BEFORE THE STATE OF WASHINGTON
ENERGY FACILITY SITE EVALUATION COUNCIL

In the Matter of: Application No. 2013-01 TESORO SAVAGE, LLC VANCOUVER ENERGY DISTRIBUTION TERMINAL	)))))))))	CASE NO. 15-001 WRITTEN DIRECT TESTIMONY OF JOSEPH WARTMAN, PH.D.

I. INTRODUCTION AND QUALIFICATIONS

1. I am currently an Associate Professor in the Department of Civil and Environmental Engineering at the University of Washington. I am Emeritus Editor of the American Society of Civil Engineers' (ASCE) *Journal of Geotechnical and Geoenvironmental Engineering*, which is among the most respected scholarly journal in my field. I have been the recipient of several international and national research honors including Commendation (as International Expert to Port Hills Response Group) from the New Zealand Society of Earthquake Engineering in 2014, selection for the U.S. National Academy of Engineering Frontiers of Engineering Program in 2011, and the 2011 Prakash Foundation Research Award. I have authored or co-authored over 70 professional articles on the topics of geotechnical engineering, earthquake engineering, natural hazards, and environmental geotechnics. I have participated in several field investigations of large-scale disasters including major earthquakes in Latin America (2001 Magnitude 8.4, Southern Peru; 2003 Magnitude 7.6, Tecoman, Mexico; 2007 Magnitude

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8.0, Pisco, Peru) and Asia (2011 Magnitude 9.0, Tōhoku, Japan), and Hurricane Katrina in New Orleans (2005).

2. Prior to my career in academia, I was a full-time engineer for five years, most recently as a licensed Professional Engineer and project manager for Golder Associates in Oakland, California. Prior to joining the University of Washington, I was an Associate Professor at Drexel University, where I served as a founding co-director of the *Engineering Cities* Initiative, a multi-disciplinary urban systems research center at Drexel. At the University of Washington and previously at Drexel University, I have taught courses on geotechnical engineering, geologic hazards, engineering geology, and earthquake engineering.

3. I was awarded a B.C.E. degree from Villanova University in 1990, and later pursued graduate studies at the University of California, Berkeley, where I earned two master degrees (M.S. in Geotechnical Engineering, M.Eng. in Civil Engineering; both in 1996) and my Ph.D. in Civil Engineering in 1999. My curriculum vitae is attached to this testimony.

4. I first became aware of plans to build crude-by-rail oil shipping terminals in Washington in 2013, when I provided an expert critique of plans for two crude oil terminals in Hoquiam, Washington. I again reviewed these projects in 2015 and provided a report for submission with comments on draft environmental impact statements. I have also reviewed the draft environmental impact statement (DEIS) for the Tesoro-Savage proposal; my report on Tesoro-Savage was submitted with comments by intervenors Columbia Riverkeeper *et al.*

5. In preparation for this testimony, I reviewed several project-specific documents, including (i) Application for Site Certification Agreement, (ii) Geotechnical Investigation report prepared by GRI, (iii) DEIS, and (iv) Vancouver Energy's (Mr. Kelly Flint) correspondence to the Energy Facility Site Evaluation Council dated January 22, 2015. I additionally referenced a

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series of relevant professional and scholarly books, reports, and articles, many of which are cited in this testimony. These books and articles are recognized in the professional community and are considered reliable by other experts in my field. Finally, I have relied upon my 20+ years of professional and research experience in the field of civil engineering (including the field investigations of several major earthquakes) when formulating the opinions in this testimony.

II. SUMMARY OF EXPERT OPINIONS

6. My opinions on the geologic hazards for the proposed Tesoro-Savage project may be summarized as follows:

- The Tesoro-Savage project is located in a seismically active region where there is a high likelihood of a large earthquake occurring during the operation of the facility. The United States Geological Survey (USGS) estimated that there is a ~15% chance that a "Great" Cascadia subduction earthquake (Magnitude 8 or greater) will affect the region within the next 50 years. [For design purposes, standard building codes typically assume that facilities will remain functional for a 50-year "life." In reality, facilities are in effect permanent and typically remain in place and functional for much longer time periods.]
- Seismic hazard analyses indicate that the design standard peak ground acceleration (PGA) [~0.42g] at the site is high enough to potentially cause significant damage to industrial port facilities and components.
- Because of the complex nature of the industrial facility and the storing and handling of a large quantity of hazardous materials, the Tesoro-Savage project is a special proposal that requires careful assessment and scrutiny to ensure the safety of the local community and environment.

