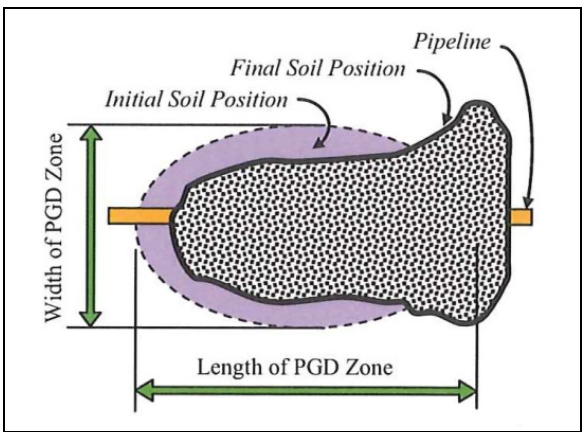


Figure 47: Longitudinal PGD schematic diagram (IITK, 2007)

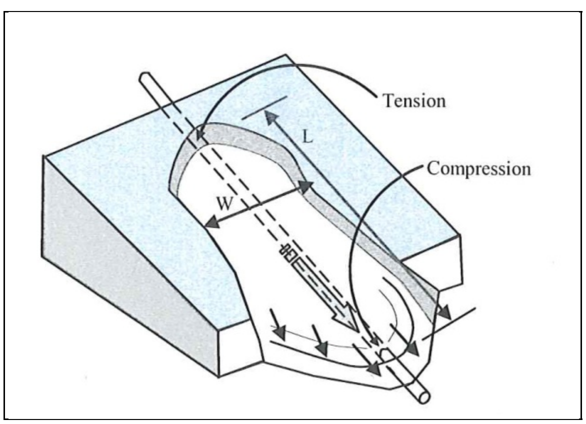


Figure 48: Areas of tension and compression from longitudinal PGD (IITK, 2007)

A variety of possible mitigation measures are available to improve the performance of pipes against PGD. Depending on the specific situation, some options might involve: soil improvement, increasing the load carrying capacity of the pipe system, reducing the friction between the pipe and soil, relocating the pipe, anchors to prevent uplift from buoyant forces, or special pipe joints or fittings that allow greater joint deflection, extension, or compression.

Non-Energy Facilities and Structures

Many other structures and facilities are located in the proximity of the CEI Hub. Structures include bridges over the Willamette River as well as other port facilities and overpasses that span the railroad tracks. Other industrial companies, including ones that handle petrochemicals and hazardous materials, are located in the CEI Hub. A major rail yard exists at the south end of the CEI Hub. A limited number of commercial and residential occupants are also located in the area. Although these facilities are not part of the energy sector and included in this study, it is important to be aware of these facilities and structures. They could become a concern after a Cascadia earthquake. For example, if the chemical company has a fire, it could spread to a nearby oil terminal, or vice versa.

Waterway Transportation to the CEI Hub

The navigational channel from the Columbia River mouth to the lower Willamette River is used to transport fuel by marine vessels. DOGAMI investigated the infrastructure and geologic conditions along the shipping channel and terminals and analyzed the situation based on discussions with engineers from the U.S. Corps of Engineers and ODOT and staff from the U.S. Coast Guard (USCG), engineering judgment from previous earthquake investigations, geotechnical engineering reports and publically available material. Our findings, which are preliminary and require additional studies, indicate that the shipping channel will be damaged and closed for river navigation until it is officially cleared for use by the USCG. Based on our findings, the likely damage includes four modes:

- Tsunami scour, damage and debris near the mouth of the Columbia River
- Underwater slope failures along portions of the steep banks of the navigable river channel
- Collapses of overhead structures such as bridges from earthquake shaking
- Broken buried pipelines at river crossing locations

Tsunami damage near the mouth of the Columbia River is based on tsunami hazard mapping (Priest et al, 1998) and DOGAMI's field observations of tsunami damage from the 2004 Sumatra and 2011 Tohoku Japan subduction zone earthquakes. Damage to the navigable river channel is based on the already marginally stable, underwater steep slopes that require periodic dredging to maintain the required channel depths during normal operating conditions. Based on discussions with the ODOT Bridge Section engineers and seismic bridge engineering practices, all of existing bridges including the bridge approach structures have been seismically under-designed compared to today's requirements and may incur damage (http://peer.berkeley.edu/events/caltrans-peer/files/Ashford_Abutment_2009_r1.pdf). Similarly, the pipe and transmission river crossings may be under-designed in particular to liquefaction and lateral spreading conditions. The structures that may be damaged and block the waterway extend from the Columbia River mouth to the fuel storage area in the CEI Hub. These structures, from west to east, include:

- 1966 Astoria-Megler Bridge crosses the Columbia River(*Figure 49*)
- Buried natural gas pipeline crosses the Columbia River to feed power plants (*Figure 50*)
- High voltage electrical transmission crossing the Columbia River (*Figure 51*)
- 1930 Lewis and Clark Bridge in the Longview, Washington area crosses the Columbia River (*Figure 52*)
- Several liquid fuel and buried natural gas pipelines at Columbia River and Willamette River crossings just north of the CEI Hub. Photo shows a natural gas gate station on Sauvie Island (*Figure 53*)
- High voltage electrical transmission crossing over Willamette River (*Figure 54*)
- 1931 St. Johns Bridge crosses Willamette River (*Figure 55*)
- 1908 BNSF rail bridge crosses Willamette River (*Figure 56*)
- 1973 Fremont Bridge, part of Interstate 405, crosses the Willamette River and is used for liquid fuel distribution by tank trucks (*Figure 57*)

Closure of the shipping channel would prevent marine vessels from delivering liquid fuel as well as emergency response and recovery equipment from being delivered.

Figure 49: The approach (foreground) to the 1966 Astoria-Megler Bridge that spans the Columbia River has major structural deficiencies according to ODOT Bridge Section. In a major Cascadia earthquake, the exterior (concrete) shear keys on the approaches would likely not withstand lateral displacement of the superstructure (approach deck) (DOGAMI photo)

Figure 50: A buried natural gas pipeline crosses underneath the Columbia River and supplies two Oregon power plants near Clatskanie, Oregon.(DOGAMI photo)

Figure 51: High voltage electrical transmission crossing over the Columbia River just west of Longview, Washington. (DOGAMI photo)

Figure 52: 1930 Lewis and Clark Bridge in the Longview, Washington area crosses the Columbia River (DOGAMI photo)

Figure 53: Several liquid fuel and buried natural gas pipelines at the Columbia River and Willamette River crossings just north of the CEI Hub. Photo shows a natural gas gate station on Sauvie Island. (DOGAMI photo)

Figure 54: The high voltage electrical transmission crossing showing transmission towers built on a river bank susceptible to lateral spreading (BPA, 2008) (DOGAMI photo)

Figure 55: The 1931 St. Johns Bridge crosses the Willamette River in the CEI Hub. The tall columns that are part of the approach are seismically deficient. (DOGAMI photo)

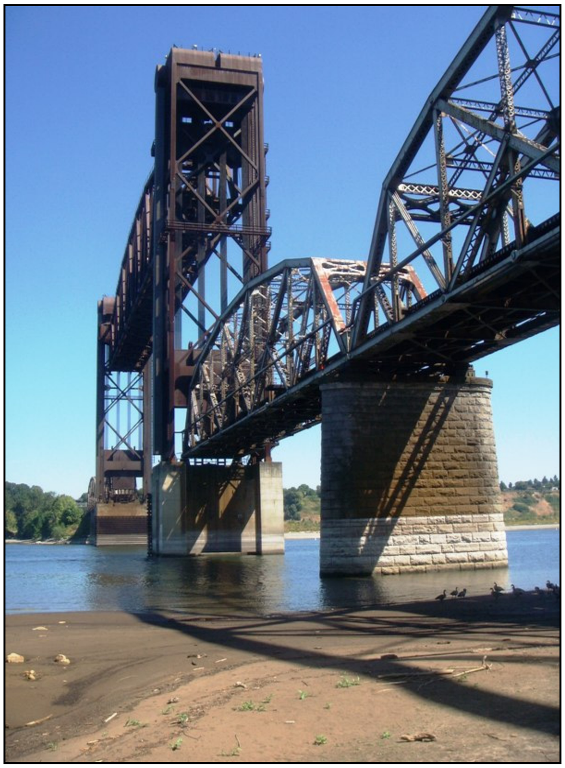


Figure 56: The 1908 BNSF rail bridge that crosses the Willamette River in the CEI Hub. The piers are seismically deficient. (DOGAMI photo)

Figure 57: The 1973 Fremont Bridge, part of Interstate 405, crosses the Willamette River and is used for liquid fuel distribution. (DOGAMI photo)

Section 6
Summary of Findings

To assess the overall seismic risk to the energy infrastructure in the CEI Hub, DOGAMI gathered information on the seismic hazards, the exposed facilities present in the CEI Hub, the seismic vulnerability of these facilities, and considered the potential consequences of earthquake-induced damage at the facilities. Our goal was to:

- Understand the facilities and system components that are present (what is "exposed")
- Assess the vulnerability of the exposed parts
- Assume failure of the highly vulnerable parts
- Evaluate the likely consequences

The consequences of the damage to the infrastructure must be considered to understand risk. For example, if a site experiences liquefaction that causes the bottom of a petrochemical tank to rupture spilling all of its contents, but the product is quickly contained and not in demand, then the consequences are manageable and the risk can be considered as low. In contrast, if a site experiences only minor shaking that temporarily jams a door opening to access fire suppressants and a fire grows to uncontrollable levels in an area with critical products, these consequences may be significant and the risk is considered as high.

Consequences can be immediate (e.g. those just described), short-term, long-term; direct or indirect; localized or far-reaching. Several examples taken from the 2010 Chile subduction zone earthquake are provided (Eidinger and Tang, in press). Limited water availability can impact immediate needs with respect to fire fighting capabilities as well as long-term needs for normal living conditions. (See *Figures 58 and 59*) In a similar vein, the lack of or limited electricity from a damaged transmission tower can impact businesses and the economy. *Figure 60* shows structural damage incurred from the 2010 Chile earthquake to a transmission tower at a major river crossing that serves a populated city. In addition, many interdependencies exist and cross cut many sectors of our society. This risk study takes initial steps to address likely consequences and interdependencies.

Figure 58: Structural damage to water tank located in fuel tank farm in Santiago from the 2010 Chile earthquake (Technical Council on Lifeline Earthquake Engineering - TCLEE)

Figure 59: An example of damaged water transmission pipelines in the 2010 Chile earthquake. This limited water availability for emergency response as well as for businesses and daily living. (Technical Council on Lifeline Earthquake Engineering - TCLEE, 2010)

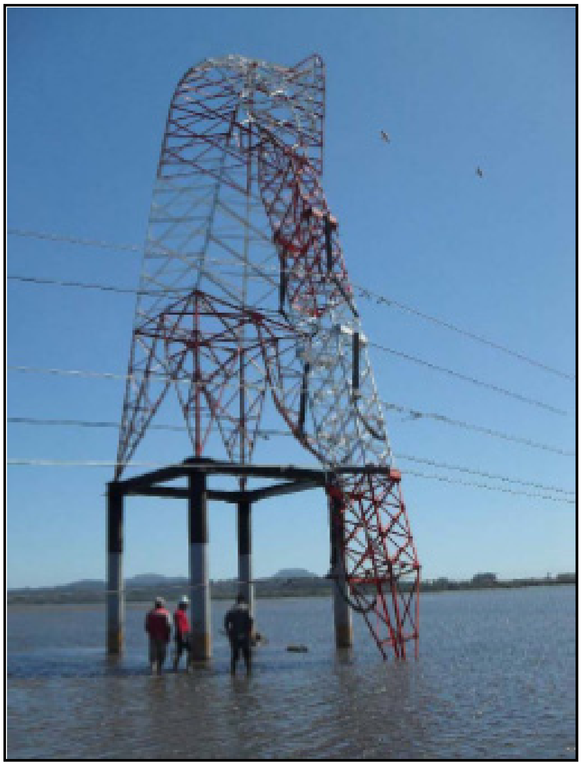


Figure 60: Structural damage to high voltage transmission tower located in river crossing in 2010 Chile earthquake. This limited electricity availability while temporary towers were installed (Technical Council on Lifeline Earthquake Engineering - TCLEE)

Seismic Risk in the CEI Hub

Figures 61 and 62 show the northern portion and southern portion of the CEI Hub where the major seismic vulnerable energy sector facilities—substations, river crossing, liquid fuel terminals, and an LNG storage facility—have been highlighted (yellow dashed lines). Also shown are potentially liquefiable soils in transparent red, existing mapped landslides in beige, and the Portland Hills fault is in red (Madin el al, 2008; Mabey et al, 1993; Burns et al, 2011; Beeson et al, 1991). Each of these highlighted facilities were visited. During our limited visual inspections we identified numerous structural elements with high seismic vulnerability that could cause serious damage and loss of function in a Cascadia earthquake. This includes the oil terminals, which have significant seismic vulnerabilities and limited redundancy.

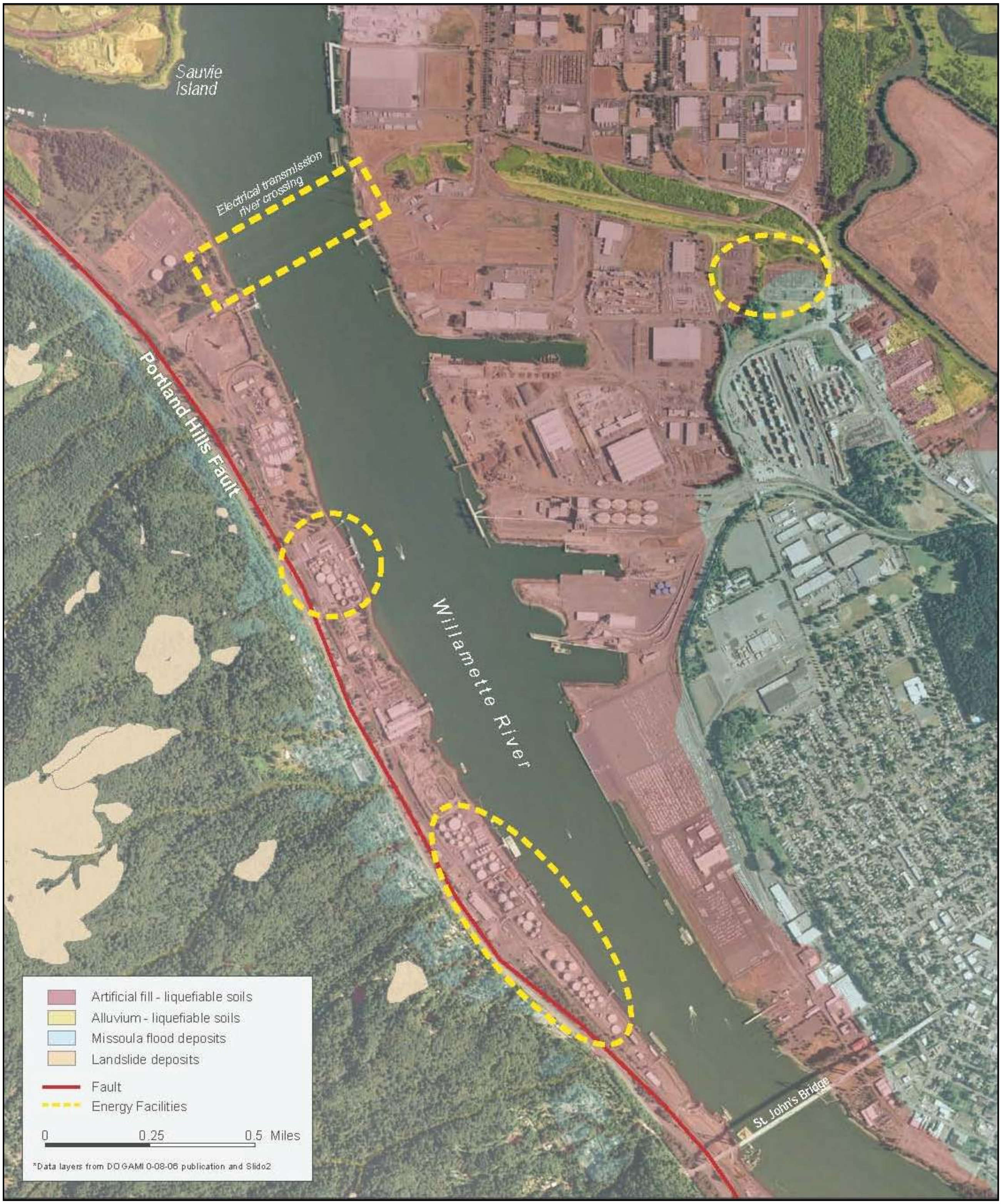


Figure 61: Northern portion of CEI Hub showing the major energy sector facilities vulnerable to damage in a Cascadia earthquake-- substations, river crossing, and liquid fuel terminals (yellow dashed lines) and potentially liquefiable soils (transparent red), existing mapped landslides (beige), and the Portland Hills fault (red). (DOGAMI)

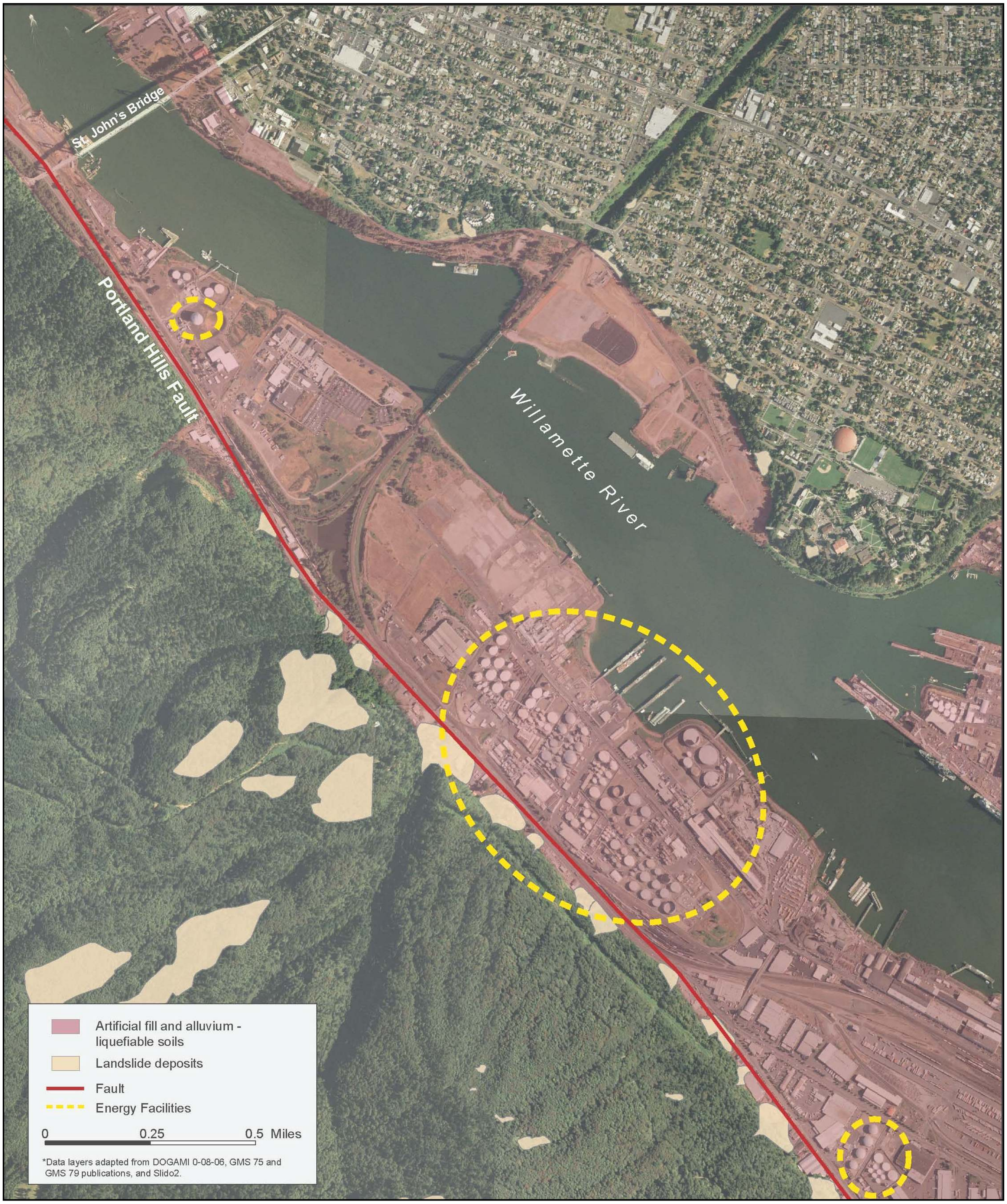


Figure 62: Southern portion of CEI Hub showing the major energy sector facilities vulnerable to damage in a Cascadia Subduction Earthquake -- LNG storage facility and liquid fuel terminals (yellow dashed lines), potentially liquefiable soils (transparent red), existing mapped landslides (beige), and the Portland Hills fault (red). (DOGAMI)

Based on the findings of this study, DOGAMI has identified the following as examples of high seismic risks to the energy sector with statewide importance. The first two risks are system-wide risks involving redundancies and interdependencies; the remaining risks are sector-specific seismic risks to liquid fuel, natural gas and electricity.

