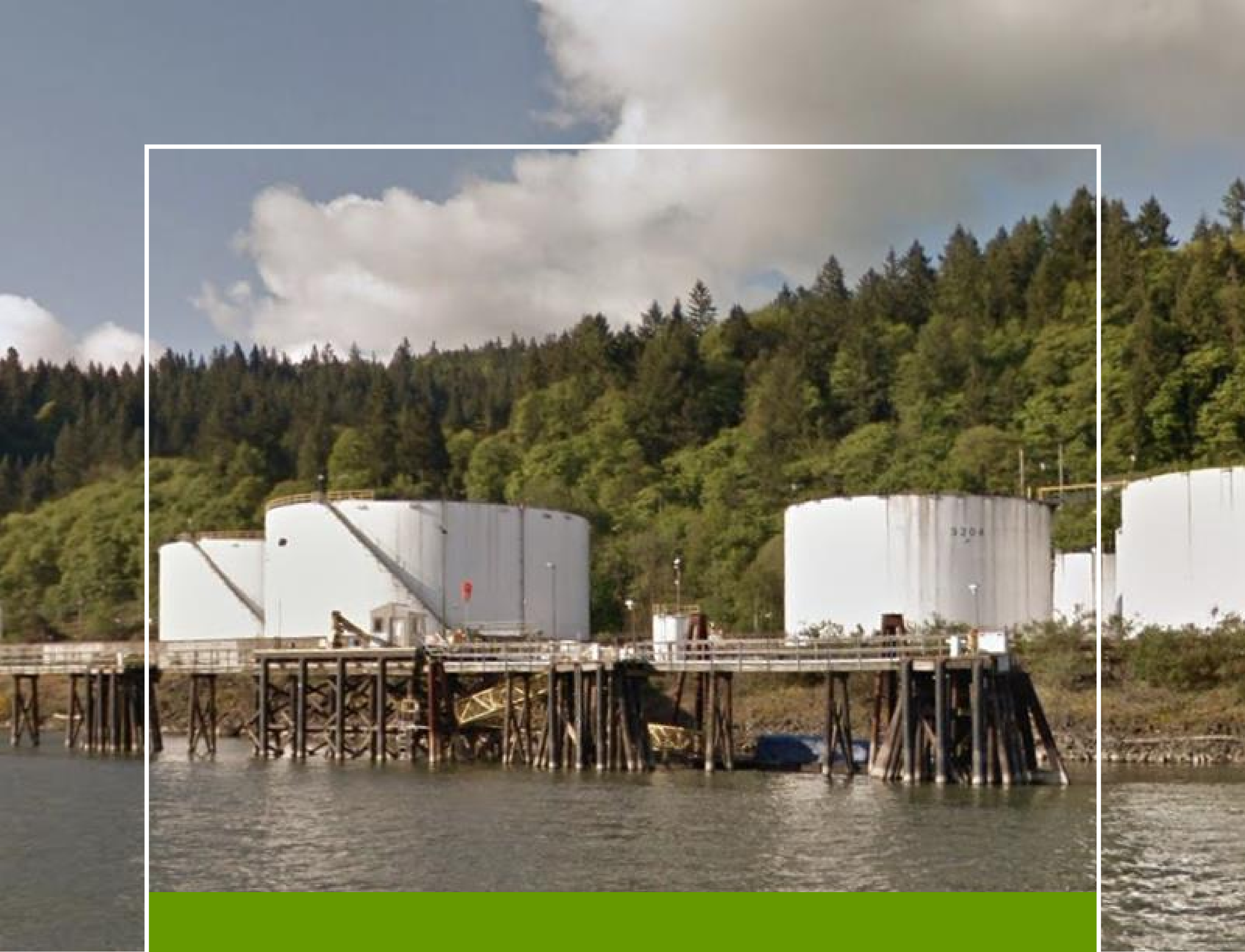

Liquid Storage Tanks at the Critical Energy Infrastructure (CEI) Hub

Seismic Assessment of Tank Inventory

May 2019

Acknowledgements

This report was written for the city of Portland's Bureau of Emergency Management (PBEM). The work was conducted though a collaboration between Mapleaf LLC and Portland State University.

Appreciation is extended to Anne Castleton, Ph.D., Emergency Management Coordinator with the Bureau of Development Services, City of Portland, for her insightful questions and perspectives.

Authors

Peter Dusicka, *PhD*, *PE*, *Professor*

Gregory Norton, *Graduate Research Assistant*

Contact

Peter Dusicka, *PhD*, *PE*, *Professor*
Department of Civil and Environmental Engineering
Portland State University
P.O. Box 751
Portland, OR, 97207

email: dusicka@pdx.edu
phone: 503-725-9558

Cover

Photograph of liquid fuel storage tanks for NuStar Energy L.P. that form part of the Critical Energy Infrastructure Hub in Portland, OR.

Source: Google Maps, 2019.

REPORT SUMMARY

Seismic vulnerability of the Critical Energy Infrastructure (CEI) hub in Portland has been recently highlighted in several regional resiliency assessments. This report focuses on the liquid fuel storage tanks located at the CEI hub due to the adverse consequences of failure. General structural and geotechnical damage of similar facilities were identified by reviewing the seismic performance of liquid fuel storage tanks during past earthquakes. Data was then gathered on the storage tanks at the CEI hub and analyzed in an effort to quantitatively assess the tank inventory. There are nine different companies with hundreds of in-service tanks holding various forms of liquid products that have a potential storage capacity of over 8.6 million barrels. Over 95% of this capacity can be stored in large tanks that are 25ft in diameter or larger. The majority of the large tanks were built prior to 1970s and the vast majority prior to 1990s, eras when regional seismicity and seismic design were not fully appreciated or developed. Consequently, the structural and geotechnical issues revealed in tanks from past earthquakes are likely to manifest at the CEI hub unless mitigation steps are taken to minimize the risk. A conceptual order of magnitude cost of seismic mitigation for the large capacity tanks was estimated to exceed $300 million. This estimate made gross assumptions on soil mitigation, structural anchoring and design/permitting costs and did not consider fuel distribution past the tanks. Based on the findings and associated limitations of this study, recommendations are made for next steps that would fill gaps in existing data and generate new critical knowledge to better quantify and mitigate the seismic risk of this critical facility.

TABLE OF CONTENTS

INTRODUCTION

Brief Background

The six-mile stretch of industrial land along the west shore of the Willamette River in Northwest Portland is often referred to as the Critical Energy Infrastructure (CEI) hub. Energy facilities in the CEI hub include liquid fuel port terminals, storage tanks, pipelines and transfer stations, natural gas transmission and storage, electrical substations, and high voltage transmission lines. There are no petrochemical refinery operations in Oregon, so all of Oregon's liquid fuel is imported and over 90% is stored at fuel storage facilities in the CEI hub. This includes gas and diesel for the Portland metro area and all of the jet fuel for the Portland International Airport. These liquid fuel storage facilities are located along the river with the original intent for ships to import the fuel through port terminals. Now, most of the liquid fuel is brought in and out through pipelines. Numerous reports have highlighted the criticality of the CEI hub, the interconnectivity and the general earthquake risk to Portland and to the State (DOGAMI 2012, Bureau of Planning and Sustainability 2012, OSSPAC 2015, City Club of Portland 2017).