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- A major seismic event could cause Tesoro-Savage's systems to fail and cause catastrophic environmental impacts. Seismic impacts could include the failure of the tanks, connectors, pipelines, and/or containment systems, releasing oil into the environment. The project site is highly susceptible to soil liquefaction, which commonly results in ground failure-induced damage to buildings, tanks, retaining structures, utilities, and other critical components at ports. Liquefaction is expected to cause substantial and permanent deformation of the ground surface, which is likely to damage to system components (including associated environmental containment structures).
- Important deficiencies have been found with the Tesoro-Savage project seismic mitigation plan. Even if this plan is modified or enhanced, it should be recognized that there are no mitigation measures capable of completely mitigating geologic risks at the facility.
- Overall, the geologic hazards at the Tesoro-Savage project together with the potentially severe consequences of failure combine in a manner that poses a significant risk to the public and the environment.

III. SEISMICITY AND SEISMIC HAZARDS AT THE PORT OF VANCOUVER

7. A megathrust earthquake on the Cascadia subduction zone is a primary geologic hazard that poses the greatest threat at the Port of Vancouver (Figure 1). The Cascadia subduction zone spans a 1,100 km (680 mile) coastal stretch between Vancouver Island, British Columbia and Cape Mendocino, California (Figure 1). The Juan de Fuca tectonic plate is subducting beneath the North American Plate at a rate of approximately 4 centimeters per year (Riddihough 1984). Satellite measurements show that the offshore portion of this megathrust is now "locked" along the entire length of the subduction zone (McCaffrey et al. 1984), and it is progressively accumulating tectonic stress and strain that will be released during a large

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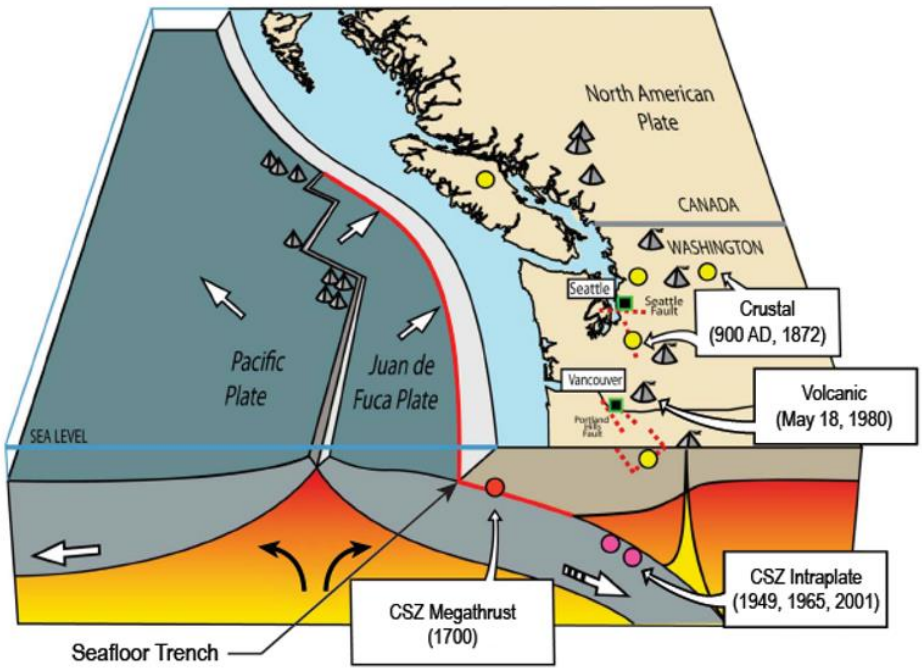
magnitude (i.e., Magnitude 8 to 9) earthquake at some time in the future. It is now well established that the Pacific Northwest has a long history (at least many thousands of years) of repeated "characteristic" Magnitude 8 to Magnitude 9 megathrust earthquakes along the Cascadia subduction zone (e.g. Atwater et al. 2005, Goldfinger et al. 2012). The last great megathrust earthquake, which occurred on January 26, 1700, was estimated to be in the range of Magnitude 8.7 to Magnitude 9.2 (Satake et al. 2003). This megathrust earthquake produced a tsunami that caused damage and loss of life as far away as Japan (Atwater et al. 2005).



Modified from: USGS Cascadia Earthquake Sources (http://geomaps.wr.usgs.gov/pacnw/pacnweq/casceq.html) and Figure 3.1-2 in EFSEC TSVEDT (2013)

Legend

CSZ	Cascadia Subduction Zone
····	Shallow crustal fault
⚠	Volcano
1949	Year of earthquake

Figure 1 - Tectonic setting of the Pacific Northwest (from AECOM (2015) Evaluation of seismic hazards at proposed Vancouver energy oil export terminal, Port of Vancouver, Washington)

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8. Owing to its setting within the Cascadia subduction zone, the coastal region of the Pacific Northwest is regarded as having a high level of seismic activity. For example, the United States Geologic Survey (USGS) estimated that there is a ~15% chance that a Great Cascadia subduction earthquake (Magnitude 8+) will strike the region in the next 50 years. 50 years is regarded as the typical design life of a structure or facility in the U.S. [Petersen et al. 2002]. The USGS considers this probability "quite high" (Petersen et al. 2002).