Lack of System Redundancies

DOGAMI determined that each energy source has a different level of redundancy in their transmission system. This determination was based on discussions with the EAP partners, interviews with personnel from the various energy sectors, and analyses of available data including maps, such as Earthquake Hazards of Lifelines along the Interstate 5 Urban Corridor: Woodburn, Oregon, to Centralia, Washington, and Earthquake Hazards of Lifelines along the Interstate 5 Urban Corridor: Cottage Grove to Woodburn, (Barnett el al, 2009), Western Electricity Coordinating Council (WECC, 2012) and US. Department of Transportation's National Pipeline Mapping System's Public Map Viewer (https://www.npms.phmsa.dot.gov/PublicViewer/composite.jsf). The redundancy of each of the systems influences the level of seismic resilience with more redundant systems favoring higher resilience. The transmission systems, such as the main electrical grid and transmission pipelines, are of key importance in the supply chain.

1. The electrical system has power generation facilities located throughout Oregon and has the most widespread and redundant transmission system. The level of redundancy surrounding and within the Portland metropolitan area is high because there exist a number of transmission systems and diminishes away from the Portland area.
2. The natural gas system in Oregon relies 100 percent on imported natural gas, most of it from the north, and has much less redundancy than the electrical system. The natural gas system has a loop configuration around the greater Portland area and this provides for some redundancy. If a break in the loop occurs, it is theoretically possible to provide natural gas to areas around the loop. The level of redundancy south of the Portland metropolitan area (e.g. Marion County) is considered to be low based on discussions with OPUC and the gas operator. In addition, the natural gas reserve capacity has limits.
3. Oregon's liquid fuel oil source relies 100 percent on imported fuel, most of it from the north, and has very limited redundancy and reserve capacity.

System Interdependencies

The three energy sources—electricity, natural gas, and liquid fuel—depend upon each other so if one system is inoperable, it will impact another. For example, all sources rely on electricity to operate their systems. Electricity is needed to power the control rooms for natural gas and liquid fuel transmission.

The energy sector also relies on the transportation and telecommunication sectors. For example, in order to transport liquid fuel to the marine oil terminals in the CEI Hub, ships enter through the Columbia River mouth and travel up the navigable waterway. If the river mouth is blocked by tsunami debris, the shipping channel is altered from sloughing of the underwater slopes or the shipping lane is blocked by downed electrical transmission lines or bridges, then moving fuel to the CEI Hub via the waterway would not be possible.

Liquid Fuel

Liquid fuel pipeline: The CEI Hub petroleum facilities receive liquid fuel via two methods: 1) the liquid fuel transmission pipeline, and 2) marine vessels. The transportation method and amounts vary due to product need, transportation costs, weather and other conditions. The liquid fuel pipeline was largely constructed in the 1960s when the regional seismic hazards were unknown and state-of-practice construction techniques at that time did not include any reference to seismic standards. The regional seismic hazards are now known to be high and the soils at the river crossings are susceptible to liquefaction and lateral spreading. The 1960s vintage pipeline design did not consider ground movements from lateral spreading at river crossings or the stresses to the pipelines induced by earthquakes that may cause pipe damage and multiple breaks. A pipe break would have a significant impact on all of the petrochemical facilities in the CEI Hub and could result in a statewide fuel shortage.

Shipping channel: The navigational channel from the Columbia River mouth to the lower Willamette River is used to transport fuel by marine vessels. DOGAMI conducted a preliminary investigation and found that the shipping channel would likely be damaged and closed for river navigation until it is officially cleared for use by the USCG. Based on our findings, the likely damage includes four modes:

- Tsunami scour, damage and debris near the mouth of the Columbia River
- Underwater slope failures along portions of the steep banks of the navigable river channel
- Collapses of overhead structures such as bridges from earthquake shaking
- Broken buried pipelines at river crossing locations

Closure of the shipping channel would prevent marine vessels from delivering liquid fuel as well as limit transport of emergency recovery equipment.

Marine terminals: All of the port facilities in the CEI Hub have significant seismic risks due to liquefaction, lateral spreading, and seiches. Some older piers were constructed without any seismic design provisions, have deteriorated, and may be damaged even in a moderate earthquake. If oil products are released and contaminate the navigable waterway, the waterway may be closed to river traffic thus impeding emergency response activities as well as the supply chain. The local capacity to fight fires and clean hazardous material spills is limited.

Fuel Tank Farms: All of the fuel tank farms in the CEI Hub have significant seismic risks due to the significant unmitigated liquefaction hazards largely posed by hydraulically-deposited river soils (also known as hydraulic fill) and native soils. Due to the long standing inadequate seismic hazard knowledge and the inadequate building code requirements, the majority of the tanks have been constructed without any or only limited seismic design criteria on unmitigated, potentially liquefiable soils. It was not until 2004 that city building officials required new construction projects, including tanks, to evaluate for liquefaction of silts. Based on discussions with City of Portland engineers from Bureau of Development Services and terminal operators, DOGAMI has identified only three existing tanks that have addressed liquefaction hazards.

Fuel supply: The fuel terminals in the CEI Hub on average have a three to five day supply in the tank farms for regular unleaded gasoline and diesel fuel. Fuel is stored in tanks and some tanks have seismic vulnerabilities (see *Figure 63*). Premium gasoline is subject to the daily delivery and heavily dependent on whether the intercompany pipeline on Front Avenue is operational. If the supply chain is disrupted by pipe breaks north of the CEI Hub and closure of the shipping channel to the west, fuel would quickly become scarce. Options to transport fuel from the east and south and by air are very limited.

Figure 63: The elements connecting the tops of these two tanks in the CEI Hub may cause damage to the tanks during shaking due to differential displacements. (DOGAMI photo)

Portland International Airport (PDX): The airlines operating at the PDX airport receive 100 percent of their liquid fuels from a terminal in the CEI Hub. There is limited on-site fuel supply at PDX. If the transmission pipe between the CEI Hub and PDX fails, then PDX would likely experience a shortfall and operations would be impacted.

Natural Gas

Natural gas pipelines: Oregon's largest natural gas service provider receives the majority of their natural gas from pipelines that cross under the Columbia River. One pipeline crosses the Columbia River to Sauvie Island and then crosses the Willamette River at Multnomah Channel near a gate station at the southern end of Sauvie Island and enters the CEI Hub. In addition to the CEI Hub, there are more natural gas pipelines at major river crossings, including crossings at the Columbia River between Washougal, Washington and Troutdale, Oregon and near Clatskanie, Oregon. The soils at these major river crossings are subject to liquefaction and lateral spreading hazards. Most of these pipelines are 1960s vintage and were constructed without seismic design provisions. The consequences of potential pipeline failures could be major for natural gas service territories and Oregon. Pipe breaks could lead to a natural gas shortfall in the state as well as explosions or fires. In addition to the above mentioned pipelines entering Oregon, there are more pipelines throughout the state.

LNG storage facility: The LNG storage facility in the CEI Hub was constructed in the late 1960s on what is strongly suspected to be highly liquefiable soils based on discussions with the operator and DOGAMI hazard maps. This facility, including the LNG tank built for the to provide peaking gas supplies, could result in unsafe conditions during a major earthquake. Furthermore, although the facility has an on-site emergency generator, based on EAP partners' site inspection with the operator, it had seismic deficiencies and would likely not operate after a major earthquake.

At the February 13, 2012 OPUC hearing, the natural gas operator with facilities in the CEI Hub reported that they had not performed seismic vulnerability assessments of the natural gas system.

Electricity

Electrical facilities: Electrical facilities and systems have significant seismic risk due to ground shaking and ground failure, including liquefaction and lateral spreading. Seismically vulnerable facilities include substations and transmission in the CEI Hub as well as facilities outside of the CEI Hub, including power plants, substations and transmission lines. At the February 13, 2012 OPUC hearing, the investor-owned utility company with facilities in the CEI Hub reported that they had not performed seismic vulnerability assessments of the electrical system.

Major vulnerabilities in the CEI Hub include the control buildings, power transformers and other electrical equipment in yards at the substations, and transmission towers near the Willamette River. Damage is likely to occur to both the transmission system and the distribution system in the CEI Hub. Damage to the electrical grid will likely result in a blackout in the CEI Hub and elsewhere.

Bonneville Power Administration (BPA) has conducted a comprehensive seismic vulnerability study of their system and has had a long-term seismic mitigation program in place since 1993. BPA’s long-term seismic mitigation program includes 1) investment protection (e.g. anchoring transformers), and 2) power system recovery of critical paths (e.g. hardening of equipment at one of multiple bays within a major substation). The first phase of BPA's mitigation program includes bracing and restraining critical equipment and seismically upgrading critical building facilities west of the Cascade Range. Seismic strengthening in the substation yard would typically include: anchoring high-voltage power transformers; bracing transformer conservators and radiators; replacing seismically vulnerable live tank circuit breakers with more robust dead tank circuit breakers; adding damping systems to existing live tank circuit breakers; hardening transformer bushing storage facilities; replacing rigid bus connections with flexible bus. These mitigation techniques will improve the reliability of seismic performance. Additional phases of the seismic mitigation program will include facilities east of the Cascade Range.

BPA has a critical 115 kV and 230 kV high voltage transmission river crossing in the CEI Hub as well as a substation. At the substation in the CEI Hub, some of the high-voltage equipment had been anchored and braced to withstand earthquake motions. BPA is in the process of conducting seismic strengthening of the control building and equipment inside the control building (e.g., brace computer floors, control cabinets, battery racks, ceiling, pipes, etc) and additional mitigation in the yard. BPA has conducted subsurface, liquefaction and lateral spreading analyses at one of the transmission tower sites at the Willamette River crossing and concluded severe ground movement up to 25 feet towards the river channel is possible. Until mitigated, it is likely that at least two transmission towers would experience extensive damage, be inoperable, require repair or replacement, and power lines could temporarily block river traffic, including the pathway to the oil terminals. The BPA transmission towers at the Willamette River crossing are scheduled to be seismically analyzed, have a seismic mitigation design completed in 2013, and be mitigated by 2014.

Recent unpublished BPA Cascadia earthquake scenario studies of the existing transmission line system indicate that their main grid would require between 7 and 51 days to make emergency damage repairs to the transmission line system (Oregon and Washington) from a magnitude 9 Cascadia earthquake. This scenario assumes many ideal conditions (BPA employees and contractor resources are immediately available, all roads and bridges are passable, available fuel, etc), which is optimistic.

Impacts to Oregon

Based on visual observations, engineering judgment, limited analyses, and limited information from the facility operators, city records, and available literature, significant seismic risk exists in the CEI Hub. Some critically important structures appear to be susceptible to significant damage in a major earthquake with potentially catastrophic consequences. Multiple liquid fuel transmission pipe breaks and natural gas transmission pipe breaks are possible. Damage to liquid fuel, natural gas, and electrical facilities in the CEI Hub is likely. The waterway would likely be closed and require clean up.

Due to a combination of the existing seismic hazards, vulnerability of the exposed infrastructure and potential consequences, Cascadia earthquakes pose substantial risk to the CEI Hub and to Oregon. Not only are the energy sector facilities in the CEI Hub dependent on other sectors and systems in Oregon, including transportation and communication, they are interdependent upon each other. A major Cascadia earthquake and tsunami would likely produce an unprecedented catastrophe much larger than any disaster the state has faced.

Western Oregon will likely face an electrical blackout, extended natural gas service outages, liquid fuel shortage, as well as damage and losses in the tens of billions of dollars in a future major Cascadia earthquake. Preparing for a catastrophic disaster to become more resilient is needed to improve personal safety and security, and safeguard communities and businesses.

Section 7
Recommendations

The most critical call-to-action that DOGAMI has concluded from this study of the CEI Hub is this: Energy sector companies must **pro-actively integrate seismic mitigation** into their business practices for Oregon's energy sector to adequately recover from a magnitude 8.5 to 9 Cascadia earthquake in a reasonable time period.

Although energy sector companies have made efforts to prepare for seismic events, such as through emergency planning and complying with the current building codes, these efforts are limited and a timely restoration of energy sector services is questionable. As discussed in the Summary of Findings section, only one company has completed comprehensive seismic vulnerability assessments and instituted seismic mitigation plans. Energy sector companies must make earthquake mitigation an integral part of their overall business plan. This is not only prudent for the impact a large magnitude Cascadia earthquake would have on Oregonians and the environment; it is good business continuity management. Oregon homes, businesses and industries depend upon reliable energy sources. Liquid fuel, natural gas and electricity are critical to our economy, environment and everyday existence, and the energy sector must do more in order to assure those services and products in the event of a large earthquake.

Recommendations

In order for the energy sector to pro-actively integrate seismic mitigation into their operations, DOGAMI makes these four recommendations to both private and public energy sector stakeholders:

1. Energy sector companies should conduct ***Seismic Vulnerability Assessments*** on all of their systems or facilities, and should work with the appropriate local, state, tribal and federal government agencies and stakeholders to achieve timely completion of the assessments to understand existing vulnerabilities.
2. Energy sector companies should institutionalize long-term ***seismic mitigation programs;*** and should work with the appropriate local, state, tribal and federal government agencies and stakeholders to achieve timely and effective mitigation to ensure facility resilience and operational reliability.
3. The State of Oregon's ***Homeland Security Council*** should review the vulnerability and resilience of the energy sector to earthquakes and other natural disasters within the scope of their mission. This could involve the EAP partners (ODOE, OPUC, and DOGAMI) as well as ODOT, Building Codes Division, and the Oregon Seismic Safety Policy Advisory Commission (OSSPAC).
4. Energy sector companies and the State of Oregon should ***build Oregon's seismic resilience*** to a Cascadia earthquake. Adopting pro-active practices and a risk management approach will help achieve seismic resilience. Encouraging a culture of awareness and preparedness concerning the seismic vulnerability of the energy sector including long range energy planning should be conducted.

Recommendation #1: Conduct Seismic Vulnerability Assessments (SVAs)

To improve energy sector resilience to a catastrophic earthquake, energy sector companies will need to conduct Seismic Vulnerability Assessments (SVAs) of each individual energy facility in the CEI Hub and on a priority basis throughout Oregon. As part of the SVA, energy sector companies should identify key nodes or links at all of their facilities that, if they were to fail, would affect many customers over an extended duration. Companies should conduct an assessment to determine if the identified key nodes or links have high risk of failure during a magnitude 9 Cascadia earthquake. They should evaluate and prioritize the best mitigation options on their highest risk key nodes or links. Energy sector companies should consider a magnitude 8.5 to 9 Cascadia earthquake and tsunami during wet conditions (including co-seismic landslides, liquefaction and lateral spreading) as the basis of their assessments.

Following are suggestions regarding SVAs:

- Energy sector companies should use sector-appropriate guidelines and standards to conduct their SVAs. For example, the electric and natural gas companies can refer to the American Lifelines Alliance and the American Society of Civil Engineers or other industry guidelines and standards to conduct SVAs on facilities, systems, and components. (See *Table 3.*) This includes considering broader influences relating to: 1) co-location and interdependencies; 2) business continuity; 3) safety; 4) environmental damage/spills; 5) reliability of service; 6) other critical factors. The liquid fuel companies can refer to the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS), a regulatory program implemented by California State Lands Commission that incorporates seismic safety.
- Energy sector companies should conduct SVAs on all their facilities and systems, including liquefaction vulnerabilities, and report to the appropriate authorities and stakeholders within a pre-determined time frame providing an overview of their assessment. This should include their evaluation in their current state of their expected down time in a Cascadia earthquake, which establishes baseline information, as well as expected recovery rate, and expected dependence on other sectors.
- Energy sector companies should report to the appropriate authorities and stakeholders within a pre-determined time frame providing an overview of their seismic mitigation plan, costs, and implementation timeframes.
- All energy sector companies should share assessments and mitigation plan with their ratepayers and shareholders in order to increase awareness and set realistic expectations for the public. This action would help develop support for a funding plan that is both transparent and accountable.
- State agencies (ODOE, OPUC, and DOGAMI) responsible for the Energy Assurance Project (EAP) should provide technical guidance to energy sector companies to achieve reliable energy-related services.
- Energy sector companies and public agencies should look for opportunities for public-private sector partnerships to prepare for Cascadia earthquakes. This would include pilot projects involving SVAs, risk management tools, and mitigation. For example, the Bonneville Power Administration (BPA) has plans to mitigate transmission towers at the lower Willamette River crossing by 2014. There could be significant cost advantages if the privately-owned adjacent towers were upgraded in coordination with the BPA effort.

Although building codes for energy sector facilities are limited, many guidelines on how to design seismically resistant systems and conduct seismic vulnerability studies for systems are available. DOGAMI compiled the *Table 5* Seismic Engineering Reference List as a service to energy facility owners as part of the EAP. DOGAMI recommends energy companies to use the sector-appropriate references, adopt high seismic standards and build for high seismic performance. *Table 5* Seismic Engineering Reference List is useful for new and existing energy-related structures and contains some information on best practices. The list should be updated as new key references are made available.

TABLE 5: SEISMIC ENGINEERING REFERENCE LIST

This Reference List was developed by DOGAMI staff for this EAP study in March 2010. It includes current and useful references for seismic vulnerability studies and mitigation efforts at energy facilities. Companies should consult with facility engineers to determine appropriate references and guidelines to conduct seismic assessment and mitigation. This will depend on each facility and their proposed or existing structures. Companies should consider the ground conditions at their facility, in particular, site-specific liquefaction and lateral spreading potential. We have listed websites where available. Some references need to be purchased.

Acronyms:
ALA - American Lifelines Alliance www.americanlifelinesalliance.org
ASCE - American Society of Civil Engineers
IBC - International Building Code
IEEE - Institute of Electrical and Electronics Engineers
MOTEMS – Marine Oil Terminal Engineering and Maintenance Standards, State of California
PRCI - Pipeline Research Council International
TCLEE - Technical Council on Lifeline Earthquake Engineering (under ASCE)

Buildings
Current IBC (for new buildings)
New IBC seismic provisions adopt ASCE 7 and only provide a few exceptions or alternatives to ASCE 7 (ref. ASCE 7-2005: Minimum Design Loads for Buildings and Other Structures, newest edition ASCE 7-10)

ASCE 31 and ASCE 41 (31 for evaluation of existing buildings; 41 for mitigation)
Seismic Evaluation of Existing Buildings, SEI/ASCE 31-03
Seismic Rehabilitation Of Existing Buildings ASCE/SEI 41/06
NOTE: Neither of these specify explicit retrofit requirements. The user needs to determine goals.