Purpose of Study

The purpose of this study was to focus on the liquid fuel storage aspect of the CEI hub and more specifically the storage tanks that hold the fuel. The storage tanks were chosen because they are some of the most visible aspects of the hub and pose the greatest risk if the tanks were to fail. The risk includes not only the regions inability to access fuel following a major earthquake, but also health and environmental concerns should failure occur.

This report summarizes the findings of the study, which had three main goals:

- Review past earthquake experiences from available literature of liquid fuel storage facilities in order to identify common vulnerabilities and key factors leading to tank damage and failure.
- Gather data from publicly available sources to identify the quantity and characteristics of the tanks and the supporting soil at the CEI hub. Contrast the information with past earthquake observations in order to gain a better appreciation of the expectations for seismic performance of the fuel storage tanks at the hub.
- Review potential mitigation options that aim to enhance the seismic performance of liquid storage tanks and estimate order-of-magnitude costs for implementing the mitigations.

The subsequent sections of the report address the above goals in a similar chronological order.

EARTHQUAKE DAMAGE TO LIQUID FUEL STORAGE TANKS

Overview from Past Earthquakes

Liquid petroleum products are commonly held in cylindrical, above-ground storage tanks. These are relatively simple structures comprised of a soil supported base-plate, a welded or riveted steel wall supported on a ring reinforced concrete foundation and a roof. The tanks are often categorized by their roof type; floating or fixed. To store liquids with low vapor pressures, such as propane, butane, or kerosene, a fixed roof tank is required to maintain pressure. For liquids that do not need to be pressurized for storage, floating roof tanks are utilized. As liquid is drained from a floating roof tank, the roof descends with the liquids surface and prevents the buildup of vapors that would otherwise form in the void of a fixed roof tank. Floating roof tanks are desirable for products such as crude oil, gasoline and diesel. The presence or absence of a floating roof in a large tank can influence the dynamic behavior when shaken by an earthquake.

Above ground storage tanks are well known to be vulnerable to seismic events. Since their simple design has been relatively unchanged for over a century, their seismic reliability has been tested numerous times. Previous earthquakes involving documented cases of tank damage are listed in Table 1. Selected examples from these earthquakes are used in the following sections to highlight some of the common vulnerabilities and the resulting damage.

Table 1: Earthquakes with Documented Significant Damage to Fuel Storage Tanks

Location	Magnitude	Date
Tokyo, Japan	8.3	September 1, 1923
Long Beach, California	6.4	March 10, 1933
Kern County, California	7.3	July 21, 1952
Prince William Sound, Alaska	9.2	March 27, 1964
Niigata, Japan	7.6	June 16, 1964
San Fernando, California	6.5	February 9, 1971
Managua, Nicaragua	6.3	December 23, 1972
Miyagi-Ken-Oki, Japan	7.7	June 12, 1978
Imperial County, California	6.5	October 15, 1979
Greenville, California	5.9	January 24, 1980
Central Greece	6.7	February 24, 1981
Coalinga, California	6.2	May 2, 1983
Loma Prieta, California	6.9	October 17, 1989
Marmara, Turkey	7.6	August 17, 1999
Tōhoku, Japan	9.0	March 11, 2011

Structural Damage

Although there are some references to an event in 1923 in Tokyo, the first reasonably well-documented case of damage to oil storage tanks followed the 1933 earthquake in Long Beach, California. The earthquake affected an industrial area that produced, refined, and stored petroleum. Complete tank failures were reported at three different locations, all less than 30 miles from the epicenter of the magnitude M6.4 earthquake. Peak ground acceleration (PGA) of 0.19g recorded at stations with similar distance from the epicenter were thought to be representative of those at the storage tanks (Housner 1952). Many tanks exhibited distortion, elongation, strain in riveted joints and buckling of the roof plates. Two of the tanks' riveted joints failed and while the tanks did not collapse as a result, the oil leaked. In one group of tanks, three partially full tanks sustained no damage while a full tank experienced total failure. The lost oil overcame the firewall and damaged neighboring buildings over 300 ft away (Nielsen & Kiremidjian 1986). There were other failures including overtopping where the roof was found 200 ft from the failed tank as shown in Figure 1. Other tanks did not necessarily fail in their structure, but were not anchored and separated from the inlet/outlet (I/O), resulting in loss of the oil. All failed tanks were of riveted construction and their structural failures were due to damage in the tank shell. The behavior of riveted shell wall tanks differs from the newer, welded shells construction. The long beach earthquake demonstrated that structural vulnerabilities of tanks relate to the riveted shell construction, to how full the tank is and to the connectivity of the I/O piping.

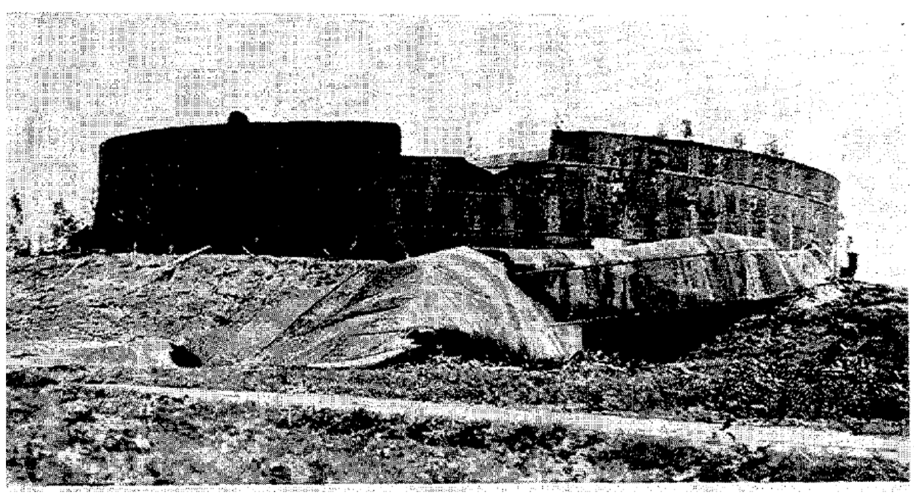

Figure 1: Failed Tank following 1933 Long Beach Earthquake (Cooper 1997)

The Great Alaskan earthquake of 1964 significantly influenced numerous aspects of earthquake engineering and also highlighted the vulnerability of petroleum storage tanks. The magnitude M9.2 subduction zone earthquake is the most powerful earthquake on record in North America. At the time of the earthquake, the petroleum industry was Alaska's largest mineral industry and damage to petroleum storage facilities was reported in the cities of Valdez, Whittier, Seward, Anchorage, and Nikiska. Direct structural damage to fuel storage tanks included: shell buckling near the bottom of the tank, buckling of cone roofs and top courses of shells, damage to floating roofs and accessories, and damage to I/O connecting piping (Rinne 1967). These were the result from liquid sloshing induced deformations, hydrodynamic pressure acting on the tank walls, shear force and overturning moment acting at the base of the tank, the buckling strength of tanks and, uplift on the axial stresses acting on the tank wall in contact with the ground. Sloshing can damage the top of the tank and can also result in roof damage. Buckling of the steel shell near the bottom of the tank is referred to as elephant-foot buckling. An example of roof damage and elephant-foot buckling is photographed in Figure 2. This type of damage usually occurs in tanks with a low height to radius ratio. Many tanks experienced elephant-foot buckling in this earthquake, all of them were near full capacity. Extreme elephant-foot buckling had resulted in leakage and also complete collapse. Sudden loss of oil from a leak can produce suction that implodes the roof of a tank. The structural damage to fuel storage tanks following the Great Alaskan earthquake exposed vulnerabilities even when the tank shells were welded.