Electrical

IEEE 693 RECOMMENDED PRACTICE FOR SEISMIC DESIGN OF SUBSTATIONS (2005)

ALA Electric Power Systems Guidelines and Commentary (for scoping studies). April 2005

ASCE 113, Substation Structure Design Guide, Manuals of Practice, Editor: Leon Kempner Jr., 2008, 164 pp

ASCE Manual No 96.Guide to Improved Earthquake Performance of Electrical Power Systems. TCLEE. Editor: Anshel Schiff. 1999 http://fire.nist.gov/bfrlpubs/build98/PDF/b98069.pdf

TABLE 5: SEISMIC ENGINEERING REFERENCE LIST (cont.)

Petroleum and Natural Gas Facilities, including Waterfront Structures, Tank Farms, and Telecommunications

ASCE Petrochemical facilities seismic guidelines (1997 and forthcoming 2011)

Guidelines for the Seismic Evaluation and Design of Petrochemical Facilities (task committee of Petrochemical Committee of Energy Division of ASCE)

Waterfront
ASCE TCLEE monograph 12. Seismic Guidelines for Ports. March 1998. Editor: Stuart Werner

MOTEMS The most current version of MOTEMS (Rev. 0) is at:
http://www.slc.ca.gov/Division_Pages/MFD/MOTEMS/MOTEMS_Home_Page.html
MOTEMS Rev. 1 is expected to become law around Q4 2010, and has already been accepted by the CA Building Standards Committee. You can view all of the changes that will be adopted (the Express Terms) at: http://www.slc.ca.gov/Division_Pages/MFD/MFD_Home_Page.html

Tanks, Piping and Control Equipment, incl. Natural Gas Piping and Well Facilities
ASME/ANSI B31E-2008, Standard for the Seismic Design and Retrofit of Above-Ground Piping Systems

ASME Piping Codes:
ASME B31.4 (2006) Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids
ASME B31.8 (2007) Gas Transmission and Distribution Piping Systems
ASME B31.3 (2006) Process Piping

Honegger, D.G. and D.J. Nyman (2004), Guidelines for the Seismic Design and Assessment of Natural Gas and Liquid Hydrocarbon Pipelines, PRCI catalog no. L51927.
http://prci.org/index.php/pm/pubs_details/

API 620 (2008), Design and Construction of Large, Welded, Low-pressure Storage Tanks

ALA (2002) Guideline for the Design of Buried Steel Pipe

API 650 (2007) Welded Tanks for Oil Storage, 11th Edition, Addendum 1 (2008) and Addendum 2 (2009), American Petroleum Institute

California Accidental Release Prevention (*CalARP*)
http://www.oes.ca.gov/Operational/OESHome.nsf/978596171691962788256b350061870e/452A4B2AF244158788256CFE00778375?OpenDocument

ALA Guide for Seismic Evaluation of Active Mechanical Equipment, 2008 (for walk through assessments)

ALA Oil and Natural Gas Pipeline Systems Guidelines and Commentary (for scoping studies)

ALA Guideline for the Seismic Design and Retrofit of Piping Systems (for scoping study purposes; used to develop B31E)

For the EAP, DOGAMI considers the primary performance target as maintaining system reliability after a major Cascadia earthquake. Maintaining service reliability does not mean maintaining 100% operation. Instead it refers to minimizing the extent and length of service disruption and quick restoration of services to high priority customers (e.g., certain emergency facilities and critical infrastructure) and in logical geographic areas (e.g., large population centers as opposed to tsunami inundated zones where people have been displaced). Other performance targets may also be important and largely depends on one's perspective. For the operator, protecting workers and preventing monetary losses may be the top priorities. As shown below, SVAs can be conducted to address one or more of these specific performance targets:

- Protect public and utility personnel safety
- Maintain system reliability
- Prevent monetary loss
- Prevent environmental damage (ALA, 2004)

Tables 6, 7 and *8* summarize examples of Seismic Vulnerability Assessments with varying scopes for liquid fuel, natural gas, and electricity. The tables are not meant to be all-inclusive.

As the first example in *Table 6*, SVAs of the liquid fuel sector could include engineering analyses of specific components, such as piers, tanks or loading racks. An SVA of the transmission system to deliver the fuel should be conducted. This would include assessing the transmission pipeline for vulnerabilities, such as river crossings, and assessing the reliability of the transportation route over water. An SVA of the facility itself could be conducted, including the waterfront structures, control building, tanks, pipes and loading racks. An SVA of the network system's interdependencies *on* other energy systems could be conducted, including the refineries, which are the upstream portion of the supply chain, the navigational waterway, and electricity for equipment such as pumps. The last example is an SVA of the system's interdependencies *by* other services, such as those who require fuel for emergency vehicles and emergency generators.

Liquid Fuel

Table 6: Seismic Vulnerability Assessment examples

Liquid Fuel **Scope of Seismic Vulnerability Assessments (SVA)**	**Example Target**
SVA of components	Pier, tank, or loading rack
SVA of transmission: pipelines and marine shipping	Transmission river crossings, Columbia river mouth tsunami damage
SVA of facility	Holistic analyses, including liquefaction potential
SVA of network system's interdependencies on others	Dependency on refineries, navigational waterway, electricity for pumps
SVA of network system's interdependencies by others	Emergency vehicles and generators

Natural Gas

Table 7: Seismic Vulnerability Assessment examples

Natural Gas **Scope of Seismic Vulnerability Assessments (SVA)**	**Example Target**
SVA of components	LNG storage tank
SVA of transmission path	Gate stations, bridge crossings, underground river crossings
SVA of network system	Holistic analyses
SVA of network system's interdependencies on others	Dependency on local communication systems
SVA of network system's interdependencies by others	Gas service reliability to hospital

Electricity

Table 8: Seismic Vulnerability Assessment examples

Electrical **Scope of Seismic Vulnerability Assessments (SVA)**	**Example Target**
SVA of components	Power transformer and switchyard equipment reliability
SVA of priority path	Path connecting critical substation components
SVA of network system	Holistic analyses including engineering data
SVA of network system's interdependencies on others	Dependency on local transportation systems
SVA of network system's interdependencies by others	Power disruption to water treatment plant and water systems to fight fires

Recommendation #2: Institutionalize Seismic Mitigation Programs

Mitigation programs should address life safety, environmental impacts, and recovery times as well as minimize potential damage. The Seismic Vulnerability Assessments should be followed by prioritized mitigation measures to protect critical links of the energy systems from irreparable damage as well as to ensure rapid recovery of energy services. After completing SVAs, energy companies should establish priorities and determine possible methods to reduce vulnerabilities and undesired effects. Assuming the costs associated with implementing the mitigation plans are significant, the high costs can be managed by implementing the mitigation plan over several years.

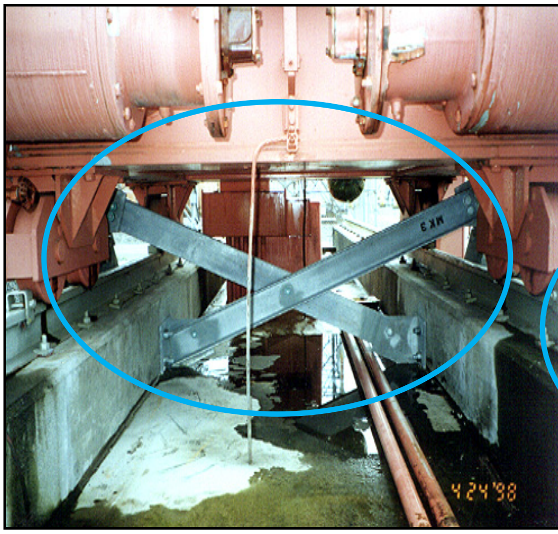
DOGAMI recommends energy companies in Oregon to develop and implement long-term mitigation plans and strategies to reduce damages from future disasters so as to maintain services. Following are suggestions regarding the development of seismic mitigation programs:

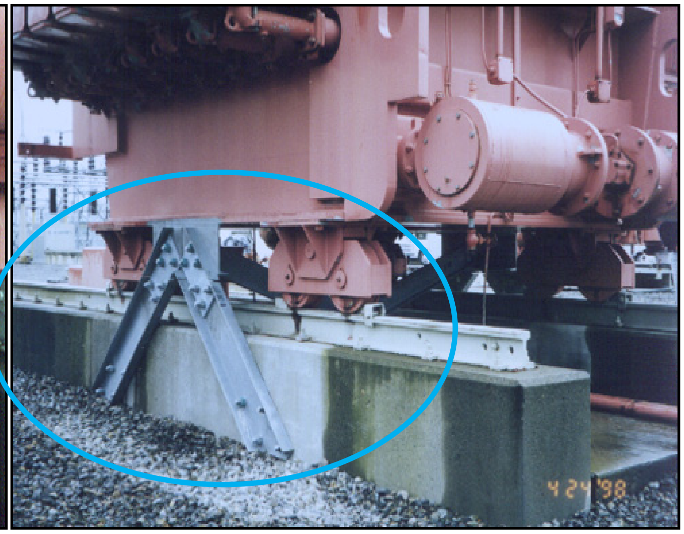
1) Consider benefits versus costs (e.g., using benefit-cost analyses) together with basic societal needs

2) Prioritize actions
3) Consider resilience (example: if there is redundancy in the system, then perhaps controlled/limited damage is acceptable)
4) Determine costs and funding source
5) Integrate plans and strategies into other company efforts, such as business continuity and emergency response planning
6) Provide updates to the appropriate authorities and stakeholders on their seismic mitigation plan, costs, and implementation timeframes.

The mitigation measures can range from changes to the energy system by strengthening, replacing, relocating, or adding redundant systems elsewhere. Liquefaction mitigation could involve a variety of approaches, including ground improvement techniques (e.g., dynamic compaction, stone columns, and compaction grouting) or specially designed liquefaction resistant foundations (e.g., pile or mat). A seismic mitigation program should consider a risk management approach in order to utilize funds efficiently for the best outcomes. Seismic mitigation program should also be integrated into the company's institutionalized programs, such as in the risk management or business continuity programs, and include stable funding. The following photos show two mitigation examples. *Figures 64 and 65* show a vulnerable battery configuration and a seismically ready battery rack for emergency purposes, which provides a reliable power source. *Figures 66* and *67* show an existing high voltage power transformer that has been seismically braced. *Figures 68* and *69* show improperly anchored transfomers. Protecting power transformers and other equipment that is difficult to replace should be a high priority.


Figures 64 and 65: Batteries should not be on a wheeled cart as in the photo on the left. Emergency batteries, as well as other components such as generators and communication devices, should be braced on an anchored rack to withstand Cascadia earthquake forces as in the photo on the right. (DOGAMI photos)





Figures 66 and 67: Left photo shows the front view of an existing transformer with seismic anchorage including steel cross bracing as mitigation. The right photo shows the side view of the same existing transformer with diagonal bracing. (Photos: Leon Kempner)


Figures 68 and 69: The photo on the left shows high voltage transformers (orange color) in the CEI Hub that require proper anchorage. The close-up photo on the right shows that the transformer is anchored, but the anchorage was poorly installed or poorly maintained as evidenced by the amount of grout that is missing. (DOGAMI photos)

Tables 9, 10 and *11* provide mitigation examples for the liquid fuel, natural gas, and electricity industries. The examples are not meant to be comprehensive, but rather convey basic ideas of possible weak areas coupled with possible strengthening methods. Companies will need to consider each and every facility, structure or system in a prioritized manner. Mitigation programs can involve short-term, medium-term, and long-term activities.

Mitigation measures for the liquid fuel sector (Table 9) could entail improving the strength of the ground at existing piers or wharves to control ground deformation from liquefaction and lateral spreading of the foundation soils. Mitigation could focus on the tank yards because of the liquefaction-induced ground settlement potential. The underlying soils and the foundation of the tanks could be strengthened, the bottom of the tanks could be strengthened, or new tanks could be installed. Pipes with rigid connections could be mitigated by adding flexible connections or rerouting the pipe configuration. Similarly, emergency shut-off valves could be added to the pipe network in strategic places to isolate fuel and control damages. Control buildings could be mitigated by structural upgrades to the building and non-structural upgrades, such as strapping computers. The last example is that the loading racks could be mitigated to improve the operation of the pumps by providing a connection for an emergency generator.

Liquid Fuel

Table 9: Mitigation examples

Liquid Fuel	Component Example	Mitigation Option Example
Piers and wharves	Ground deformation from lateral spreading of soils	Improve ground to control ground failure
Tank yards	Ground settlement of tanks from liquefaction	Strengthen tank foundation
Piping	Pipes with rigid connections	Add flexible connections
Control building (inside)	Operations room	Strap computers
Loading racks	Electrical for pumps	Add connection for portable emergency generator

Natural Gas

Table 10: Mitigation examples

Natural Gas	Component Example	Mitigation Option Example
Gate station	Ground deformation from soil liquefaction	Ground improvement using drains and grout
LNG storage facility	LNG tank	Install base isolation system
Control building	Uninterruptible power supply (UPS)	Remove wheels and anchor rack
Control building (inside)	Back up batteries	Strap batteries on earthquake resistant battery rack Figure 9
Transmission pipe	Transmission pipes at river crossing	Strengthen soils to prevent liquefaction and lateral spreading

Electricity

Table 11: Mitigation examples

Electrical	Component Example	Mitigation Option Example
Substation control building	Structural stability of building	Add exterior shear walls
Substation control building (inside)	Stability of control equipment	Brace tall cabinets and communication trays
Substation yard	Power transformer	Anchor to prevent sliding (Figure 10)
Substation yard	Bus support structure	Add flexibility and slack to power connections between equipment
Transmission corridor	Transmission tower at river crossing	Strengthen foundation system for liquefaction

Recommendation #3: Oversight by Homeland Security Council

To secure a stable energy supply, Oregon must provide a resilient supply chain during normal operations as well as during extreme crisis conditions, such as after a Cascadia earthquake. In addition to performing mitigation activities on energy facilities, vulnerabilities of essential transportation and telecommunication systems that support energy sector operations and recovery need to be addressed in order to ensure that the energy sector is not hindered by interdependencies with other critical infrastructure. DOGAMI recommends the State of Oregon's ***Homeland Security Council*** review the vulnerability of the critical energy sector in Oregon and consider action within the scope of their mission to improve the resilience of the system to natural disasters. Important considerations would include the energy sectors' interdependencies with each other as well as with the transportation, telecommunication, and other critical sectors. The Council could involve the EAP partners (ODOE, OPUC, and DOGAMI) as well as other agencies and commissions, including ODOT, Building Codes Division, and the Oregon Seismic Safety Policy Advisory Commission (OSSPAC). The Council could consider long term energy planning and goal setting efforts and requiring accountability on progress in seismic energy security and reliability.

Seismic Energy Security Efforts

As part of this study, the EAP partners considered who could ensure that adequate progress is being made towards achieving reliable energy sector services after a major Cascadia earthquake. We identified a number of existing relevant organizations that could address reliability of services in the energy sector. We concluded that the current efforts being made by existing organizations were inadequate as they mostly focused on emergency response and not on reliability of energy sector services. As an example, Oregon Emergency Management's (OEM) Oregon Emergency Response System (OERS) includes Emergency Support Function #12 — which focuses on restoration of damaged energy systems and components during a potential or actual emergency or major disaster (http://www.oregon.gov/OMD/OEM/plans_train/docs/eop/esf_12.pdf). We considered recommending the formation of a new group with this specific focus but quickly determined rather than creating another group, that tapping into an existing organization would be preferable. We determined that group of a high-level individuals who could make major decisions and create new policies was preferred. As such, we identified the Homeland Security Council as the best option. Its membership consists of: (a) Four members from the Oregon Legislative Assembly; (b) The Governor; (c) The Adjutant General; (d) The Superintendent of State Police; (e) The Director of the Office of Emergency Management; and (f) Additional members appointed by the Governor who the Governor determines necessary to fulfill the functions of the council, including state agency heads, elected state officials, local government officials, a member of the governing body of an Indian tribe and representatives from the private sector (http://www.oregonlaws.org/ors/401.109). In May 2012, OPUC and DOGAMI met with the General Mike Caldwell, director of OEM, and OEM staff to explore whether or not the Homeland Security Council would be an appropriate group to take on this task. At the meeting, we learned that the Homeland Security Council had limited productivity, was recently downsized, but also received very positive feedback on it as a likely appropriate group to address seismic security of the energy sector.

The EAP partners initiated efforts to evaluate possible emergency land, air and river transportation routes, including by air reconnaissance with the assistance of the Civil Air Patrol (CAP), in August 2010. Based on the initial findings, DOGAMI recommends that the Council examine the transportation and telecommunication sectors to better understand and address shortcomings in critical operational interdependencies. Reliable critical transportation routes during earthquake disasters are vital for emergency response and recovery, including fuel distribution. Information on telecommunication frameworks and seismic preparedness guidelines are provided in Appendix C: Telecommunications: Seismic Codes and Guidelines.

The Council could work with Building Code Division, OSSPAC, engineering and construction industries and other key stakeholders to identify and rectify existing gaps in the seismic provisions of the current building codes. For example, the current codes do not require facilities that are operating well beyond their design life to be re-examined even when there are significant public safety concerns.

Recommendation #4: Build Oregon's Seismic Resilience

Oregon energy facilities are generally prepared for most natural hazards, such as localized severe winter storms. However, the energy sector is not prepared for a catastrophic Cascadia earthquake disaster. The CEI Hub is one critical part of a state economy that is within a disaster-prone area. If damaged, Oregon's economy could result with catastrophic consequences. To date, there are inadequate safety protocols to protect Oregon from significant earthquake impacts to the CEI Hub as this study has shown. On the state level, Oregon is considered to have low resilience to a major Cascadia earthquake.

In contrast, on a national level, the U.S. will be able to absorb the shock from a major Cascadia earthquake and tsunami. Oregon would be assisted by many others, including the federal government, the non-profit sector, and a variety of private companies. Many energy sector organizations that operate in Oregon would have extensive assistance from their own companies as well as other energy sector companies that have mutual aid agreements in place. In order to build seismic resilience for critical energy infrastructure operations and interdependencies in Oregon, we need to pursue the recommendations listed on the following pages. In additional to the recommendations, Oregon can adopt a risk management strategy. The concept of "resilience," which is a relatively new term in disaster preparedness, is described below.

"Resilience" has a variety of definitions. One definition of resilience is the capacity of a system or a structure to absorb and recover from a shock (Bruneau et al, 2005; http://mceer.buffalo.edu/research/resilience). Resilience can be defined to include four elements:

1. ***Robustness*** - strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;
2. ***Redundancy*** - the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of function;
3. ***Resourcefulness*** - the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis (resourcefulness can be further conceptualized as consisting of the ability to supply material - i.e., monetary, physical, technological, and informational - and human resources to meet established priorities and achieve goals); and
4. ***Rapidity*** - the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption. (http://mceer.buffalo.edu/research/resilience/resilience_10-24-06.pdf)

In 2011, the National Research Council (NRC) released a report, *"National Earthquake Resilience."* This report included the following list and *Table 12* addressing resilience:

- Relevant hazards are recognized and understood.
- Communities at risk know when a hazard event is imminent.
- Individuals at risk are safe from hazards in their homes and places of work.
- Disaster-resilient communities experience minimum disruption to life and economy after a hazard event has passed. (NRC, 2011)

The National Research Council's report made these observations on what condition a state with high resilience should be in following a catastrophic earthquake:

- *No systematic concentration of casualties.* Important or high-occupancy structures (e.g. schools, hospitals, and other major institutional buildings; high-rise commercial and residential buildings) do not collapse, and significant numbers of specific building types (e.g. hazardous unreinforced masonry structures) do not collapse. There are no major hazardous materials releases that would cause mass casualties.