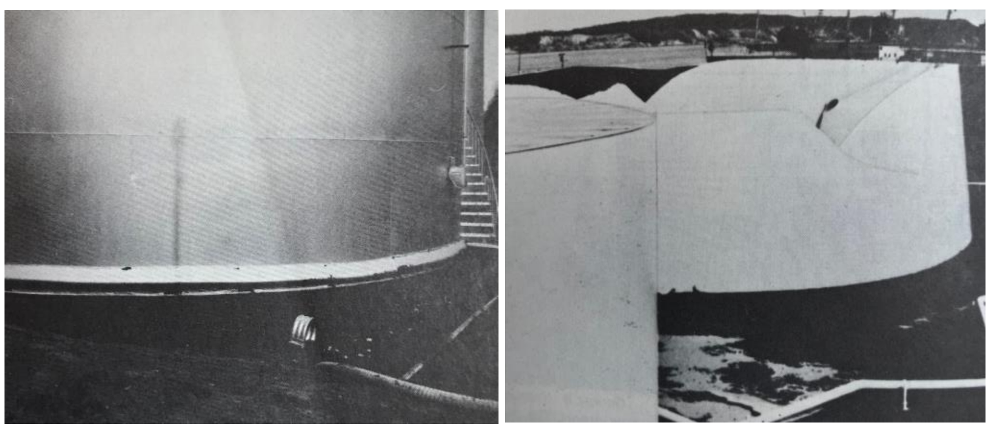

Figure 2: Elephant Foot Buckling (left) and Roof Collapse (right) following 1964 Great Alaskan Earthquake (Hanson 1973)

In 1978, a magnitude M7.4 earthquake occurred of the east coast of Japan with the epicenter approximately 95 km to 120 km from several oil storage or refineries. The peak ground acceleration near Sendai City was thought to have exceeded 0.25 g. The complex of over 87 fixed and floating roof tanks containing various petroleum products was constructed in 1971 and had been designed with reasonable seismic criteria. All piping as well as the tanks were anchored, where the tank anchors were located around the perimeter and embedded into a concrete pad (NBS 1980). Stretched anchor bolts indicated that tank uplift was limited to approximately 6 inches. Three crude oil tanks failed and the contents spilled. The tanks were surrounded by a reinforced concrete dike, but the volume of spilled oil exceed the capacity of the dike and the oil escaped as shown by the dark areas in Figure 3. The top of the fixed roof tank buckled inward due to low pressure caused by rapid evacuation of the oil through the ruptured connection of the base and wall of the tank. While containment areas in the form of dikes or walls are common, the consequence of failure of fuel storage tanks can extend beyond these containment areas due to overtopping following multiple tank failures or due to potential earthquake damage to the walls themselves.

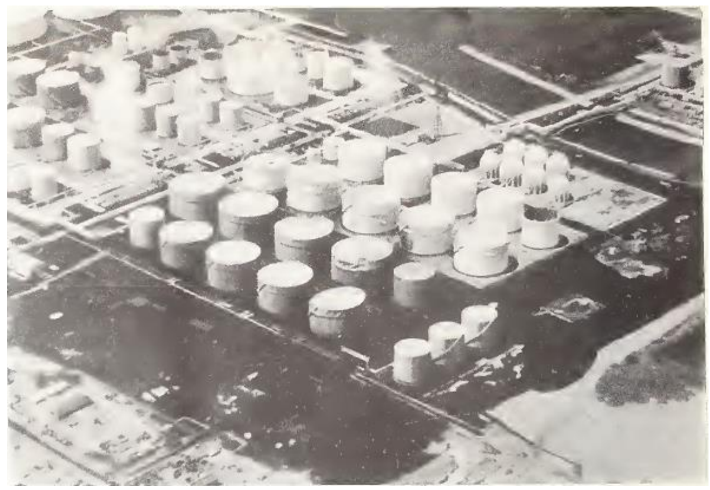

Figure 3: Spilled Oil Past the Containment Dikes following 1978 Earthquake in Japan (NBS 1980)

SOIL INDUCED DAMAGE

There are two major aspects of soil behavior during an earthquake that can influence the overall damage to the fuel storage tanks; amplification and liquefaction. Amplification of the ground motion has been recognized and documented for soft soils in numerous earthquakes, including the iconic 1985 Mexico City and 1989 Loma Prieta. The resulting accelerations manifest in the severity of the above discussed structural damage. Liquefaction of the ground on the other hand, can result in additional damage that is related to permanent settlement of the ground or to lateral soil movement referred to as lateral spreading.

The Great Alaskan earthquake of 1964 resulted in numerous examples of damage caused by liquefaction. Another 1964 earthquake occurred in Japan and was a magnitude 7.6 near the city of Niigata. Two oil refineries were located near a river and had liquid fuel storage tanks built on loose sandy ground. Settlements due to liquefaction were observed to be 8 to 12 inches on compacted ground and up to 20 inches of unequal settlement in uncompacted sand. These resulted in many damaged tanks in both refineries. In contrast, newly built tanks constructed on compacted soil at the refineries settled uniformly, and approximately 1 in. These tanks exhibited minimal to no damage and remained operational, while surrounding tanks were severely damaged from large ground settlement (Watanabe 1966).

Liquefaction induced lateral spreading can move entire tanks or cause relative ground deformations of the tank. During the 2011 Tohoku subduction zone earthquake, surrounding soil spread and caused uplift on the side of a tank of approximately 20 inches, resulting in the tank cracking and the contents leaking out (Zama et al 2012). An example of tank settlement and of lateral spreading induced uplift is photographed in Figure 4. In addition to damaging the tank itself, liquefaction can sever I/O connectivity. These examples underscore that minimizing the effects of liquefaction can minimize the risk of damage to liquid fuel storage facilities.

Figure 4: Liquefaction Induced Settlement following 1964 Niigata and 2011 Tohoku Earthquakes in Japan (Watanabe 1966, Zama et al 2012)

FIRE

While fire can be thought of as a secondary effect resulting from the damage caused by the earthquake, it is particularly relevant given the volatile contents of the tanks. Numerous instances of fires at liquid fuel storage facilities following an earthquake have been reported, with examples provided in Figure 5. Approximately 37 miles from the epicenter of the Great Alaskan earthquake, oil storage tanks were constructed in the port city of Whittier on fill that consisted of delta deposits and glacial outwash. All of the storage tanks were completely destroyed by a fire that broke out and burned for three days. The fire, and subsequent tsunami, destroyed the evidence and the cause of the fire was never determined. Two possible causes included a live power line that was snapped during the earthquake, or fuel from a leaking tank could have spilled into an operating boiler (Kachadoorian, 1965).

A refinery was located approximately 19 km from the epicenter of magnitude 7.4 earthquake near Istanbul, Turkey. Constructed in 1961 and expanded in 1974 and

1983, the facility had a large tank farm with over 100 unanchored, aboveground liquid storage tanks. The tanks were designed by American contractors adhering to seismic design code of California in 1961 (Sezen & Whittaker 2004). The damage at the refinery is thought to have been largely overlooked due to the extensive damage in more populated areas. The majority of the damage was caused by a fire that was ignited by sparks created from the collision of a metallic floating roof seal against the tank wall. The tanks contained naphtha, a highly volatile and flammable petroleum product. A total of 6 tanks of diameter 33ft to 82 ft, completely burned down. The fire spread to other tanks and 30 of the 45 floating roof tanks were damaged (Yazici and Cili 2008). More recent examples of fire at fuel storage was also observed in 2011 Tohoku, Japan in different refineries built in 1963 and 1971. The fire was attributed in different instances to damage to the tanks themselves or to leaks in the surrounding pipes. In these examples, fire remains a threat to fuel storage facilities despite construction practices that had at least some awareness of the associated earthquake risk.

Figure 5: Fire Caused by Tank Damage following 1999 Turkey (left) and 2011 Tohoku Earthquakes (right) (French Ministry of Ecology, Sustainable Development and Energy, 2013)

LIQUID FUEL STORAGE TANKS AT THE CEI HUB

OPERATING COMPANIES

While the CEI Hub is generally referred to as a singular area, the liquid storage tanks are actually clustered in a few distinct locations and are owned by different operating companies. Map with relative locations of the various companies between U.S. Route 30 and the Willamette River is shown in Figure 6. The majority of the fuel storage facilities are either near the Linnton neighborhood to the north or within the Northwest Industrial Area to the south.

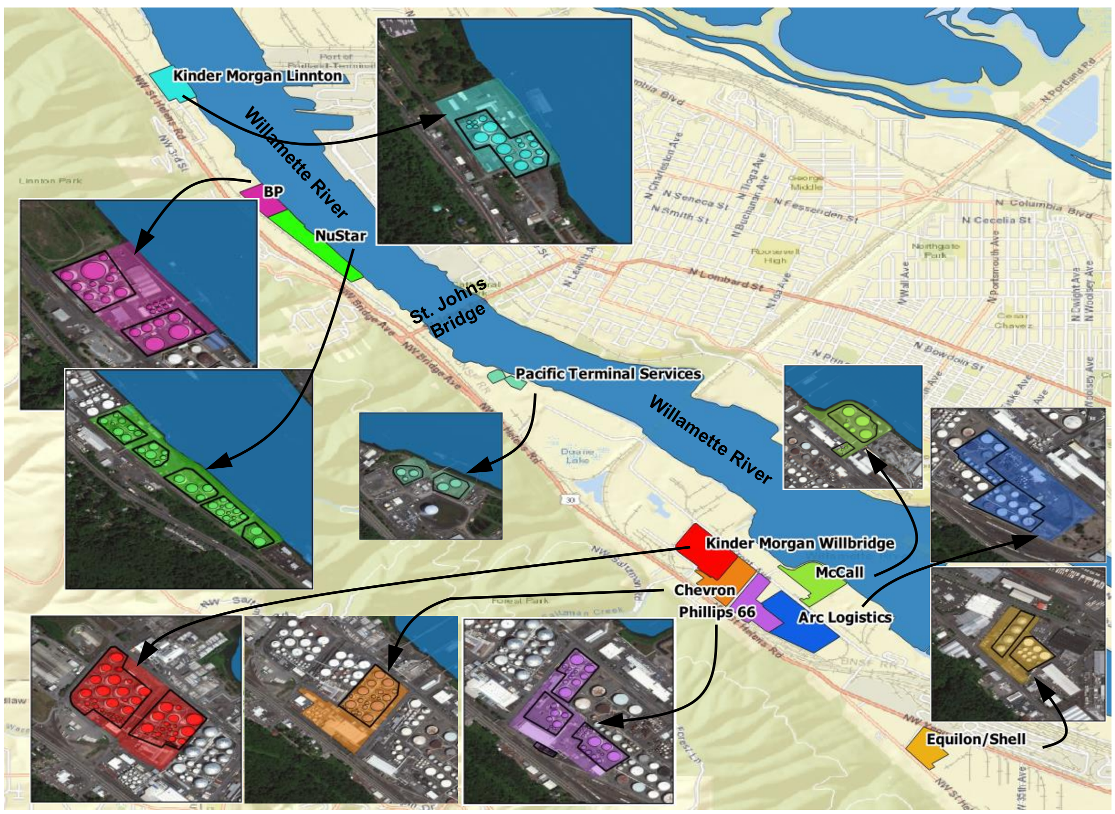

Figure 6: Companies with Liquid Fuel Facilities at the CEI Hub (background Google Maps)

The petroleum storage tank owners are required to submit an oil spill contingency plan to the Department of Environmental Quality (DEQ). In 2015 Oregon Public Broadcasting (OPB) made a public records request and attained records from seven owners of liquid fuel storage tanks (Schick 2015). These included BP, Chevron, Kinder Morgan, McCall, NuStar, Pacific Terminal Services and Phillips 66. Further queries into the City of Portland permits database indicated that no additional fuel storage tanks were constructed since 2015, making the data set relevant to date. In addition to this dataset, two additional companies were identified through review of The City of Portland Bureau of Planning and Sustainability documentation from 2016 (Bureau of Planning and Sustainability 2016). These companies were Arc Logistics and Shell/Equilon.

In all, there were 10 properties with liquid fuel storage tanks, owned by 9 different companies. Within each property, large tanks appear to be collocated within shared secondary containment areas that are built to contain potential spillage or leaks. These containment areas are typically intended to contain the volume of the largest tank in the group and are constructed using soil dikes or structural walls. No data was found related to the secondary containment aspect of the facilities in any of the properties, so the areas were manually traced and acreage calculated based on satellite imagery. The resulting tank locations and associated containment areas are depicted in Figure 6 via zoomed in details for each property. The acreage and the number of storage tanks are summarized in Table 2 for each company. To help parse the data when available, the tanks were grouped into tank diameters that were 25 ft and larger or smaller than 25 ft.