- *Financial loss and societal consequences are manageable, not catastrophic.* Damage to the built environment is reduced to avoid catastrophic financial and societal losses due to overwhelming cost of repair, casualties, displaced populations, government interruption, loss of housing, or loss of jobs. Community character and cultural values are maintained following disasters; there is not wholesale loss of iconic buildings (including those designated as historic), groups of buildings, and neighborhoods of architectural, historic, ethnic, or other significance.

- *Emergency responders are able to respond and improvise.* Roads are passable, fire suppression systems are functional, hospitals and other critical facilities are functional. It is noteworthy that during the 9/11 attacks, New York City's response was hampered by the need to set up a new Emergency Operations Center as the existing one had been located in the World Trade Center.

- *Critical infrastructure services continue to be provided in the aftermath of a disaster.* Energy, water, and transportation are especially critical elements. Telecommunications are also very important. Continued service is needed for critical facilities such as hospitals to function, as well as for residents to remain sheltered in their homes.

- *Disasters do not escalate into catastrophes.* Infrastructure interdependencies have been anticipated and mitigated, so that disruptions to one critical infrastructure do not cause cascading failures in other infrastructures (e.g. levee failures in New Orleans escalated the disaster into a catastrophe). Fires are quickly contained and do not develop into major urban conflagrations that cause mass casualties and large-scale neighborhood destruction.

- *Resources for recovery meet the needs of all affected community members.* Resources for recovery are available in an adequate, timely, and equitable manner. To a large extent, local governments, non-profit organizations, businesses, and residents would have already materially and financially prepared for a major disaster (e.g. are adequately insured; have undertaken resilience activities on their own and in cooperation with others). Safety nets are in place for the most vulnerable members of society.

- *Communities are restored in a manner that makes them more resilient to the next event.* Experience is translated into improved design, preparedness and overall resilience. High-hazard areas are rebuilt in ways that reduce, rather than recreate, conditions of disaster vulnerability (NRC, 2011).

Table 12: Resilience applications to social, ecological, physical, and economic recovery by time period. (National Research Council - NRC, 2011)

Timescale	Emergency Response	Health & Safety	Utilities	Buildings	Environmental /Ecological	Economic
Immediate < 72 hours	Tactical emergency response	Deal with casualties/ Reunite families	Use of emergency back-up systems	Remove Debris	Limit further ecological damage	Maintain supply of critical goods & services
Emergency 3-7 days	Strategic emergency response	Provide mass care	Begin service Restoration	Provide shelter for homeless	Remove debris	Prioritize use of resources/ substitute inputs/conserve
Very short 7–30 days	Selective response	Fight infectious outbreaks	Continue restoration	Provide shelter for homeless	Protect sensitive ecosystems	Shore-up or over-ride markets
Short 1-6 months	Assist in recovery	Deal with post-traumatic stress	Complete service restoration	Provide temporary housing and business sites	Deal with ensuing problems	Cope with small business strain
Medium 6 months–1 year	Reassess for future emergencies	Deal with post-traumatic stress	Reassess for future emergencies	Provide temporary housing and business sites	Initiate remediation	Cope with large business strain/recapture lost production
Long >1 year	n.a.	Reassess for future emergencies	Mitigation for future events	Rebuild & Mitigation	Mitigation for future events	Cope with business failures/ mitigation

For the EAP, DOGAMI developed the resilience triangle graph with the resilience triangle shown in green. (*Figure 70*) The basic principle of the resilience triangle is that the smaller the triangle, the higher the resilience. Higher resilience requires minimal reductions in critical lifeline services after a disaster, speedy recovery of those services, and an overall improved service level as a result of rebuilding damaged systems and implementing better systems. Chile and Japan have high levels of earthquake resilience on the basis of their performance after the 2010 magnitude 8.8 earthquake in Chile and 2011 magnitude 9.0 earthquake in Japan (notwithstanding the nuclear energy issues). At the current stage, Oregon's energy sector has low resilience and is expected to have significant loss of energy sector services and a slow recovery time.

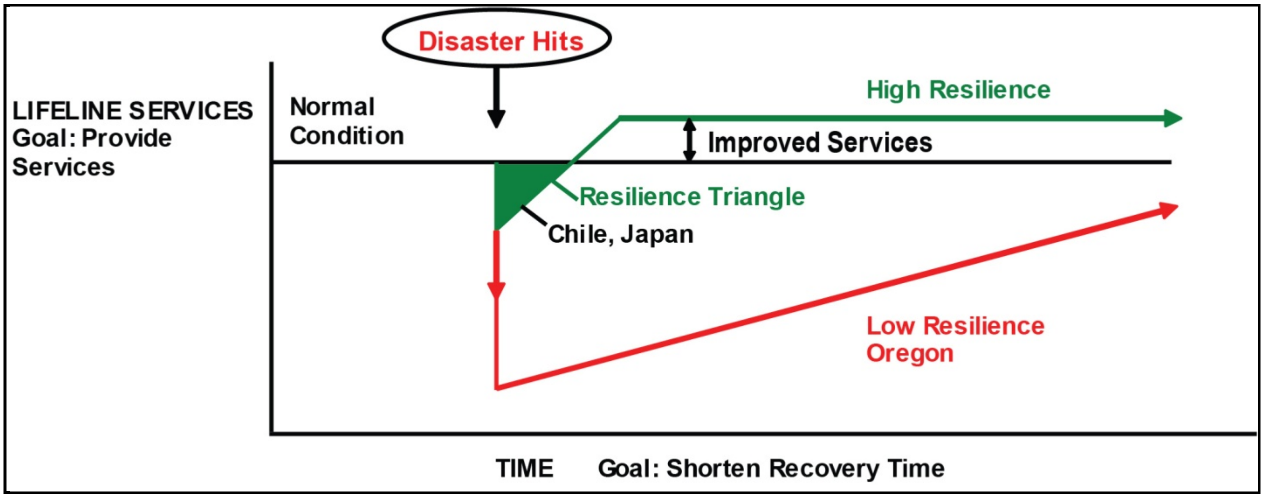


Figure 70: DOGAMI Resilience Triangle illustrates that high resilience is due to a combination of low losses, quick recovery and services improved to a higher level than before the disaster (DOGAMI modified from Bruneau et al, 2005)

Recommended Practices for Building Seismic Resilience

The following list is composed of suggested practices for energy sector companies. These suggestions are not prioritized and are not all-inclusive. The first four suggestions concern emergency response and recovery; the remaining suggestions pertain more to pre-disaster planning.

- Energy sector companies should have specific memorandums-of-understanding (MOUs) in place with energy sector organizations and nearby businesses/industries to assist one another during emergency situations. This would include MOUs with industry partners throughout the US who can be called upon for assistance. These MOUs must be in place and coordinated in advance of an earthquake.
- Energy sector companies should have essential spare parts readily available to repair damaged equipment and keep equipment operational. For example, electrical utilities should have an adequate supply of insulators on hand as insulators are susceptible to breakage during earthquakes. Oil companies should have fuel hoses available to keep equipment operational on a temporary basis.
- Energy sector companies should maintain safe conditions following a major Cascadia earthquake, and if necessary, have earthquake-resistant emergency generators, fuel cells or battery banks to power critical operations. Existing generators in flood prone areas may require relocation to higher points or placement in water-proof vaults.
- Energy sector companies should consider where they would set up company emergency headquarters if current facilities are unavailable. A reliable facility outside the CEI Hub and, perhaps, east of the Portland area, may be a good choice to serve as a control center following a Cascadia earthquake. The energy sector may want to establish a regional emergency operation center—perhaps a virtual clearing house—to help coordinate restoration of energy sector services.
- Both the public and private sector should assess what resources may be needed to continue critical energy operations following a Cascadia earthquake. They should

proactively make provisions to minimize the impact, rather than rely on a robust response operation. Existing entities, including the Department of Homeland Security (DHS) Fusion Center, DHS U.S. Coast Guard Area Maritime Security Committees, and the Oregon Emergency Response System Council should consider taking steps to reduce potential damage to the energy sector before a Cascadia earthquake, which requires partnering to ensure readiness.

- Energy sector companies should review and learn pertinent information from prior earthquakes, such as the 2004 magnitude 9.1 Sumatra earthquake, 2010 magnitude 8.8 Chile earthquake, and 2011 magnitude 9.0 Japan earthquake. Although it can be difficult to extract practical information depending upon the country and situation of the prior earthquake, two non-profit organizations provide sources of information on impacts from major earthquakes. These include: 1) American Society of Civil Engineers that publishes lifeline information, including the energy sector, on "Technical Council of Lifeline Earthquake Engineering" after major worldwide earthquakes (http://www.asce.org/Content.aspx?id=2147488653) , and 2) Earthquake Engineering Research Institute's (EERI) that has the Learning from Earthquakes Program (http://www.eeri.org/projects/learning-from-earthquakes-lfe/). The EERI focus is broad (geosciences, emergency response, building, and more).
- Energy sector companies should turn to industry-specific seismic documents to help evaluate and improve existing components and systems and design new construction. The goal is to reduce and control potential damage. For example, the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS) is a regulatory program implemented by California State Lands Commission that incorporates seismic safety for the liquid fuel industry's oil terminals. *Figure 71* shows a seismic instrument at a facility regulated by MOTEMS. The American Lifelines Alliance and American Society of Civil Engineers provide similar seismic guidelines for the electrical, natural gas and liquid fuel industries.
- Energy sector companies should look for engineering solutions that are industry appropriate. For example: Liquid fuel companies could construct new tanks and piping to withstand liquefaction hazards by strengthening the underlying soils, designing robust foundations and installing flexible piping connections. Seismically mitigation for existing important tanks could also be conducted. Natural gas companies could consider in-ground LNG tanks such as those commonly built in Japan. In-ground tanks can be designed to address buoyancy forces in liquefiable soils. Oil and gas companies could design their systems to be able to isolate certain blocks of areas using control valves in order to better control or contain damage. Isolating areas prone to liquefaction to prevent cascading damage is a possibility. Electrical companies could build micro-grids for important facilities or districts so areas could be isolated and continue to operate if the main grid goes down. A micro-grid in Sendai, Japan performed well after the 2011 earthquake (http://spectrum.ieee.org/energy/the-smarter-grid/a-microgrid-that-wouldnt-quit).
- Energy sector companies should determine target performance levels to provide service after a Cascadia earthquake, and in time, achieve those performance objectives. For example, after a winter storm, an electricity company may determine that a target performance level to restore 75 percent of customers' within 24 hours, 90 percent within 48 hours, and 100 percent within one week is achievable. Energy sector companies

should evaluate the cost to achieve the "target" by using sound methods (e.g., benefit cost assessments to verify that the upgrades are cost effective). Any targets that are discovered to be unachievable (e.g., after reasonable mitigation efforts have been made) after should be adjusted on an iterative basis. For a Cascadia earthquake, target time frames should be longer than under typical downtime events, due to the expected widespread damage and interdependencies. Seismic mitigation efforts and temporary workarounds should be factored into this target performance level. For example of a possible workaround, temporary piping or hoses can be installed to bypass damaged pipes for liquid fuel or damaged oil terminal piers to address for fuel supply and distribution services. Restoration goals would likely vary between the heavy commercial areas in the Portland metro area, the heavily populated I-5 corridor, rural areas, and coastal areas. As an example, after 10 years of mitigation implementation, a target performance level for electricity restoration might be set for the Portland metro area at 75 percent restored by 48 hours, 90 percent by 4 days, 95 percent after 1 week and about 100 percent after 1 month. For the coastal area above the tsunami inundation zone, the target might be at 75 percent restored by 5 days, 90 percent by 2 weeks, 95 percent after 2 months and about 100 percent after 4 months. (These restoration rates for electricity are not recommendations, but provided as illustrations.)

- Energy sector companies should institutionalize comprehensive seismic mitigation plans that include costs and implementation timeframes.
- Both the public and private sectors should improve the available redundancy in systems where little or no redundancies are currently available. For example, oil companies should explore building expanded or new fuel terminals on stable ground (i.e., not susceptible to liquefaction). Likewise, natural gas companies should consider building redundancy into the natural gas system south of the greater Portland metropolitan area. The proposed Palomar transmission line to connect an eastern Oregon natural gas pipeline in Molalla and the proposed LNG terminal in Coos Bay are two options under recent consideration.
- Energy sector companies with co-located facilities can look at joint opportunities to make ground improvements to mitigate liquefaction.
- Energy sector companies should discuss the length of time for restoring services with critical customers such as water treatment plants. If the projected restoration time is too long for critical customers, those customers might be encouraged to find other emergency power sources such as emergency generators with ample fuel supply or alternative energy sources. Similarly, energy sector companies could discuss the anticipated restoration time for geographic areas such as along the Oregon coast. It may be prudent to install systems for emergency electricity purposes in distributed geographic regions expected to have slower restoration of services, for example, in Coos Bay, Newport, and Astoria.

Figure 71: This photo shows an example of an oil company in California that is following best practices learned from other earthquakes. The white box contains an accelerometer that records site-specific data. Having the recorded ground motion data will allow engineers to better understand the performance of the structures at the oil terminal and help them evaluate the structural performance and improve future designs. (DOGAMI photo)

Risk Management Approach

A major Cascadia earthquake and tsunami will deliver a simultaneous shock to many of the energy systems that Oregonians depend on to support our lives and communities. As damaging as a Cascadia earthquake will be, prudent investments in resilient energy infrastructure can save lives, minimize a catastrophe and accelerate economic recovery. Creating resilience by using an earthquake risk management strategy is recommended. (*Figure 72*)

Earthquake risk management includes five components:

1. Hazard identification
2. Risk assessment
3. Engaging stakeholders
4. Risk prioritization, and
5. Risk mitigation.

The approach should be holistic and realistic— it is not possible to eliminate the risk of damage and impacts, but it is possible to reduce the expected damage to a controllable level. Because Cascadia earthquakes occur infrequently, adopting a long-term view of building resilience is reasonable.

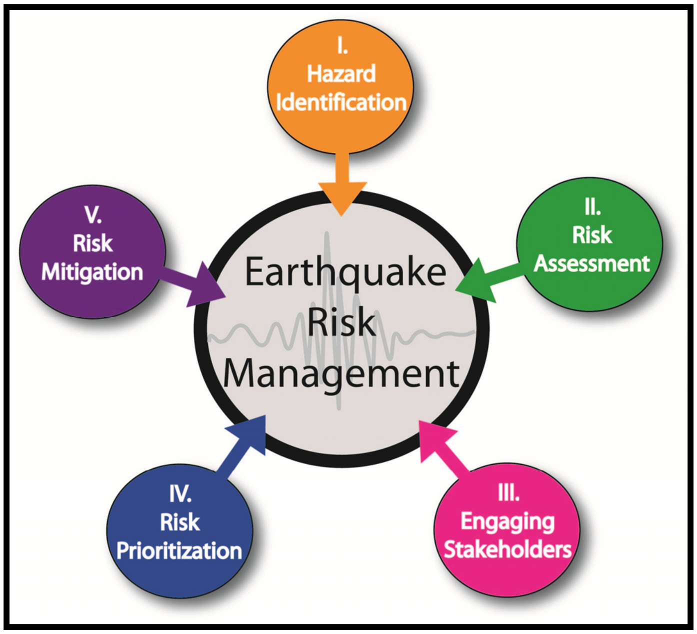


Figure 72: Earthquake Risk Management Strategy (Wang, 2010)

As part of this project, DOGAMI, OPUC and ODOE (the EAP partners) promoted seismic awareness of Oregon's critical energy infrastructure. We developed productive relationships with other state agencies, federal agencies, energy sector companies, associations, emergency response organizations and other major stakeholders regarding seismic preparedness giving about 60 presentations. We conducted table-top exercises and extensive outreach, including:

- 2009 EAP partner hosted fuel sector table-top held at NWN headquarters
- 2010 DOGAMI testimony to House of Representatives Transportation Committee
- 2010 DOGAMI testimony to House of Representatives Veterans and Emergency Services Committee
- 2010 Interagency Hazard Mitigation Team meeting held at the Oregon Emergency Management
- 2011 Energy Assurance: Lessons from Japan's Earthquake Disaster symposium held at the Oregon Capitol. Sponsored by OPUC and DOGAMI, co-sponsored by Cascadia Region Earthquake Workgroup and Oregon Seismic Safety Policy Advisory Commission. Speakers included Senate President Peter Courtney, Representative Deborah Boone, Susan Ackerman (PUC Commissioner), Chris Goldfinger (scientist), Kit Miyamoto (engineer). Participants included Vicki McConnell (director of DOGAMI), General Mike Caldwell (director of OEM), Carmen Merlo (director of Portland Bureau of Emergency Management), Eric Corliss (COO of Oregon Red Cross).
- 2011 EAP partners joint presentation to Oregon Emergency Response System held at the Oregon Emergency Management
- 2011 Pacific Northwest Economic Region Annual Summit, Disaster Resilience Energy Assurance session, co-organized by Alice Lippert, Program Manager, the U.S. Department of Energy's Energy Assurance Program and co-moderated by Ken Murphy, the then FEMA Region X Administrator (http://www.pnwer.org/2011AnnualSummit/LongAgenda.aspx).

These efforts were minimal, however, considering the task at hand. In order to build resilience in Oregon's energy sector, it is necessary to increase awareness on the risk to the energy sector and Oregonians from a Cascadia earthquake. There needs to be a cultural shift by Oregonians to become an earthquake preparedness culture. More transparency and accountability in the energy sector on Cascadia preparedness is required.

Encourage a Culture of Earthquake Preparedness

Since the terror attacks in the US on September 11, 2001, Americans have become much more aware of and supportive of security precautions. Rather than wait for an earthquake disaster to strike, Oregon should take precautions today and become better prepared.

It is not a question of *if* a large magnitude Cascadia earthquake will occur, but *when* it will occur. This study has demonstrated that Oregon's CEI Hub is vulnerable to a Cascadia earthquake, and its failure will impact our supply and sources of liquid fuel, natural gas and electricity throughout Oregon. Oregonians have experienced gas shortages during the 1970s, and power outages during winter storms.. Following a Cascadia earthquake, there will likely be *no* gas available to the public for a considerable period of time. During a winter storm, power outages last hours to days long. After a Cascadia earthquake, many Oregonians could be without heat and electrical power for months.

Oregonians should heed this study's findings, that:

- A Cascadia earthquake will occur.
- Oregon's CEI Hub – where critical energy infrastructure is located in a six-mile stretch of land – is vulnerable to a Cascadia earthquake.
- Oregon's resilience to a Cascadia earthquake is low.
- Energy sector companies must adopt best practices and pro-actively integrate seismic mitigation efforts into their business operations to prepare their facilities and systems to absorb and recover from a Cascadia earthquake and to sufficiently restore critical electric, natural gas and liquid fuel services to Oregon homes, businesses and industries in a reasonable time period.
- More stringent oversight on seismic preparedness in the energy sector (liquid fuel, electricity and natural gas) may be needed. ###

Section 8
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Section 10
Appendices

A Oregon Economic Interdependency Assessment of the Energy Sector
B Lateral Spreading Sensitivity Study
C Telecommunications: Seismic Codes and Guidelines

Appendix A
Oregon Economic Interdependency Assessment of the Energy Sector

Scott B. Miles, Associate Professor, and Alexis Blue, Graduate Student, Resilience Institute, Western Washington University

The goal of the study included in this appendix was determine the economic interdependencies of Oregon's energy infrastructure with itself, broader critical infrastructure, and Oregon's commercial economy. This study characterizes critical infrastructure and commercial economy for the entire state at a county resolution. Characterizing the interdependencies quantitatively facilitates the general understanding of potential economic ripple effects of earthquake-induced disruption of energy infrastructure on the State of Oregon. The primary task of the study was to model the effects of lower sales of electricity, fuel and natural gas -- the three Oregon Energy Assurance sectors –to other critical infrastructure industries and the rest of Oregon's economy. Limitations in this study approach are discussed in the analysis overview.