Table 2: Total Area and Fuel Storage Overview

Company	**Site Area** (acres)	**Secondary Containment** No.	(acres)	**No. of Storage Tanks** ≥ 25ft	< 25ft	**Tank Capacity** (million Gallons) ≥ 25ft	< 25ft
Kinder Morgan							
Linnton Terminal	13	1	5.5	19	14	20.4	0.3
Willbridge Terminal	33	2	17.0	46	88	70.0	1.5
BP	18	2	5.6	26	6	23.9	0.0
NuStar	22	5	11.8	31	4	53.4	0.1
Pacific Terminal Services	2	2	3.2	5	2	11.6	0.0
Chevron	21	1	8.5	35	109	47.4	3.0
Phillips 66	21	4	10.8	36	61	29.3	1.1
McCall	19	2	10.0	10	16	40.0	0.5
Arc Logistics	39	2	14.0	25		61.6	
Equilon/Shell	38	2	6.8	13		16.8	

Tank Type and Quantity

The records for seven of the companies list a total of 514 tanks, of which 146 were tagged to be out-of-service (O.O.S). While it is unclear if O.O.S. tanks could be brought back to service, examination of aerial photographs of some of the known locations of large O.O.S. tanks show visual signs of tank deterioration that make that possibility less likely. The data for each tank include the storage capacity, substance, and year built for each tank. Tank type is also included, although this identification is not consistent across the different companies.

Phillips 66 reported container type as welded or riveted steel while the others reported container type by the roof characteristics (e.g. floating roof, fixed roof, cone roof, vertical fixed roof). There were no tank details available for Shell/Equilon and Arc Logistics, so the additional 38 tanks were estimated from satellite imagery. The number of tanks breakdown along with the fuel storage capacity for each of the companies is summarized in Figure 7. Given that floating roof tanks can exhibit different dynamic behavior to fixed roof under earthquake motion, the tank types are differentiated where known.

Discounting the O.O.S. tanks, there are at least 362 tanks with a total capacity of 8.64 million barrels (362.9 million gallons) of liquid product of various types. Despite approximately 40% of the tanks being 25 ft in diameter or larger, they can hold over 95% of the total volume capacity. The total volume is not present on site at any given time because the tanks are not always full. The average fill varies, nonetheless there is a significant amount of liquid fuel products stored in above ground storage tanks at the CEI Hub. There also appear to be a wide spectrum of tank types. The tank construction includes riveted and welded, as well as fixed and floating roof. The variability in construction and tank type make relevant all of the aforementioned structural damage vulnerabilities exposed by past earthquakes.

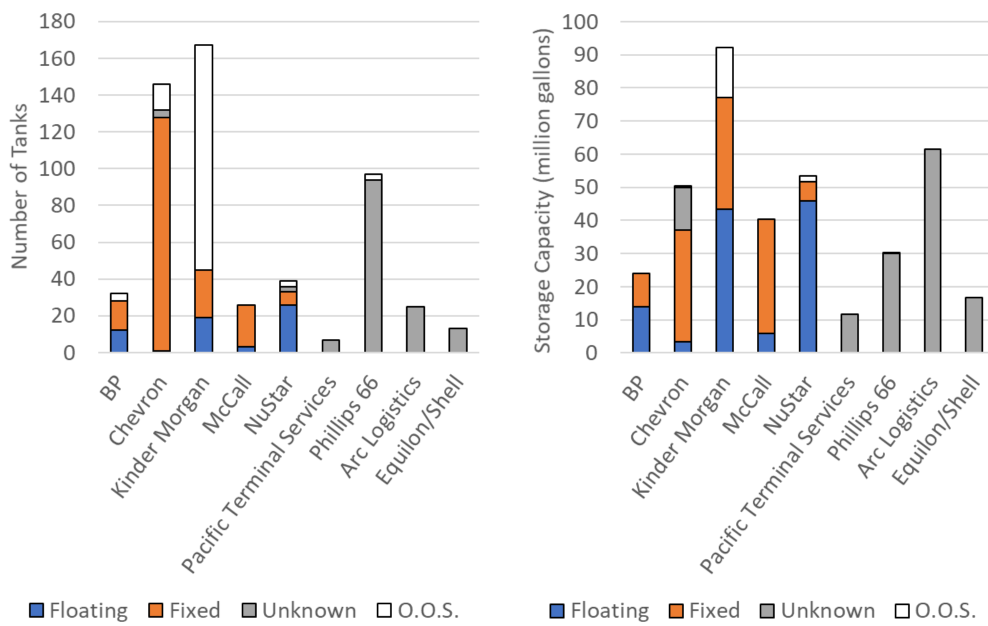

Figure 7: Number of Tanks (left) and Total Storage Capacity (right) by Company

Tank Age and Size

Knowledge about a seismic hazard evolves over time. In Oregon, our understanding of the threat of the looming Cascadia Subduction Zone (CSZ) has only come to light in the last 20 years. Design standards follow and therefore the age of any structure is often a strong indicator of the potential vulnerability. To get a sense of the age of the tank inventory at the CEI Hub, the tank age is summarized in Figure 8 by showing the number of in-operation storage tanks built within a particular decade. Within each decade, the number of tanks are binned by the tank diameter in increments of 20 ft. This allows for a visual representation of the physical size of the tank and indirectly the volume of fuel capacity. The tank diameters were only provided for approximately half of the tanks. Regression model based on the tank volume and the known tank diameters was developed and used to estimate the tanks for which diameters information was not available.

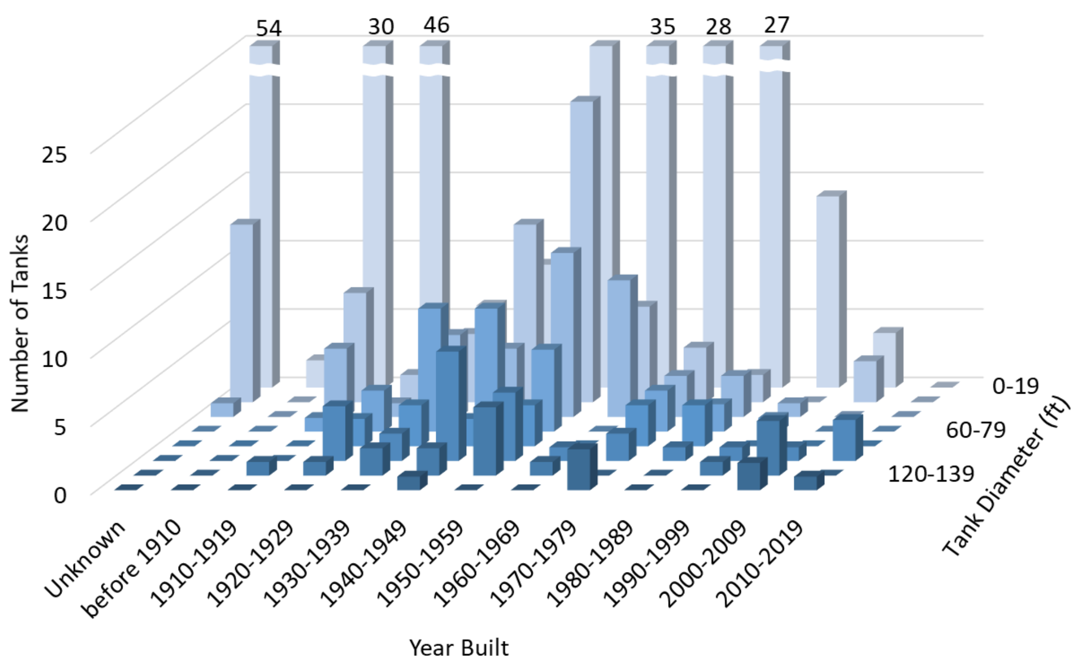

Figure 8: Distribution of In-operation Tank Age and Size

There are numerous in-service large tanks built prior to 1930s. Most significantly, majority of the tanks and majority of the fuel capacity within the hub has been built prior to 1960s. Even if the designers were fully aware of the seismic hazard, this time frame is prior to any design and performance lessons learned from the damaging Great Alaskan earthquake of 1964 and the many other documented earthquakes that followed. The next construction active period in the CEI hub spanned 1970s-1980s, with only a few large tanks built in the last couple of decades.

The industry standard for the design of petroleum storage tanks is published by the American Petroleum Institute (API); API Standard 650 establishes the minimum design requirements for welded tanks. It is unclear what standards were used for the design of the tanks as the City of Portland had not been overseeing these non-building structures. Even so, the seismic load requirements in Portland have significantly increased for buildings during the 1990s, reflecting the state of science of the regions seismicity. Regardless of the design standards followed, the vast majority of the tanks were constructed with minimal, if any, considerations of seismic loading given their vintage.

SOIL CHARACTERIZATION

Detailed subsurface information at CEI hub in general is very limited. Based on the available information, loose to medium dense silty sand lie below the groundwater table and the soil is susceptible to liquefaction (Beaty et al 2014). There is also a possibility of landslides from the nearby slope entering the area. Raster data that included permanent ground deformations from liquefaction was made available by the Oregon Department of Geology and Mineral Industries (DOGAMI 2012) and was overlaid on the fuel storage facilities as shown in Figure 9. Because of the proximity to the river, the permanent ground deformations due to liquefaction and lateral spreading is expected to be very high at all fuel storage tank locations. The underlying raster data is a high level assessment and serves only as an indicator for liquefaction risk at any particular location within the hub. More detailed geotechnical assessment would be needed to quantify the severity, nonetheless, liquefaction clearly poses a significant risk for all of the liquid fuel tanks in the CEI Hub. If left unmitigated, the seismically induced damage observed in past earthquakes is likely to manifest.

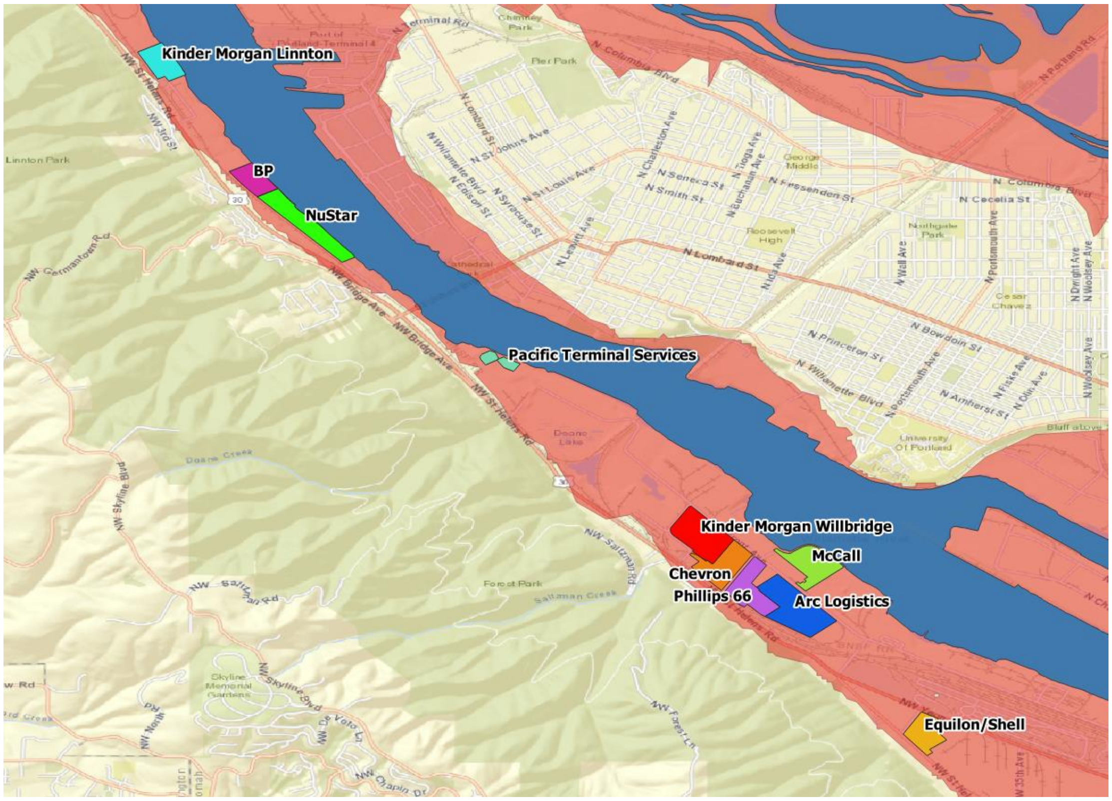

Figure 9: Areas of High Permanent Ground Deformations (shaded red) following CSZ Earthquake (background Google Maps)

POTENTIAL SEISMIC HAZARD MITIGATIONS

SEISMIC HAZARD

Factors contributing to seismic performance of above ground storage tanks include the amount of shaking, the existence of anchorage, subsurface soil condition and the amount filled at the time of the earthquake. The amount of shaking relates to the seismic risk characteristics and for Portland and Oregon, the CSZ is one of the more significant considerations. The expected severity of the shaking is represented by the 5% critically damped spectral acceleration plot in Figure 10 and includes a probabilistic hazard of a 500 year return and 1000 year return earthquake as well as the anticipated full rupture of the CSZ. These values consider the location of the CEI hub relative to the earthquake as well as a relatively soft soil (Vs_{30}=270 m/s). The expected accelerations ranging between 0.2g and 0.56g are well within the range of accelerations where structural tank damage as well as soil liquefaction were reported in past earthquakes. The level of shaking is therefore expected to be significant and have the potential to cause damage or failure to vulnerable fuel storage tanks.