The objectives of this study were the following:

1. Aggregate industries to represent energy and critical infrastructure sectors to characterize the interdependencies of power, natural gas, and fuel industries with other critical infrastructure industries, and Oregon's commercial economy
2. Develop an energy infrastructure-focused input-output table for the State of Oregon
3. Analyze the economic impacts of financial loss within the created energy infrastructure sectors for a range of energy infrastructure financial loss scenarios

<u>Analysis Overview</u>
The study used input-output analysis to understand economic interdependencies between energy infrastructure sectors and other sectors, as well as to estimate economic impacts of various energy infrastructure financial loss scenarios. The financial loss scenarios are used as a rough proxy for energy infrastructure disruption. The analysis described below does not model physical infrastructure disruption or cascading functional impacts.

The software tool and data set called IMPLAN by MIG Inc., was used to conduct the input-output analysis of this study (http://implan.com/). IMPLAN data is a compilation of data for describing employment, employee compensation, proprietary income, other property income, indirect business taxes, output, inter-institutional transfers, and household and government purchases. For this study, the data is reported at the state level, even though the data is available at a finer resolution. IMPLAN was used to model the impact of negative sales as a proxy for infrastructure disruption. IMPLAN models how this loss of sales and jobs flows back through inter-industry purchasing.

Interdependency Assessment

The interdependency assessment was conducted using the 2008 IMPLAN database (the latest dataset available at the time of the study) with no additional or modified data. IMPLAN data describes 440 North American Industry Classification System (NAICS) industry classes in the dataset. The 440 NAICS industries were aggregated into 19 sectors for the purpose of this analysis. The first priority of the aggregation was to group industries associated with each respective energy infrastructure sector (petroleum, natural gas, and electricity), while grouping the remaining industries in sectors typically used in similar input-output studies. The energy infrastructure groupings were based on input and review from the Oregon EAP Team. The 19 sectors for grouping the 440 NAICS industries are listed in Table A1.

After aggregation, an input-output (I-O) analysis was conducted to produce the input-output table shown as Table A2. The inside 19 by 19 matrix of the table (labeled 1 through 19) shows amount of sales and purchases between the 19 sectors. The columns represent the purchasing of inputs (payments) to create the respective sector's products or services. The rows indicate the selling of outputs (receipts) by each sector. The second to last row, labeled "Value Added" indicates the combination of payments for labor, profits, and imports. The sum of all intermediate inputs plus value added equals the last row, labeled "Total Inputs." The second to last column of Table 5 is labeled "Final Demand," which includes sales to consumption (by consumers), investments, governments, and exports. Final demand plus the sum of all intermediate outputs equals the final column, labeled "Total Outputs." The value in the cell of the intersection of the last row and last column is referred to as gross output. Gross output is equal to gross state product (net output) plus intermediate consumption.

Table A1: Sectors in Interdependency Assessment

01 Petroleum
02 Electricity
03 Natural Gas
04 Communication
05 Transport by Air
06 Transport by Rail
07 Transport by Water
08 Transport by Truck
09 Transport by Pipeline
10 All Other Transportation
11 Utilities
12 Agriculture/Forestry
13 Mining
14 Construction
15 Services
16 Wholesale/Retail
17 Non-Durable Goods
18 Durable Goods
19 Government Services - Public Safety

Table A2: Baseline Inputs-Outputs for Interdependency Assessment

Inputs (Receipts, $ Millions)	Outputs (Payments, $ Millions)																				
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	Final Demand	Total
01 Petroleum	11.9	40.5	29.0	1.4	14.5	2.7	0.0	19.4	0.1	11.2	0.0	21.1	0.3	31.6	27.7	11.9	43.5	14.4	11.8	236.8	530.0
02 Electricity	3.2	4.5	35.6	19.7	0.9	0.3	2.6	6.7	0.0	13.5	0.1	106.5	15.9	74.0	1035.9	328.4	303.6	621.7	23.0	2356.4	4952.5
03 Natural Gas	7.8	2.2	11.4	19.6	0.1	0.0	1.2	2.3	0.0	9.2	0.3	30.9	9.4	24.3	239.7	45.2	301.4	431.5	57.3	433.7	1627.6
04 Communication	0.6	8.0	0.9	1240.5	11.2	0.9	2.3	18.9	0.0	11.5	0.3	5.7	0.7	137.4	1672.8	261.4	59.8	239.9	7.3	3407.3	7087.3
05 Transport by Air	0.2	2.0	0.4	12.5	0.1	0.2	0.7	5.1	0.0	10.3	0.0	2.5	0.1	15.8	159.9	23.1	23.7	67.4	1.0	886.7	1211.6
06 Transport by Rail	0.7	74.7	1.8	2.1	0.4	2.5	0.1	25.7	0.0	7.9	0.0	25.0	5.5	20.3	26.7	4.5	113.3	175.1	2.9	364.6	853.9
07 Transport by Water	0.2	3.3	0.4	0.3	1.7	0.4	0.0	2.1	0.0	6.4	0.0	15.0	0.5	8.7	41.9	1.4	29.7	27.9	1.1	386.3	527.3
08 Transport by Truck	1.7	14.5	2.5	11.1	2.8	3.7	3.4	129.8	0.0	17.1	0.1	95.5	8.2	202.8	255.5	156.0	334.7	649.1	22.0	1493.0	3403.6
09 Transport by Pipeline	0.1	3.4	2.8	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.3	0.1	0.7	2.8	11.1
10 All Other Transportation	0.3	6.9	0.8	40.3	89.6	11.8	76.3	231.5	0.0	69.9	0.1	2.4	1.1	10.8	807.4	604.4	20.5	62.0	9.7	1139.9	3185.8
11 Utilities	0.1	14.8	0.3	6.1	0.1	0.2	1.8	0.6	0.0	14.5	0.0	34.2	0.1	11.7	155.2	18.3	22.6	38.4	36.8	-296.1	59.8
12 Agriculture/Forestry	0.4	0.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1774.4	1.5	41.0	107.6	20.1	1955.3	284.5	0.1	6096.5	10283.8
13 Mining	0.2	79.1	1.2	0.9	0.0	0.1	0.0	0.0	0.0	0.0	0.0	5.1	14.4	23.0	6.4	0.1	14.2	103.2	3.7	316.7	568.1
14 Construction	7.2	99.1	1.2	47.2	0.3	27.9	0.0	2.1	0.2	13.2	4.0	24.5	0.0	13.4	856.6	70.8	69.2	163.5	172.9	17016.0	18589.2
15 Services	41.0	329.9	54.4	1480.5	146.4	128.0	77.9	365.6	0.8	285.1	6.8	693.6	48.1	2343.2	29237.8	5486.9	2339.6	6725.0	541.9	74279.8	124612.2
16 Wholesale/Retail	8.4	20.5	10.2	49.8	12.4	11.0	2.2	75.1	0.1	32.1	0.2	256.5	7.1	1389.2	1356.4	895.1	1294.3	3733.1	43.9	23784.7	32982.3
17 Non-Durable Goods	5.6	4.4	7.4	32.2	0.5	1.3	0.8	10.7	0.0	9.5	0.0	400.3	2.3	170.3	1158.4	178.4	2266.0	907.6	18.9	17469.5	22644.2
18 Durable Goods	3.5	16.5	6.9	80.2	10.2	13.5	23.1	24.7	0.1	27.0	0.2	32.1	7.3	1109.2	612.1	124.0	234.8	5732.0	62.1	49927.9	58047.3
19 Government Services - Public Safety	0.0	0.0	0.1	5.1	0.0	0.0	0.0	0.3	0.0	5.2	0.0	0.2	0.0	0.0	140.3	9.8	11.1	16.5	42.4	19346.4	19577.5
Value Added	436.8	4227.8	1458.4	4037.9	920.3	649.4	334.7	2482.7	9.8	2642.3	47.5	6758.4	445.9	12962.2	86713.8	24742.3	13206.6	38054.3	18518.0		
Total	530.0	4952.5	1627.6	7087.3	1211.6	853.9	527.3	3403.6	11.1	3185.8	59.8	10283.8	568.1	18589.2	124612.2	32982.3	22644.2	58047.3	19577.5		310755.2

Note: * Value Added = Employee Compensation + Proprietor Income + Indirect Business Taxes + Other Property Type Income

The same information in Table A2, except for value added and final demand amounts, is provided in Figure A1 in graphical form, with the increasing dollar values represented by increasingly hotter colors from blue (cool) to red (hot). Note the hot colors, represent values of $100 million or greater, where maximum values listed in Table A2 are in the tens of billions. The threshold was chosen in order to easily visualize lower values.

Figure A2 presents the information of Table A2 in bar chart form to emphasize the relationship between each respective energy infrastructure sector and the rest of the Oregon economy to understand whether the particular energy sector is more or less dependent on the other 18 individuals sectors than each of the 18 sectors are on the respective energy sector. The outputs of each energy sector are represented by a dark color (blue for petroleum, red for electricity, and purple for natural gas, respectively) and inputs of the remaining sectors by a lighter respective shade. A higher dark bar (e.g., dark blue for 01 Petroleum) at the x-axis location of another sector (e.g., 08 Transport by Truck, represented by light blue) means that the transportation by truck sector purchases more petroleum than the petroleum sector purchases from the transportation by truck sector. In other words, the transportation by truck sector is more dependent on the petroleum sector than the petroleum sector is dependent on the transportation by truck sector. Figures A3, A4, and A5 show the same information as Figure A2 but include inputs and outputs for only one respective energy sector.

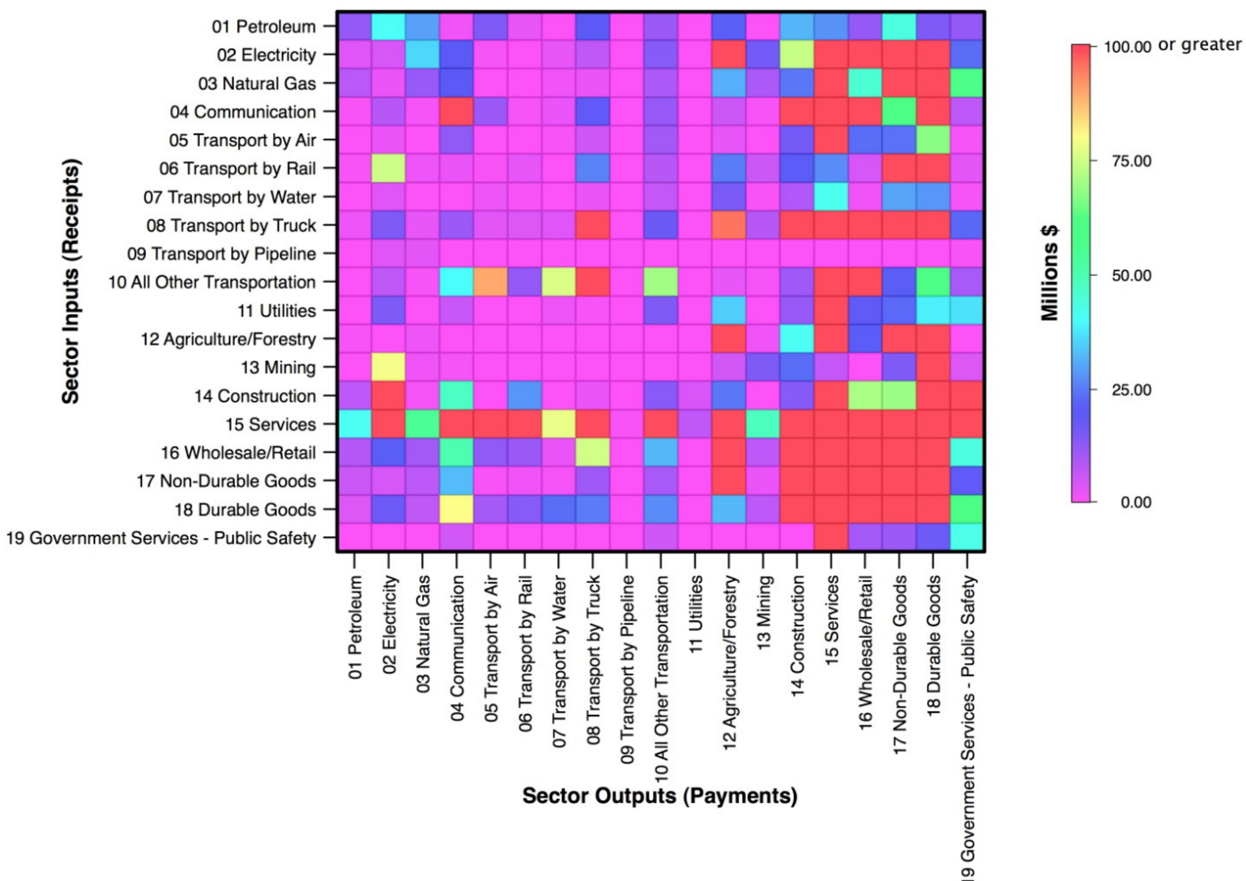

Figure A1. Visual representation of the input-output table of Table A2. Hotter colors (red, orange) indicate higher dollar value. Red indicates $100 million or greater.

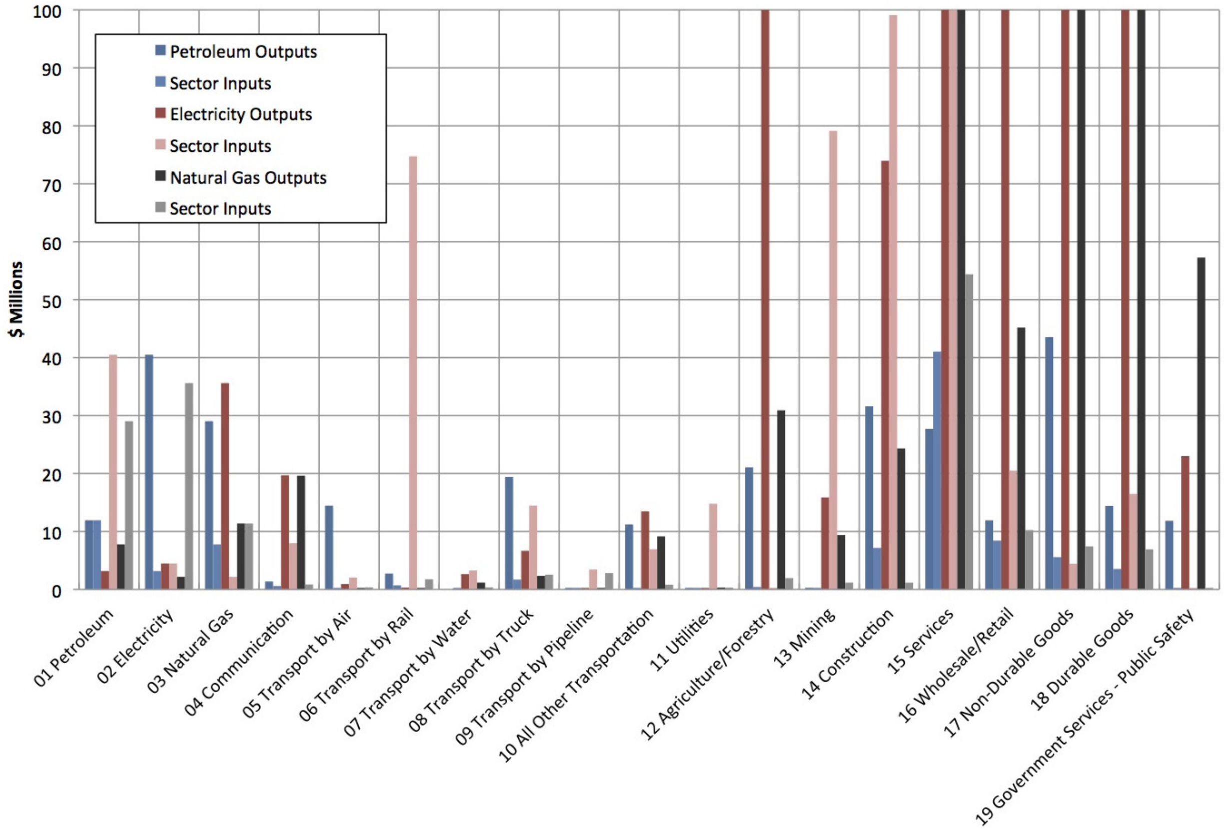

Figure A2. Petroleum, electricity and natural gas outputs (receipts) and inputs (payments) with respect to all analyzed sectors. Note: Vertical scale is capped at $100 million to facilitate comparison.

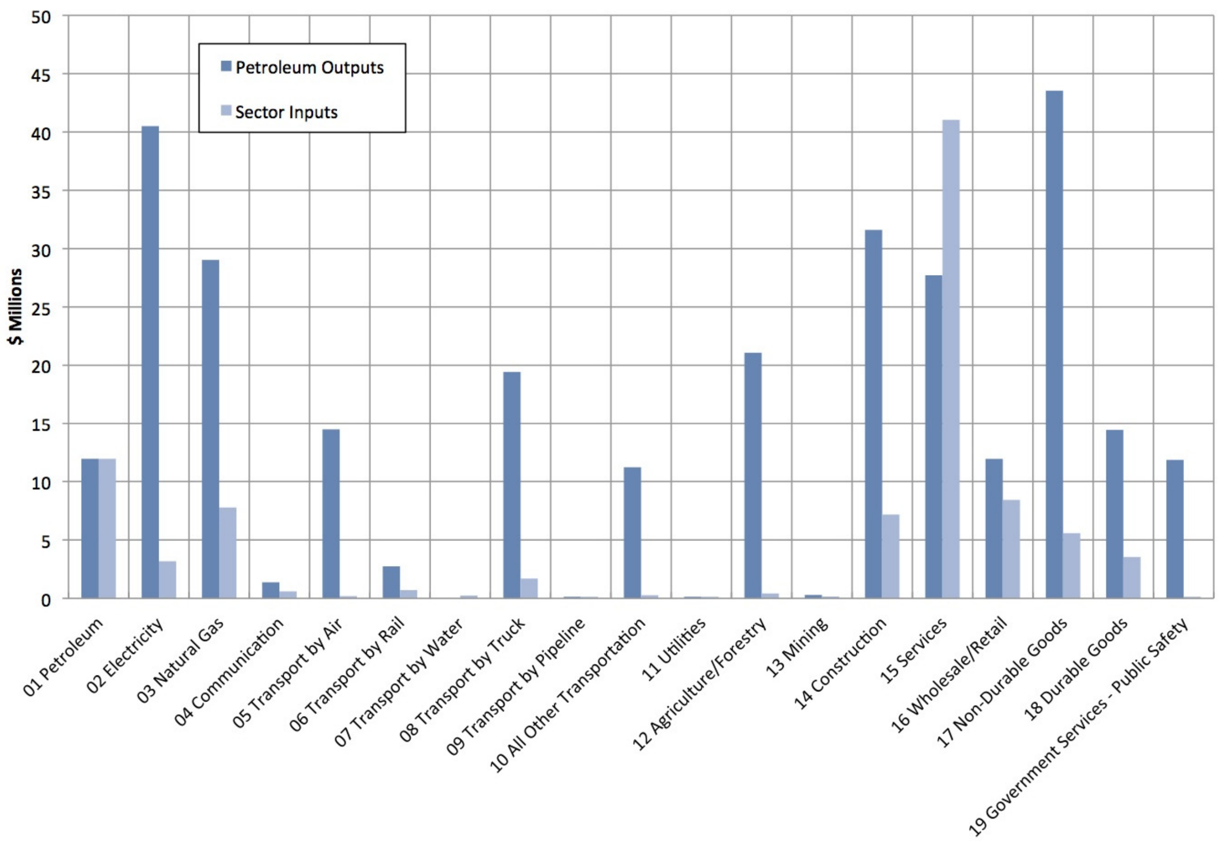

Figure A3. Petroleum outputs (receipts) and inputs (payments) with respect to all analyzed sectors.