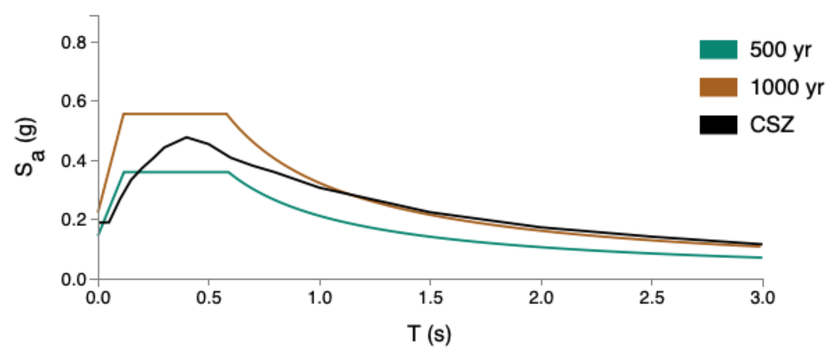

Figure 10: Spectral Acceleration for Portland's CEI Hub

The stresses generated on the tank can be correlated to the amount of fuel in the tank. Performance during past earthquakes have indicated a lower susceptibility to damage for tanks that are partially filled. One potential mitigation of the risk of damage can therefore employ practices that at maximum only partially fill any vulnerable tank.

STRUCTURAL MITIGATION

The large diameter fuel storage tanks are typically above-ground and constructed with flexible floors and steel perimeter shell that is supported on a reinforced concrete ring foundation. Smaller diameter tanks are likely to be supported by a reinforced concrete slab on grade. In either case, anchorage for the tanks have the potential to limit or minimize the uplift of the walls of the tank as the liquid imposes stresses on the tank walls. Effectiveness of anchoring storage tanks has been demonstrated in past earthquakes and would most likely be implemented for any new tank construction. Tanks in the CEI hub are unlikely to be anchored and would need to be retrofitted. As with most seismic retrofit cases, mitigating existing structures is more challenging than starting with a blank site. The anchorage would need to be implemented around the perimeter, connecting the steel shell with the foundation. The details of the connectivity will need to be evaluated depending on the individual tank as additional challenges may arise from having the ability to attach to the tank wall or the foundation. Issues with welding ranging from the steel vintage to shell thickness need to evaluated as is the ability of the foundation to resist the anchorage forces.

SOIL MITIGATION

For storage tanks located further away from the edge of the river, lateral spreading may not necessarily be as great a concern. However, liquefaction settlement and bearing capacity failures could result in damage to the tanks. To mitigate liquefaction settlement, the ring foundations could be mitigated by installing sheet piles or compaction grout columns around the perimeter. Sheet piling consists of installing steel interlocking sheets around the perimeter. Compaction grouting displaces and densifies loose granular soils by staged injection of fluid grout. These sub surface columns would support the tank shell and potentially the I/O connections, but the centers of the tanks could still settle. Site specific studies would be necessary to assess the differential.

To mitigate lateral spreading in addition to settlement, jet grout columns could be installed under the tanks. Jet grouting is a hydrodynamic jet process that breaks up and loosen the ground, and mixes fluid grout with the soil. The jet grouting can be inserted at an angle, potentially reaching and mitigating soil under the tank as well as the perimeter. For large diameter tanks the jet grouting might require the tanks to be drained and cut open so that low-overhead equipment can work from within the tank.

Alternatively and less conventionally, instead of treating the soil, the water table could be lowered because without water, no liquefaction of the soil can occur. An example of this was implemented in three sites in Japan in 1970s. Underground cutoff wall was constructed using the slurry wall technique with soil/bentonite backfill. The cutoff wall surrounded a group of tanks and the water table was lowered. The refinery reported that these tanks had no damage after the 2011 Tohoku Earthquake.

Conceptual Estimation of Seismic Mitigation Costs

In order to get a sense of the magnitude of costs required to mitigate the major vulnerabilities of the liquid fuel storage tanks at the CEI hub, a high level cost estimation was made based on the tank data available. Three components of the mitigation costs were estimated; soil mitigation, structural anchoring and associated design/permitting. These were estimated as follows:

- Soil mitigation – in order to address both liquefaction induced settlement as well as lateral spreading, jet grouting was selected for estimating the cost. Jet grouting estimates were obtained from one of the major national geotechnical construction contractors. The calculated cost include an initial mobilization of $100K/tank plus the cost of the grouting procedure. While economies of scale could be employed to lower the mobilization costs, there is much uncertainty at this conceptual stage to be fine-tuned. The grouting procedure costs were estimated at $400/cubic yard of grout, 35% grouted mixing for 40ft depth under the entire area of the tank. This cost was calculated for each 25ft diameter or larger tank, each rounded to the nearest $100K. The resulting cost aims to represent the material and labor cost of soil mitigation implementation for the larger tanks.

- Tank anchoring – as an initial estimate, mobilization cost of $50K/tank was used plus an additional $1K/ft of the tank perimeter. This cost was calculated for each 25ft diameter or larger tank, each rounded to the nearest $100K. The resulting cost aims to represent the material and labor cost of implementation for the larger tanks.

- Design and permitting – in order to implement the above mitigation, engineering assessment, design and permitting needs to be conducted. This cost was simply estimated as 10% percent of the total cost for both soil and structural mitigation implementation combined.

The calculated cost is summarized in Figure 11. Values are separated for floating tanks and other because floating tanks on average have larger diameters and at a future date could also include the cost of installation of fire suppression measures, which at this time were not estimated. The total cost for implementing these conceptual mitigation measures to storage tanks of 25 ft diameter and larger is estimated to exceed $300 million. Over one third of the cost is for floating roof tanks alone. Unsurprisingly, the cost of soil remediation dominates the overall cost for all tanks, especially for floating roof tanks that tend to have a higher ratio of area to perimeter given their general larger size. The cost of mitigating storage tanks smaller than 25 ft in diameter is expected to only incrementally add to the overall cost as the mitigation measures would more likely be associated with structural anchoring rather than deep soil mitigation.

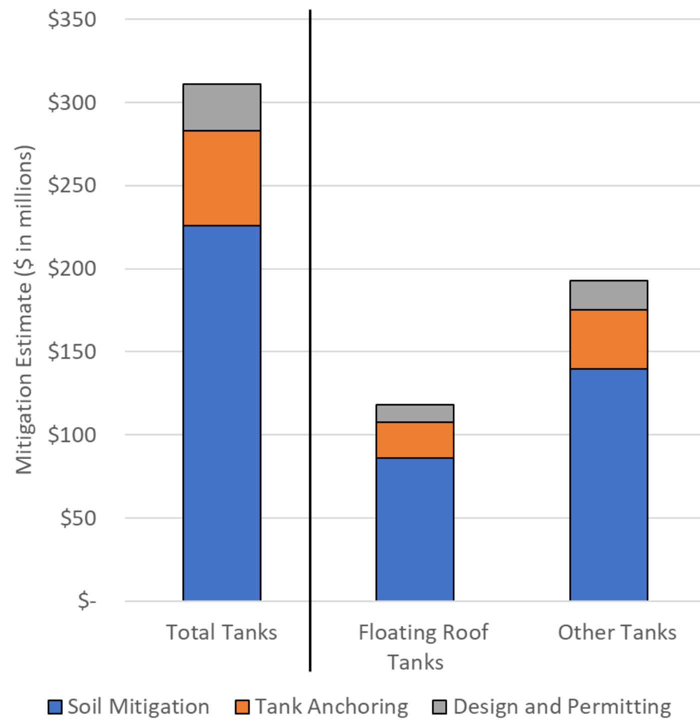

Figure 11: Conceptual Seismic Mitigation Cost Estimates for Tanks 25ft in Diameter and Larger

The conceptual cost estimate was intended as a first pass order of magnitude number for mitigating the damage and failure of only the tanks. No cost consideration was given to maintaining integrity of the fuel distribution system, support mechanical systems, secondary containment areas or the shore terminals that are also located on the site. And, the aim of the remediation measures for the tanks was to minimize the potential for failure that would result in loss of fuel. Much more detailed analyses would need to be conducted to estimate each property ability to operate following a major earthquake event.