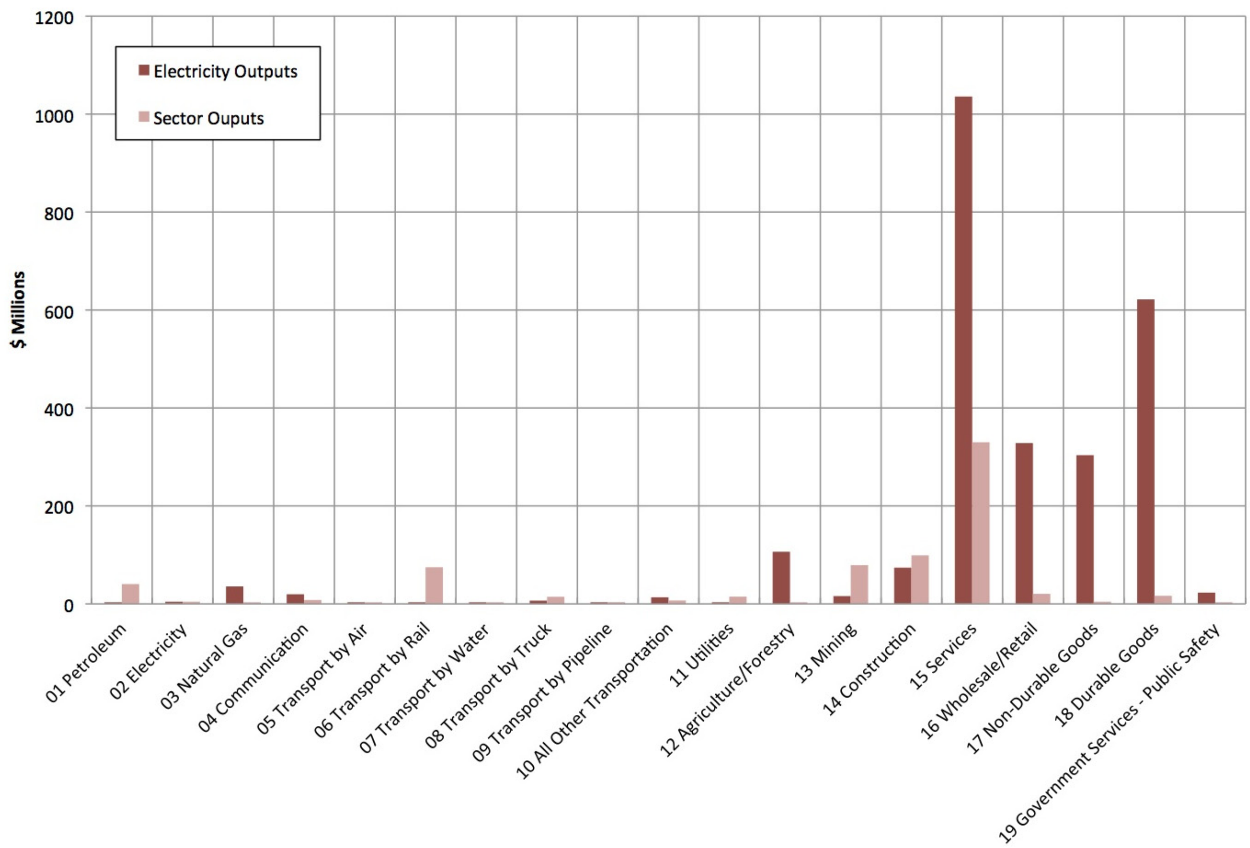

Figure A4. Electricity outputs (receipts) and inputs (payments) with respect to all analyzed sectors.

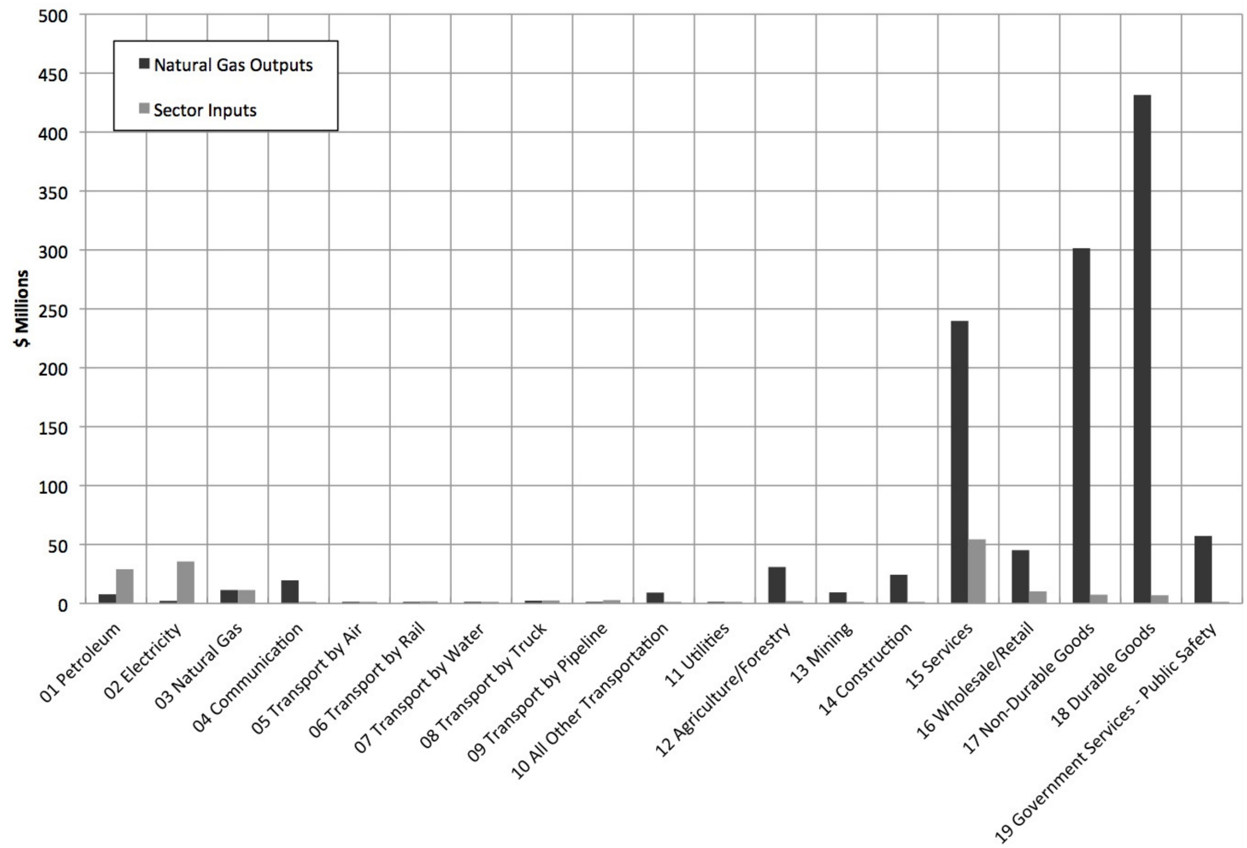

Figure A5. Natural gas outputs (receipts) and inputs (payments) with respect to all analyzed sectors.

Petroleum: Figures A2 and A3 show that the petroleum sector has relatively high unequal monetary relationships with several sectors. The electricity, natural gas, transport by air, transport by truck, other transportation, agriculture/forestry, construction, non-durable goods, durable goods, and government services are significantly more dependent on the petroleum sector than the other way around. The only other strong dependency of the petroleum sector on another sector is between it and the services sector.

Electricity: Figures A2 and A4 show that the electricity sector is more dependent on the transport by rail and mining sectors than the reverse. This is also minimally the case for the petroleum and construction sectors. Alternatively the agriculture/forestry, services, wholesale/retail, non-durable goods, and durable goods sectors are more dependent on electricity than the reverse

Natural Gas: Figure A2 and A5 show that there are strong monetary relationships with communications, agriculture/forestry, construction, services, wholesale/retail, non-durable goods, durable goods, and government services sectors are all more dependent on the natural gas sector than the other way around. The inverse is true for the petroleum and electricity sectors.

Impact Analysis

A suite of scenarios was developed to estimate the impacts of reduced levels of energy sector products being purchased *over the course of one year* (in this case 2008, the most recent year available for IMPLAN) as an approximate proxy for energy infrastructure loss. The impact analysis does not model the impact of physical or functional loss of the energy infrastructure, only loss of purchases of sector goods and services. The analysis also does not represent when within the year loss in purchases occurs. The results of the analysis are only representative of purchases loss within the year and don't include any losses in subsequent years. The scenarios analyzed using IMPLAN are summarized in Table A3. The values in Table A3 are percent reduction in purchases. In order to avoid divide by zero errors in IMPLAN, zero was approximated using a value close to zero. Table A4 lists, in the second column, the total output when each energy infrastructure sector purchases are normal (based on 2008 data in IMPLAN), which represents no hazard impact. The remaining columns to the right show the reduction in output for 75 percent, 50 percent, 25 percent and 0 percent of normal purchase levels to approximate hazard impacts.

Input-output analysis has some associated limitations in modeling economic impacts. For this particular application, again, input-output modeling does not model functional relationships of infrastructure. The loss modeled is financial in the form of reduced purchases of some good or product – in this case related to an energy infrastructure sector. Changes in inputs and, thus, outputs cannot be represented at any temporal resolution less than a year. Data for input-output analysis are only available a few years after the year the data describes. (In this case, the most recent data available are for 2008.) No consideration is made within the analysis for price effects, substitutions, or economies of scale. A basic input-output model, such as used here, is a demand-side model and so assumes that supplies are infinite. As a result, the absolute and relative financial relationships of purchases (inputs) and receipts (outputs) are reliable. The limitations in the context of modeling the influence of supply disruptions (such as a reduction of energy infrastructure service in a disaster) will results in significant under-estimation of actual loss. The predicted loss should be considered a lower-bound. Due to limitations of this interdependency model, the actual losses could be orders of magnitude higher because of supply-side and functional dependencies.

Table A3. Percent operability for the respective energy infrastructure sector

	Fuel	Electricity	Nat'l Gas
Baseline	100%	100%	100%
All 75	75	75	75
All 50	50	50	50
All 25	25	25	25
All 0	0	0	0
Fuel 75	75	100	100
Fuel 50	50	100	100
Fuel 25	25	100	100
Fuel 0	0	100	100
Elec 75	100	75	100
Elec 50	100	50	100
Elec 25	100	25	100
Elec 0	100	0	100
NatGas 75	100	100	75
NatGas 50	100	100	50
NatGas 25	100	100	25
NatGas 0	100	100	0

Table A4. Outputs values, in dollars, for each scenario.

	100%	75%	50%	25%	*0%
Petroleum	529,967,073	-132,491,768	-264,983,537	-397,475,305	-524,667,403
Electricity	4,952,514,064	-1,238,128,516	-2,476,257,032	-3,714,385,548	-4,902,988,923
Natural Gas	1,627,604,600	-406,901,150	-813,802,300	-1,220,703,450	-1,611,328,554

*The computations in the 0% scenario have been approximated and theoretically should be the negative equal value of the 100% scenario

Figure A6 shows the total impact (direct + indirect + induced) for all energy infrastructure loss scenarios. The three energy infrastructure types, as well as all infrastructure types simultaneously, are listed along the x-axis (all, electricity, natural gas, and petroleum) with each scenario listed in decreasing percent of operability (75%, 50%, 25%, 0%). The greatest amount of loss of any scenario is expectedly for all energy sectors with purchases 0% or normal for the year, at close to $7 billion dollars, with about $2.6 billion of that loss being non-direct (indirect + induced). The greatest loss associated with just one energy infrastructure sector is close to $7 billion (with about $2 billion of that non-direct loss) and is for the electricity purchases at 0% of normal scenario. Notice that the ratio between non-direct and direct loss is constant.

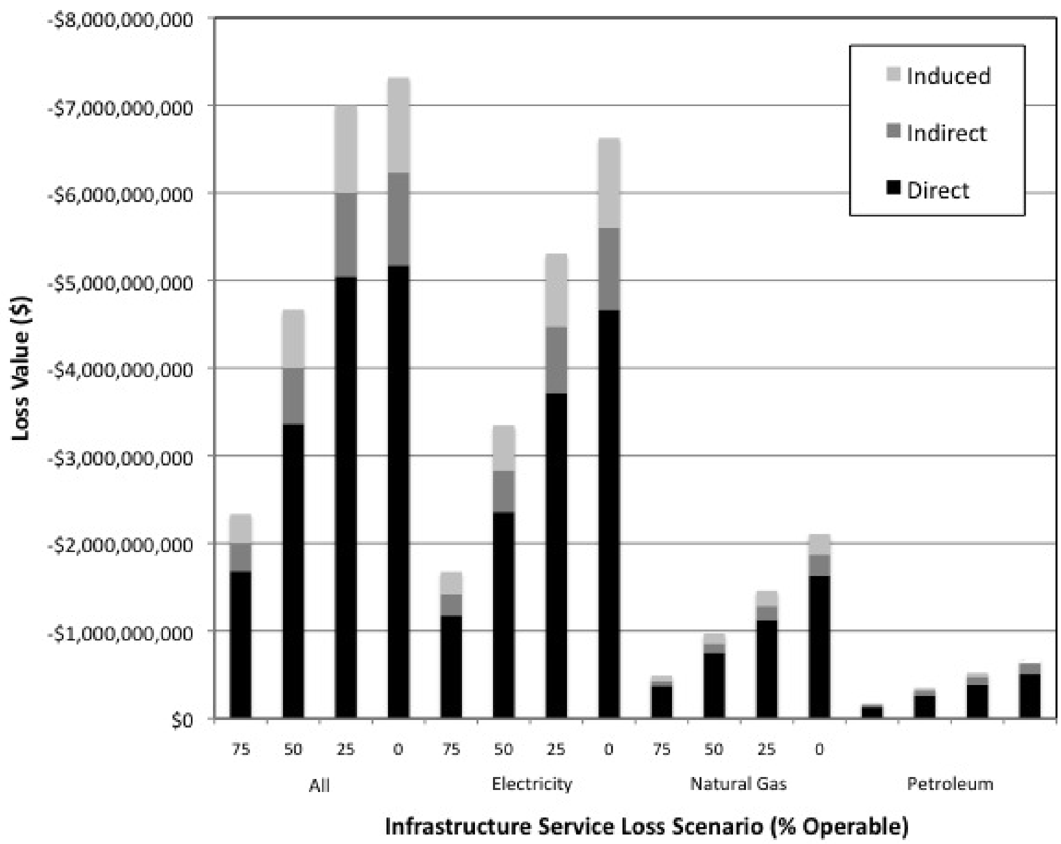

Figure A6. Total impact, including direct, indirect, and induced, for all energy infrastructure disruption scenarios.

Table A5 shows the indirect dollar losses and multipliers related to the disruption of each energy infrastructure (including all at once) with respect to output and employment. The second column of Table A5 shows the value in dollars of non-direct (indirect + induced) loss for each dollar of assumed direct loss. The direct loss is assumed as part of the energy infrastructure disruption scenarios. Thus, if $100,000 of direct loss were suffered for all energy infrastructure, an additional $39,000 would be lost as a result of non-direct loss. Similarly, the third column shows how many non-direct jobs are lost as result of one direct job lost. Thus if 1,000 jobs are lost as a result of disruption to all energy infrastructure, an additional 2,420 non-direct jobs would be lost. It is important to note that the two columns are not coupled. For example, $100,000 of direct loss to all energy infrastructure does not result in 242,000 non-direct jobs lost.

Table A5. Indirect Dollar and Jobs Loss Relationship For Energy Sectors. Data are preliminary.

	All		Petroleum		Electricity		Natural Gas	
Sector	In-Direct Loss for Every Dollar of Direct Loss	In-Direct Jobs Lost for Every Direct Jobs Lost	In-Direct Loss for Every Dollar of Direct Loss	In-Direct Jobs Lost for Every Direct Jobs Lost	In-Direct Loss for Every Dollar of Direct Loss	In-Direct Jobs Lost for Every Direct Jobs Lost	In-Direct Loss for Every Dollar of Direct Loss	In-Direct Jobs Lost for Every Direct Jobs Lost
Total	$0.387	2.4185	$0.357	1.6376	$0.420	2.6028	$0.295	2.1087
01 Petroleum	$0.011	0.0138	$0.021	0.0205	$0.008	0.0098	$0.016	0.0265
02 Electricity	$0.012	0.0127	$0.012	0.0094	$0.008	0.0077	$0.027	0.0343
03 Natural Gas	$0.004	0.0033	$0.014	0.0084	$0.002	0.0017	$0.007	0.0074
04 Communication	$0.012	0.0261	$0.009	0.0159	$0.013	0.0284	$0.008	0.0223
05 Transport by Air	$0.002	0.0052	$0.001	0.0030	$0.002	0.0056	$0.001	0.0048
06 Transport by Rail	$0.011	0.0260	$0.002	0.0033	$0.015	0.0344	$0.002	0.0050
07 Transport by Water	$0.001	0.0010	$0.001	0.0007	$0.001	0.0012	$0.000	0.0007
08 Transport by Truck	$0.006	0.0348	$0.005	0.0264	$0.006	0.0375	$0.004	0.0289
09 Transport by Pipeline	$0.001	0.0001	$0.000	0.0000	$0.001	0.0001	$0.002	0.0002
10 All Other Transportation	$0.005	0.0552	$0.004	0.0302	$0.006	0.0616	$0.003	0.0430
11 Utilities	$0.000	0.0011	$0.000	0.0003	$0.000	0.0013	$0.000	0.0005
12 Agriculture/Forestry	$0.004	0.0299	$0.004	0.0270	$0.003	0.0270	$0.004	0.0435
13 Mining	$0.012	0.0429	$0.001	0.0017	$0.016	0.0579	$0.001	0.0056
14 Construction	$0.018	0.1130	$0.016	0.0768	$0.023	0.1404	$0.003	0.0227
15 Services	$0.216	1.5755	$0.189	1.0580	$0.239	1.6944	$0.152	1.3831
16 Wholesale/Retail	$0.042	0.3563	$0.041	0.2626	$0.045	0.3672	$0.035	0.3642
17 Non-Durable Goods	$0.014	0.0295	$0.022	0.0342	$0.013	0.0266	$0.015	0.0388
18 Durable Goods	$0.012	0.0258	$0.013	0.0216	$0.012	0.0263	$0.010	0.0261
19 Government Services - Public Safety	$0.006	0.0662	$0.004	0.0375	$0.006	0.0739	$0.003	0.0512

If the available electricity, natural gas and liquid fuels were significantly reduced, then the non-direct dollar losses would have major socioeconomic consequences to Oregon. In the hypothetical scenario that 100% energy infrastructure is disrupted, a minimum of $0.39 of non-direct loss would be expected for every dollar of loss up to a maximum of the aggregate output value of the energy sectors. The sectors most impacted for this scenario are Services, followed next by Wholesale/Retail, followed by Construction, Non-Durable Goods, Electricity, Communications, Mining, Durable Goods, Petroleum, and Transport by Rail. The impact to Services is about an order of magnitude greater than the other sectors. For employment impacts, under the same scenario, a minimum of 2.42 jobs would be expected to be lost for every direct job lost in the energy sectors. Again, the greatest impacted by this scenario, by an order of magnitude, is the Service industry, followed again by Wholesale Retail, as well as Construction. The impact to services is very similar across the individual energy sector disruption scenarios. Most significant is the finding that the Electricity sector has the greatest monetary and employment impact potential of the three energy sectors.

The scenarios from this study have not been linked with specific studies of energy sector impacts from a Cascadia earthquake, and it is not possible to relate any of the modeled scenarios to estimated damage and losses to the energy sector due to a Cascadia earthquake.

Improving the energy sector's resilience to major disasters, in particular a Cascadia earthquake would require mitigation actions to reduce the restoration time of energy services. The total impact from a disaster to the energy sector would include the direct damage to the energy facilities, the loss of sales (such as by amounts as shown in the scenarios), non-direct losses and non-direct job losses (as shown in Table A5), and a multitude of cascading functional impacts, which would also potentially have economic impacts of their own.

Comparison with Other Studies

After the Northridge earthquake, Tierney (1997) found that after debris clean up, loss of electricity was the most commonly cited reason for business closure (Table A6). The most significant impacts were seen in the finance, insurance, and real estate industries (FIRE; classified as services in the current study) and construction. FIRE services were also impacted the most in the current study on Oregon energy disruption. In a study by Tierney and Nigg (1995) comparing the dependency of businesses to five types of infrastructure between Memphis, TN and Des Moines, IA with respect to potential (Memphis; earthquake disruption) and actual (Des Moines; 1993 Midwest floods) disruption. Table A7 (Des Moines) and Table A8 (Memphis) shows the results of that study. In both cases, businesses depend most on electricity, while depending on natural gas third most. Lastly, in the study of the business impacts from the 1993 Midwest floods, Tierney (1994) wrote the following, which provides further insight into the importance of energy infrastructure amongst other required business resources and the impacts of the services sector (FIRM) from these disruptions:

> Overall, electricity was rated as the most critical lifeline service by both large and small businesses, with the former considering electric service more important than the latter. Large manufacturing and construction firms and both large and small companies in the finance, insurance, and real estate sectors were more likely than other businesses to rate electricity as critical to their operations. While small businesses generally considered telephone service to be the second most critical lifeline, large businesses appeared to view telephones, water, sewer service, and natural gas as equally critical.

A study by Rose et al. (2007) on the economic impacts of electricity outage due to a terrorist attack on Los Angeles, CA found that the services sector was most impacted by a significant margin. This is not surprising as the input-output analysis found that services and manufacturing are the two main business users of electricity.

None of the above studies included direct dependence on liquid fuel. Looking at Table A6, one could conjecture that a few factors leading to business closure are related to lack of access to liquid fueling, putting disruption of fuel near the top of the factors. Even so, what studies have been done confirm the general validity of the findings of the current study and the importance of resilient infrastructure, as well as the significant economic impact that would arise due to energy disruption from a Cascadia earthquake in Oregon. The general lack of studies of the dependence of and impacts to businesses from energy infrastructure disruption suggests the importance and innovation of this study.

Table A6. Ranked factors determined to have lead to business closures after the 1994 Northridge earthquake (Tierney, 1997).

Reason	Percentage
Needed to Clean-up Damage	65.2
Loss of Electricity	58.7
Employees Unable to Get to Work	56.4
Loss of Telephones	49.8
Damage to Owner or Manager's Home	44.4
Few or No Customers	39.9
Building Needed Structural Assessment	31.5
Could Not Deliver Products or Services	24.0
Loss of Machinery or Office Equipment	23.7
Building Needed Repair	23.4
Loss of Inventory or Stock	21.9
Loss of Water	18.2
Could Not Get Supplies or Materials	14.9
Building Declared Unsafe	10.1
Could Not Afford to Pay Employees	9.5
Loss of Natural Gas	8.7
Loss of Sewer or Waste Water	5.3
Other	15.8
Number of Businesses That Closed	617

Table A7. Results of surveys to businesses in Des Moines IA asking the degree of importance on five types of infrastructure (Tierney and Nigg, 1995).

	LIFELINE SERVICES				
IMPORTANCE	Electric	Water	Natural Gas	Water Treatment	Telephone
Critical	55%	29%	37%	34%	36%
Very Imp	35	34	27	29	36
Important	8	30	26	28	15
Not Very Important	2	8	8	7	8
Not Imp at all	0	1	2	1	5
Total	100%	102%*	100%	99%*	100%

*Does not total 100% due to rounding

Table A8. Results of surveys to businesses in Memphis, TN asking the degree of importance on five types of infrastructure (Tierney and Nigg, 1995).

LIFELINE SERVICES					
IMPORTANCE	Electric	Water	Natural Gas	Water Treatment	Telephone
Very Imp	82%	27%	18%	23%	78%
Important	14	34	29	32	17
Not Very Important	3	31	39	33	3
Not Imp at all	1	8	13	13	2
Total	100%	100%	99%*	101%*	100%

*Does not total 100% due to rounding

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Appendix B
Lateral Spreading Sensitivity Study

by Steven Bartlett, PE, University of Utah and Yumei Wang, PE, DOGAMI

Introduction

The potential amount of ground deformation resulting from liquefaction-induced lateral spread in the Critical Energy Infrastructure (CEI) Hub in Portland, Oregon was jointly evaluated. The University of Utah was the lead modeler, and DOGAMI was the lead in framing the sensitivity study and provided some of the input variables including the geotechnical soils data. The evaluations were done using empirical equations developed by Youd et al. (2002) and by nonlinear numerical modeling using a finite difference computer program called FLAC (Fast Lagrangian Analysis of Continua) (v.5) developed by Itasca, 2005. The lateral spread evaluations were done using several earthquake time histories and slope conditions for two cases of soil conditions: (1) unimproved ground, and (2) improved ground. Unimproved ground denotes analyses performed for the existing ground conditions that have not been modified by any type of ground improvement technology. Improved ground denotes analyses that were done to estimate the potential reduction in lateral spread displacement that might be achieved by modifying the properties of the potentially liquefiable soil using some type of ground improvement technology (e.g., stone columns, rammed aggregate piers, etc.).

Seismic Input

The evaluations involved selection of representative acceleration time histories for magnitude 9.0 (M9.0) and magnitude 8.0 (M8.0) earthquakes and slightly adjusting them for use in the numerical modeling. A total of ten subduction zone earthquake time histories were considered for the final numerical analyses (Figure B1). Two of these are synthetic time histories obtained from Art Frankel of the US Geological Survey (1msoil and 1ssoil), and the remaining eight time histories are from other subduction zone earthquakes from the 1985 Chilean and 1985 Mexican earthquakes. Each candidate time history was analyzed using both of its horizontal components. All candidate time histories were scaled to a peak ground acceleration (pga) value of 0.3 g to be more representative of the expected strong motion for a 1000-year return period event (Figure B2). For example, the pga value for a deterministic Cascadia M9.0 event is about 0.18 g; however, when this event is considered in probabilistic terms at a 1000-year return period, the expected pga increases to approximately 0.3 g for rock and stiff soil sites. In addition to the 0.3-g scaling of pga, the candidate time histories were baseline-corrected to ensure that no artificial displacement occurs when analyzing the records in the numerical model.

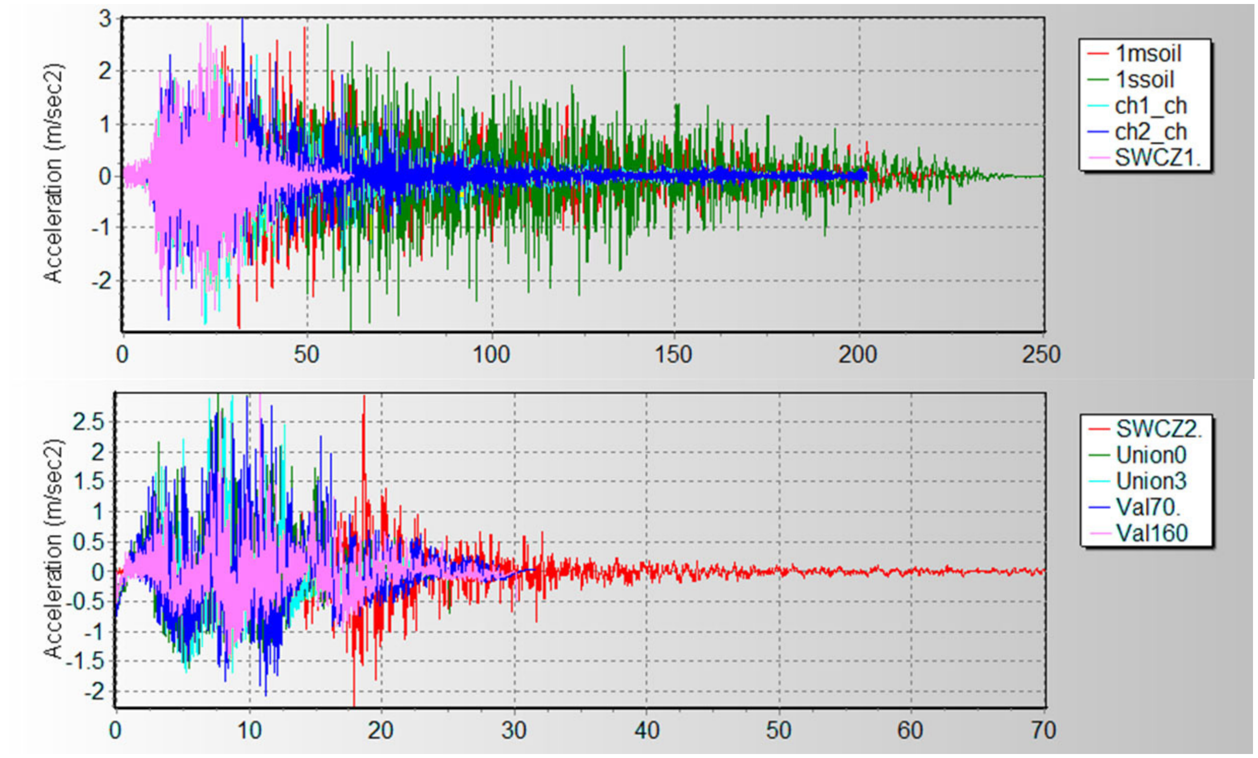


Figure B1. Representative time histories used in FLAC analysis

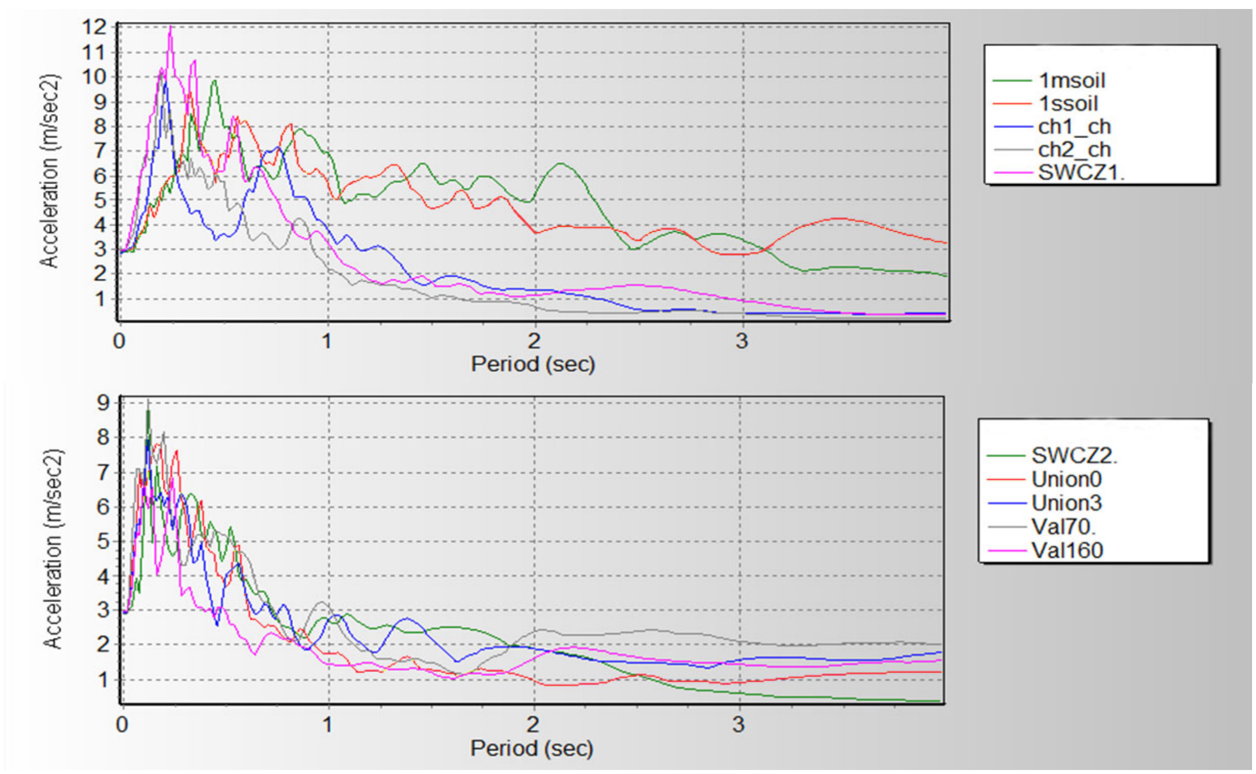


Figure B2. Acceleration response spectra for the time histories used in FLAC analysis

Subsurface Conditions

In-situ soil data from a BPA tower site in the CEI Hub were used to develop representative soil profiles and used in conjunction with other generic soil properties from the area (BPA, 2008; CH2MHill, 2006). Figure B3 shows in-situ soil data (cone penetrometer soundings) from the CEI Hub, which were used in the evaluations. From a lateral spread viewpoint, the primary zone of interest is that from about 21 to 46 feet deep. Much of this zone has q_{c1}values of 60 tons / sq. foot, and except for the zone between 38 to 40 feet, the soils appears to be granular and susceptible to liquefaction due to their low penetration resistance. (Note that materials with penetration resistance greater than 60 tons / sq. foot were not considered in the evaluations because they are probably not susceptible to damaging lateral spread displacement due to their higher density and strength.)

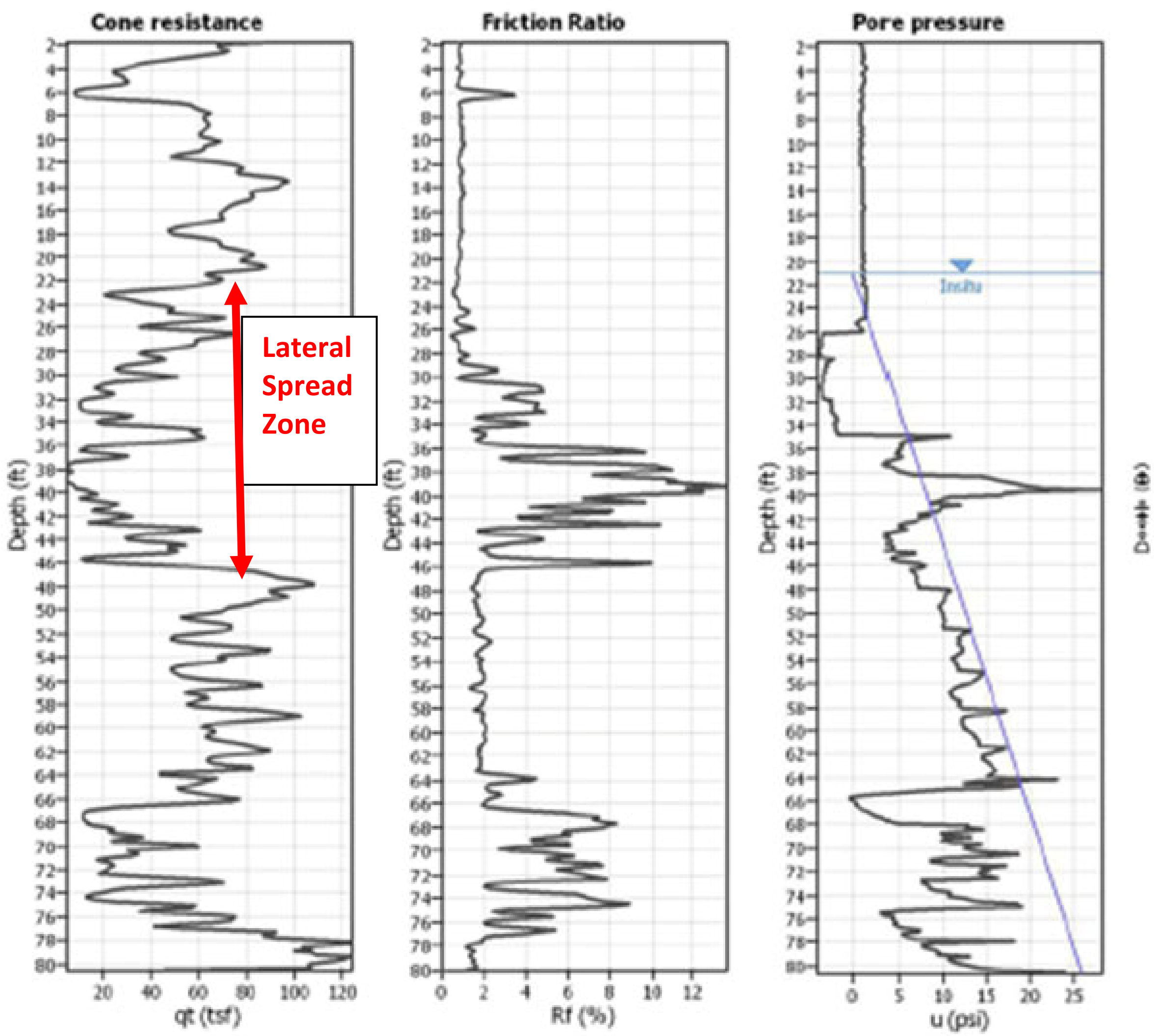


Figure B3. Soils layering and profile considered in FLAC analyses (modified from BPA, 2008)

Numerical Model

Figure B4 shows the FLAC cross sectional model that was used in the parametric analyses. It has the following dimensions 1,000 m wide; height at left and right edges was varied to evaluate a range of ground slope angles from 0.5 to 5 degrees; 5 m depth to ground water table; depth to base of lateral spread zone 12.5 m (41 feet) and 7.5 m (25 feet) of lateral spread zone. Note that because of the mesh spacing of the developed model, the lateral spread zone depth and thickness varies slightly from that shown in Figure B3. These slight differences do not significantly affect the modeling results.