RECOMMENDATIONS FOR NEXT STEPS

This study provided a closer look at the seismic vulnerability of the CEI hub by assessing more quantitatively the available inventory of fuel storage tanks at the site. The recommended next steps aim to build on this work to fill information gaps and generate new critical knowledge with the overarching goal of quantifiable assessment and mitigation of seismic risk.

- Develop seismic performance criteria for storage tanks at the CEI hub:

  The philosophy behind majority of design standards and codes is to prevent catastrophic failure. Given the criticality of the fuel, specific seismic performance criteria for the storage tanks in the CEI hub need to be developed. The criteria need to address the input earthquake motion as well as the desired output performance goals, such as tank collapse, prevention of leakage, access to fuel or continued operations. Having established criteria will provide basis for evaluation and eventual design. The decisions made in establishing the criteria can significantly affect the mitigation costs and if adhered to, the associated performance level of post-earthquake performance.

- Quantify tank seismic fragility:

  Seismic fragility describes the anticipated performance for a particular ground motion input parameter. For example, the potential for tank wall collapse given the earthquake peak ground acceleration. Limited literature exists on the topic, quantifying liquid storage tank fragility difficult. To address this shortcoming, archetype tanks should be defined that represent different storage sizes, roof types, structural as well as soil characteristics. Numerical models of the archetypes need to be analyzed to determine their seismic fragility. This new knowledge would be used to inform the seismic loss assessment process and provide a tool to quantify the effectiveness of particular mitigation measures. For example, the amount of fuel fill in the tank can be used as a variable in the analyses to determine the seismic performance benefit gained by lowering the amount of fuel stored. The fragility is useful on individual tank basis, can be applied across the tank inventory and can be used to better understand cost/benefit.

- Investigate mitigation options for fuel distribution:

  The focus of the study has been on the storage tank inventory, but aspects related to connectivity and distribution of the fuel are also important. Pipelines, support mechanical systems and access terminals need to be better understood, existing condition assessed and mitigation options investigated.

- Conduct subsurface geotechnical investigations:

  All of the sites are located close to the river and have been generally identified as susceptible to liquefaction. Detail survey of the properties of the soil at depth are needed. This information could then be used to estimate soil amplification of ground motion, the amount of settlement as well as lateral spread from liquefaction, and be used to refine the cost of the extent of the soil remediation required.

- Obtain detailed structural tank information:

  The current tank data set is incomplete and basic information that was inferred needs to obtained, including missing tank diameters, tank roof types and physical locations. Additional structural data currently not available needs to be gathered. Details of existing foundation size, tank to foundation anchorage, tank wall thickness, roof support and I/O connectivity. Some of this information can be gathered through site visits while other would require more direct tank owner cooperation.

- Prioritize fuel storage tanks:

  From the hundreds of tanks identified, certain types of fuel and certain size of tanks are likely to be more critical to post-earthquake recovery than others. Prioritization of the tanks based on post-earthquake needs and consequences of failure should be conducted. Having prioritized tanks would help focus the associated assessment and mitigation efforts.

REFERENCES

Beaty, M., Schlechter, S., Greenfield, M., Bock, J., Dickenson, S., Kempner, L., and Cook, K. (2014). Seismic evaluation of transmission tower foundations at river crossing in the Portland-Columbia River region, 10th National Conference on Earthquake Engineering.

Bureau of Planning and Sustainability (2012). Portland Local Energy Assurance Plan. Portland: City of Portland.

Bureau of Planning and Sustainability (2016). Fossil Fuel Terminal Zoning Amendments. Portland: City of Portland.

City Club of Portland (2017). Big Steps Before the Big One: How the Portland area can bounce back after a major earthquake. City Club of Portland Bulletin, Vol. 99, No. 2.

Cooper, T. W. (1997). A Study of the Performance of Petroleum Storage Tanks During Earthquakes, 1933-1995. Gaithersburg: National Institute of Standards and Technology.

DOGAMI (Oregon Department of Geology and Mineral Industries) (2012). Earthquake Risk Study for Oregon's Critical Energy Infrastructure Hub.

French Ministry of Ecology, Sustainable Development and Energy. (2013). Overview of the Industrial Accidents Caused by the Great Tohoku Earthquake and Tsunami. Lyon: Bureau for analysis of industrial risks and pollution.

Hanson, R. D. (1973). Behavior of liquid-storage tanks. In The great Alaska earthquake of 1964 - Engineering (pp. 331-339). Washington: National Academy of Sciences.

Housner, G. W. (1952). Intensity of Ground Motion During Strong Earthquakes. Office of Naval Research.

Kachadoorian, R. (1965). Effects of the earthquake of March 27, 1964 at Whittier, Alaska. 1965: United States Government Printing Office.

NBS (National Bureau of Standards) (1980). An investigation of the Miyagi-ken-oki, Japan, earthquake of June 12 1978. Washington: United States Government Printing Office.

OSSPAC (Oregon Seismic Safety Policy Advisory Commission) (2013). The Oregon Resilience Plan Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami, Report to 77th Legislative Assembly.

Nielsen, R., & Kiremidjian, A. S. (1986). Damage to Oil Refineries from Major Earthquakes. Journal of Structural Engineering, 112(6), 1781-1491.

Rinne, J. E. (1967). Oil storage tanks. In The Prince William Sound, Alaska Earthquake of 1964 and Aftershocks (pp. 245-252). US Department of Commerce Environmental Science Service Administration.

Schick, T. (2015). How We Mapped NW Portland's 'Tank Farms'. Oregon Public Broadcasting.

Sezen, H., & Whittaker, A. S. (2004). Performance of Industrial Facilities During the 1999, Kocaeli, Turkey Earthquake. World Conference on Earthquake Engineering. Vancouver.

Watanabe, T. (1966). Damage to Oil Refinery Plants and a Building on Compacted Ground by the Niigata Earthquake and Their Restoration. Japanese Geotechnical Society Journal of Soils and Foundations, 6(2), 86-99.

Yazici, G., & Cili, F. (2008). Evaluation of the Liquid Storage Tank Failures in the 1999 Kocaeli Earthquake. World Conference on Earthquake Engineering. Beijing: Research Gate.

Zama, S., Nishi, H., Hatayoma, K., Yamada, M., Yoshihara, H., & Ogawa, Y. (2012). On Damage of Oil Storage Tanks due to the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), Japan. World Conference on Earthquake Engineering, 15. Lisboa.