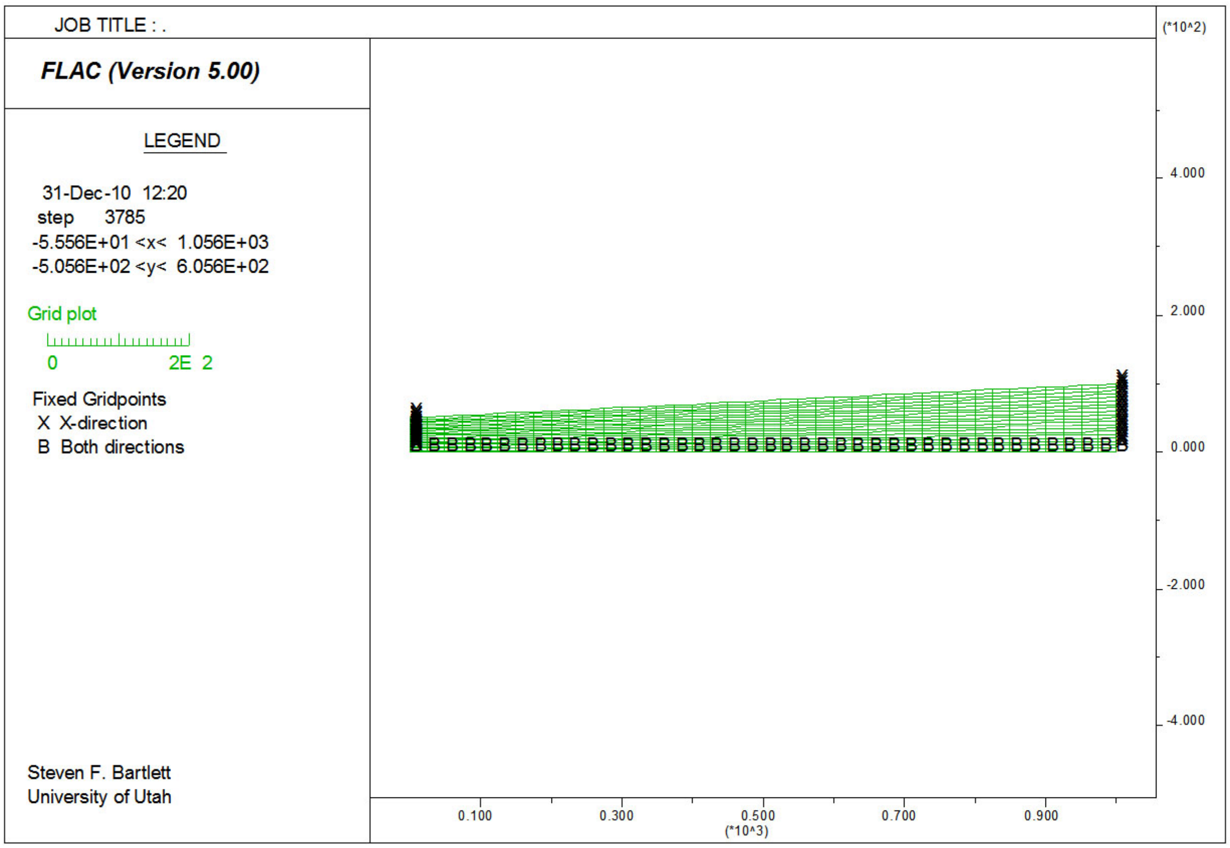


Figure B4. The FLAC model of a slope from the CEI Hub deformation analysis. This is an example run with the modeled slope gently sloping towards the left.

The following modeling approach was used to analyze the potential lateral spread displacement at the site:

- The model was first brought to static equilibrium for the groundwater conditions to calculate the state of in situ stress in the soil profile before the onset of the earthquake and liquefaction.
- The soil properties of the subsurface soils were set to a drained friction angle of 32 degrees and the initial (maximum) shear modulus was calculated based on a subsurface shear wave velocity of 150 m/s (500 feet/s).

- The candidate time histories were input at the base of the FLAC model and the earthquake motion was propagated through the model. Slight scaling of the time history was done to ensure that the 0.3 g was produced at the surface of the model without liquefaction effects present in the model.
- Each candidate time history was analyzed using both a positive polarity (+) and a negative polarity (-) to evaluate the sensitivity of lateral spread displacement to the polarity of the record.
- Liquefaction effects were introduced in the modeling using the following approach and assumptions:
    - Liquefaction is triggered approximately when the first 0.1 g acceleration spike is encountered in the candidate time history based on liquefaction triggering analyses.
    - Maximum shear strength and soil stiffness values for the soil profile were used at the onset of strong motion.
    - These values were linearly degraded to residual values to represent complete liquefaction at the time when the first 0.1 g acceleration spike occurred in the respective time history.
        - The initial shear modulus at the beginning of the earthquake record was degraded to 10 percent of its initial value at complete liquefaction.
        - The friction angle of the liquefied soil was degraded from its peak value of 32 degrees at the beginning of the earthquake record to 6 degrees when complete liquefaction was encountered. This residual value was selected because it allows the residual strength to be approximately 10 percent of the initial mean effective stress under hydrostatic conditions, which is a reasonable estimate of the residual strength for loose, liquefied sand.
- The lateral spread horizontal displacement was calculated for each of the candidate time histories. The slope of the FLAC model was varied from 0.5 to 5 degrees for each of the candidate time histories to account for potential variation of slope in the CEI Hub.
- The FLAC model results were also compared against displacements predicted from the Youd et al. (2002) regression equation to evaluate the reasonableness of the FLAC model.

Lateral Spread Displacement Estimates for Unimproved Ground

Using the modeling approach described above, a parametric study was conducted to estimate the order of magnitude and characteristics of the possible lateral spread displacement for unimproved ground. Table B1 shows the main parameters used in the study, as well as the deformation results for the various earthquakes and ground slope cases. In addition, the FLAC results are compared and complemented with empirically derived mean estimates of horizontal displacement obtained from the empirical relationships developed from the Youd et al. (2002) for M9.0 and M8.0 earthquakes (Figure B5). Note that Youd et al. (2002) found that actual displacements can vary by a factor of 2 from the mean estimate. Thus for example, the upper bound lateral spread displacement for a 5 percent slope and a M9.0 event is approximately 10 m based on a mean estimate of about 5 m for that same event.

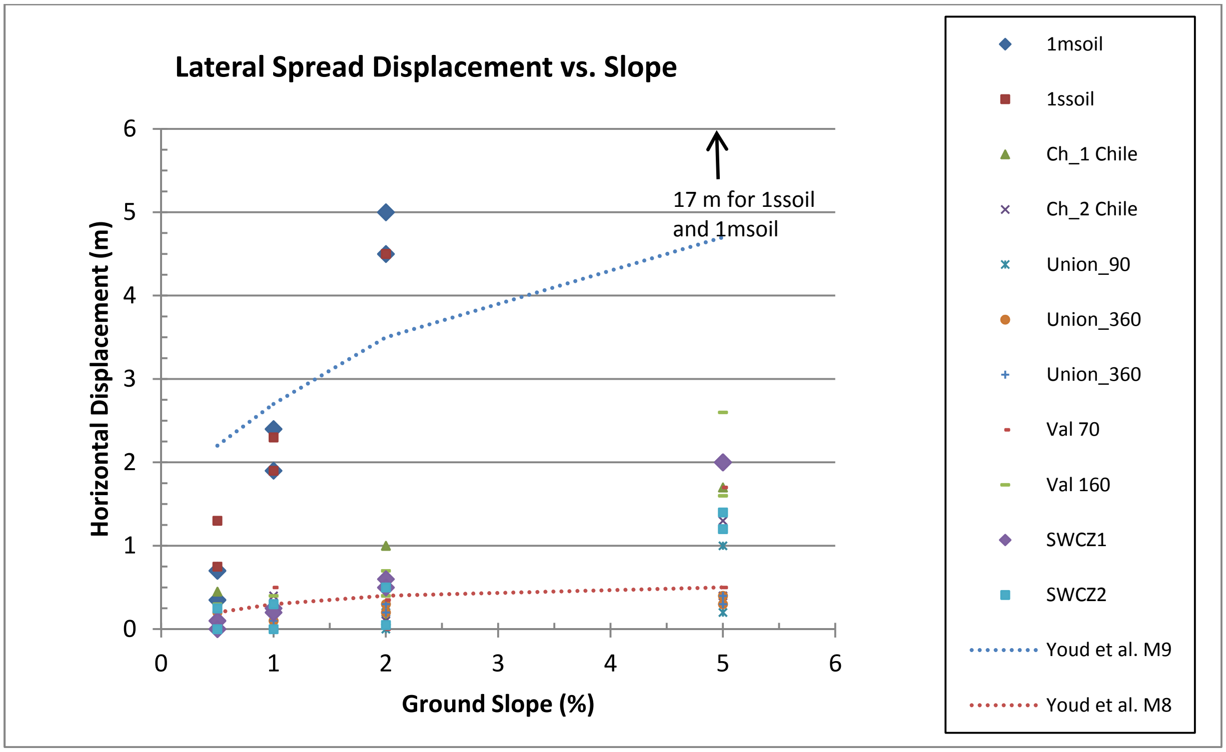


Figure B5. Estimates of horizontal displacement versus ground slope for M9.0 and M8.0 earthquakes compared with mean estimates from Youd et al. (2002) regression equation.

The FLAC modeling results for records 1msoil and 1ssoil produce about 17 m of predicted ground displacement for a M9.0 event on a 5 percent slope. This is somewhat higher than the 10 m upper bound estimated by the Youd et al. (2002) regression equation. The reason for the relatively large displacement produced by the FLAC model can be seen by comparing the magnitude and duration of the strong motion represented by histories 1msoil and 1ssoil with the other candidate time histories used in the modeling. The 1msoil and 1ssoil records both have strong motion duration that exceeds 200 s and ground accelerations that exceed 1 m/s^2 (0.1 g) for much of the record (Figure B1). The amplitude and duration of strong motion for these two records are notably higher than the other records used in the evaluations. Certainly the amount of lateral spread displacement would decrease if these records were used unscaled instead of the 0.3-g scaling that was used. However, we choose to use the scaled time histories for these events and evaluate the corresponding ground improvement needed to remediate the lateral spread, as discussed in the next section.

Lateral Spread Displacement Estimates for Improved Ground

The soil properties used in the FLAC model were modified to represent the case where the ground has been improved by some type of ground improvement technology. For these analyses, the soil properties were modified accordingly to represent the effects of improved ground in the lateral spread zone.

- The friction angle in the liquefied zone was increased from its residual value in the FLAC model to a value where deformations became small. From this, the shear strength required to ameliorate the lateral spread was calculated.
- The residual shear modulus for the treated zone was set equal to 30 percent of the initial unliquefied value of the shear modulus, G.
- The shear strength of the improved ground required to mitigate the lateral spread was uniformly distributed throughout the potential lateral spread zone.
- It was assumed that excess pore pressure generation from cycling (partial liquefaction) does not affect the shear strength of the improved ground.

The evaluation of improved ground was not repeated for all cases. Instead, representative time histories were used to estimate what treatment was required to mitigate the lateral spread hazard. The selected time histories were: (1) 1msoil, which was selected to represent a M9.0 event at a distance of 100 km, and (2) SWCZ1, which was selected to represent a M8.0 event at a distance of 100 km. These particular earthquake records were selected because they produced displacement near the upper bound displacement for the unimproved ground case (Figure B-5); hence they represent a conservative case to analyze the effects of improved ground.

The results of the improved ground evaluations presented in Table B-2. These analyses show that the improved soil must have a minimum composite strength of about 30 to 50 kPa (600 to 1000 psf) to mitigate the lateral spread hazard for a M9.0 event. The analyses also show that the improved soil must have a minimum composite strength of about 20 to 45 kPa (400 to 900 psf) to mitigate the lateral spread hazard for a M8.0 event. We anticipate that if these composite strengths can be obtained using ground improvement, then the expected lateral spread displacement will be 0.05 m (2 inches), or less. These preliminary evaluations were done using limited geotechnical data and simplifying assumptions. More detailed, site specific evaluations can be made for the individual facilities.

Table B1: Parametric Study Inputs and Results for FLAC Deformation Analyses for Unimproved Ground

Time History	Polarity	Untreated slope (%)	Untreated Residual residual phi' (deg)	Depth Ground Water (m)	Untreated Predicted Displace-ment (m)	Treated phi' (deg)	Mean eff. stress (kPa)	Equivalent S_u (kPa)	Treated Predicted Displace-ment (m)
1msoil	+	0.5	6	5	0.7	15	110.00	28	0.05
1msoil	-	0.5	6	5	0.35				
1msoil	+	1	6	5	1.9	19	110.00	36	0.05
1msoil	-	1	6	5	2.4				
1msoil	+	2	6	5	4.5	22	110.00	41	0.05
1msoil	-	2	6	5	5				
1msoil	+	5	6	5	17	27	110.00	50	0.15
1msoil	-	5	6	5	17				
1ssoil	+	0.5	6	5	0.75				
1ssoil	-	0.5	6	5	1.3				
1ssoil	+	1	6	5	1.9				
1ssoil	-	1	6	5	2.3				
1ssoil	+	2	6	5	4.5				
1ssoil	-	2	6	5	4.5				
1ssoil	+	5	6	5	17				
1ssoil	-	5	6	5	17				
Ch_1 Chile	+	0.5	6	5	0.45				
Ch_1 Chile	-	0.5	6	5	0.05				
Ch_1 Chile	+	1	6	5	0.15				
Ch_1 Chile	-	1	6	5	0.2				
Ch_1 Chile	+	2	6	5	1				
Ch_1 Chile	-	2	6	5	0.1				
Ch_1 Chile	+	5	6	5	2				
Ch_1 Chile	-	5	6	5	1.7				
Ch_2 Chile	+	0.5	6	5	0.05				
Ch_2 Chile	-	0.5	6	5	0.03				
Ch_2 Chile	+	1	6	5	0.06				
Ch_2 Chile	-	1	6	5	0.4				
Ch_2 Chile	+	2	6	5	0.1				
Ch_2 Chile	-	2	6	5	0.2				
Ch_2 Chile	+	5	6	5	1.3				

(continued)

Table B1 *(continued)*

Ch_2 Chile	-	5	6	5	0.4				
Union_90	+	0.5	6	5	0.1				
Union_90	-	0.5	6	5	0.1				
Union_90	+	1	6	5	0.2				
Union_90	-	1	6	5	0				
Union_90	+	2	6	5	0				
Union_90	-	2	6	5	0.2				
Union_90	+	5	6	5	1				
Union_90	-	5	6	5	0.2				
Union_360	+	0.5	6	5	0				
Union_360	-	0.5	6	5	0.2				
Union_360	+	1	6	5	0.1				
Union_360	-	1	6	5	0.3				
Union_360	+	2	6	5	0.3				
Union_360	-	2	6	5	0.2				
Union_360	+	5	6	5	0.4				
Union_360	-	5	6	5	0.3				
Val 70	+	0.5	6	5	0				
Val 70	-	0.5	6	5	0.1				
Val 70	+	1	6	5	0				
Val 70	-	1	6	5	0.5				
Val 70	+	2	6	5	0				
Val 70	-	2	6	5	0.35				
Val 70	+	5	6	5	1.7				
Val 70	-	5	6	5	0.5				
Val 160	+	0.5	6	5	0.1				
Val 160	-	0.5	6	5	0.3				
Val 160	+	1	6	5	0.2				
Val 160	-	1	6	5	0.4				
Val 160	+	2	6	5	0.4				
Val 160	-	2	6	5	0.7				
Val 160	+	5	6	5	1.6				
Val 160	-	5	6	5	2.6				
SWCZ1	+	0.5	6	5	0.1	10	110.00	19	0.05
SWCZ1	-	0.5	6	5	0				
SWCZ1	+	1	6	5	0.25	15	110.00	28	0
SWCZ1	-	1	6	5	0.2				

(continued)

Table B1 *(continued)*

SWCZ1	+	2	6	5	0.6	20	110.00	38	0.05
SWCZ1	-	2	6	5	0.5				
SWCZ1	+	5	6	5	2	25	110.00	46	0.05
SWCZ1	-	5	6	5	2				
SWCZ2	+	0.5	6	5	0.25				
SWCZ2	-	0.5	6	5	0				
SWCZ2	+	1	6	5	0.3				
SWCZ2	-	1	6	5	0				
SWCZ2	+	2	6	5	0.5				
SWCZ2	-	2	6	5	0.05				
SWCZ2	+	5	6	5	1.4				
SWCZ2	-	5	6	5	1.2				
Youd et al. M9		0.5			2.2				
		1			2.7				
		2			3.5				
		5			4.7				
Youd et al. M8		0.5			0.2				
		1			0.3				
		2			0.4				
		5			0.5				

Table B2: Parametric Study Inputs and Results for FLAC Deformation Analyses for Improved Ground

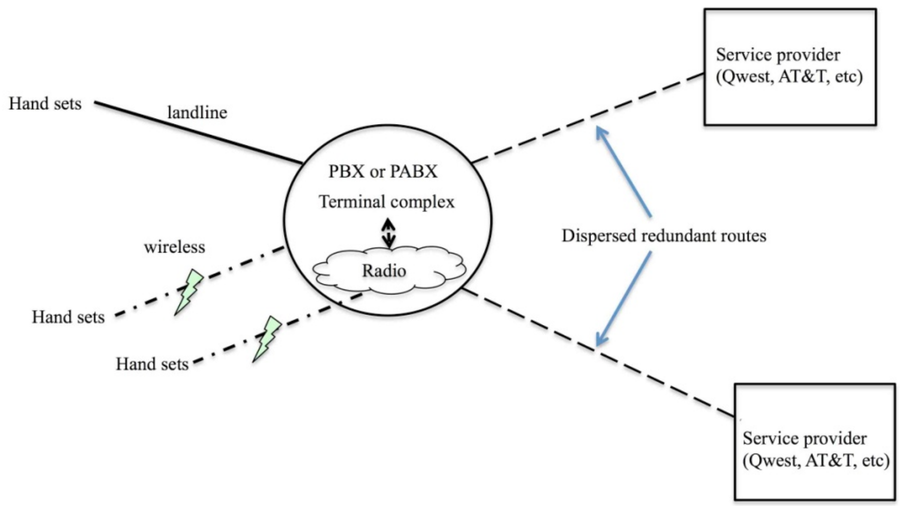
	Polarity	Untreated	Untreated	Depth	Untreated	Treated	Mean eff.	Equivalent Su	Treated
Time History		slope (%)	residual phi' (deg)	Grd Water (m)	Predicted Displacement (m)	phi' (deg)	stress (kPa)	(kPa)	Predicted Displacement (m)
1msoil	+	0.5	6	5	0.7	15	110.00	28	0.05
1msoil	-	0.5	6	5	0.35				
1msoil	+	1	6	5	1.9	19	110.00	36	0.05
1msoil	-	1	6	5	2.4				
1msoil	+	2	6	5	4.5	22	110.00	41	0.05
1msoil	-	2	6	5	5				
1msoil	+	5	6	5	17	27	110.00	50	0.15
1msoil	-	5	6	5	17				
SWCZ1	+	0.5	6	5	0.1	10	110.00	19	0.05
SWCZ1	-	0.5	6	5	0				
SWCZ1	+	1	6	5	0.25	15	110.00	28	0
SWCZ1	-	1	6	5	0.2				
SWCZ1	+	2	6	5	0.6	20	110.00	38	0.05
SWCZ1	-	2	6	5	0.5				
SWCZ1	+	5	6	5	2	25	110.00	46	0.05
SWCZ1	-	5	6	5	2				

Appendix C
Telecommunications: Seismic Codes and Guidelines

All companies with facilities in the CEI Hub are encouraged to conduct seismic vulnerability assessments that include interdependencies on other systems, such as telecommunication systems. Telecommunication systems are not only important for communication systems, but also many different types of systems, such as pipeline and electrical systems, need telecommunications to operate. Telecommunication systems can help monitor and control data and systems so many systems are dependent on them. Seismic codes and guidelines for telecommunication systems are provided below. The list should be updated as new key references are made available.

Telecommunications

To increase service reliability, facilities should incorporate redundancy of wired, wireless and radio services (see figure; PBX = Private branch exchange for private telephone network)



NEBS - Network Equipment-Building System, including GR-63 Physical Protection
Bellcore http://telecom-info.telcordia.com/site-cgi/ido/docs2.pl?ID=160834912&page=nebs

ASCE - American Society of Civil Engineers (ASCE) 7-10 American Society of Civil Engineers

ASCE - monograph No. 10 Methods of Achieving Improved Seismic Performance of Communications Systems

TIA/EIA-222-G (2009) Structural Standard for Antenna Supporting Structures and Antennas