9. Seismic hazard assessments indicate that earthquakes are expected to result in a design-level peak ground acceleration (PGA) of approximately 0.42 g at the site region. The design level PGA is a measurement of ground motion that corresponds to the standard "return period" provisions of the International Building Code. It corresponds to an earthquake ground motion having a 2% chance of being exceeded in a building design life of 50 years, which equates to a return period of about 2,475 years. To provide context for this acceleration level, 0.42 g is roughly equivalent to a Modified Mercalli Earthquake Intensify scale of VIII (Wald et al. 1999), which is associated with "severe" shaking and "moderate to heavy" damage potential. Shaking at this level would be expected to result in "considerable damage in ordinary substantial buildings with partial collapse; great damage in poorly built structures; and collapse and fall of chimneys, factory stacks, columns, monuments, walls." (USGS 2016).

10. The PGA value is important since it directly represents earthquake shaking intensity and also provides an indication of an earthquake's ability to cause damage and to trigger soil liquefaction. For industrial facilities, the PGA threshold for failure of piping systems is between 0.14 g and 0.20 g, and for tanks between 0.12 and 0.27 g (i.e., significantly less than the expected PGA of 0.42 g for the project site, implying a high likelihood of damage to industrial components) [Lanzano et al. 2004]. The lower threshold for liquefaction triggering is even less:

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0.09 g (Santucci et al. 2013), which suggests a high propensity for this phenomenon to occur at the project site.

11. In addition to having a high intensity (i.e., acceleration amplitude) of shaking, Cascadia earthquake ground motions at the project site are expected to be long in duration due to the subduction system rupture mechanism. A recent example of such long-duration shaking occurred during the 2011 Magnitude 9 Tōhoku, Japan subduction earthquake, which lasted more than one and a half minutes at many locations along the coast (Wartman et al. 2013).

12. Based on this, it is my opinion that the Tesoro-Savage project site has a very high seismic hazard because it would be subject to strong ground shaking. The chance (~15%) that the facility will experience a large magnitude (Magnitude 8+) earthquake during a 50-year design life is "quite high" (Petersen et al. 2002).

IV. SOIL LIQUEFACTION HAZARD

13. The Tesoro-Savage terminal site has an extremely high susceptibility to soil liquefaction. Liquefaction is the transformation of a granular material from a solid to a liquefied state as a consequence of earthquake shaking; it is the primary cause of damage during many earthquakes (e.g. Seed et al. 2003). In a recent monograph, the Earthquake Engineering Research Institute (Idriss and Boulanger 2008) explains that liquefaction occurs in soft, saturated soil deposits because "loose sand tends to contract (densify) under cyclic loading imposed by earthquake shaking ... which results in a reduction of effective confining stress within the soil and an associated loss of strength and stiffness that contributes to deformations of the soil deposit." This strength loss and softening of soil results in deformation (i.e., permanent movement) of the ground surface and loss of support and failure of structures and industrial systems.

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14. Soil liquefaction has been repeatedly observed in many dozens of earthquakes over the past decades. Its effects are especially pronounced in subduction earthquakes due to the long duration of shaking. The effects of soil liquefaction vary based on several factors including geologic setting, soil layering, earthquake ground motion (intensity and duration), ground surface morphology (gradient and topography), and the local built environment, among others. As illustrated in Figures 2 to 4 (Seed et al. 2003), these effects have been observed to result in:

- Lateral spreading or displacement of the ground surface by translation- or flow-type movements
- Flow failures
- Translational movement
- Rotational failures
- Ground surface "spreading" and cracking
- Vertical settlement of the ground surface
- Slumping of embankments
- Loss of building foundation support (i.e., bearing capacity failure).

15. These mechanisms may result in permanent deformation of the ground surface as shown in the figures. The devastating effects of liquefaction-induced ground deformation on the built environment are well documented and has included (Idriss and Boulanger, 2008): the collapse of structures, uplift or "floating" of tanks and underground pipes, and lateral spread-induced failure of underground pilings leading to structural collapse.

16. Owing to their marine setting, port facilities are commonly underlain by soft, saturated soil deposits, which are materials well recognized as having a high susceptibility to liquefaction. This is also true for the Tesoro-Savage Project site.

17. There are three main questions that must be answered when assessing soil liquefaction (Idriss and Boulanger, 2008): (1) Will liquefaction be triggered by the design ground motions? (2) What will be the consequences for the structure or facility? (3) What are the options for mitigating the potential consequences? I address these three questions below.

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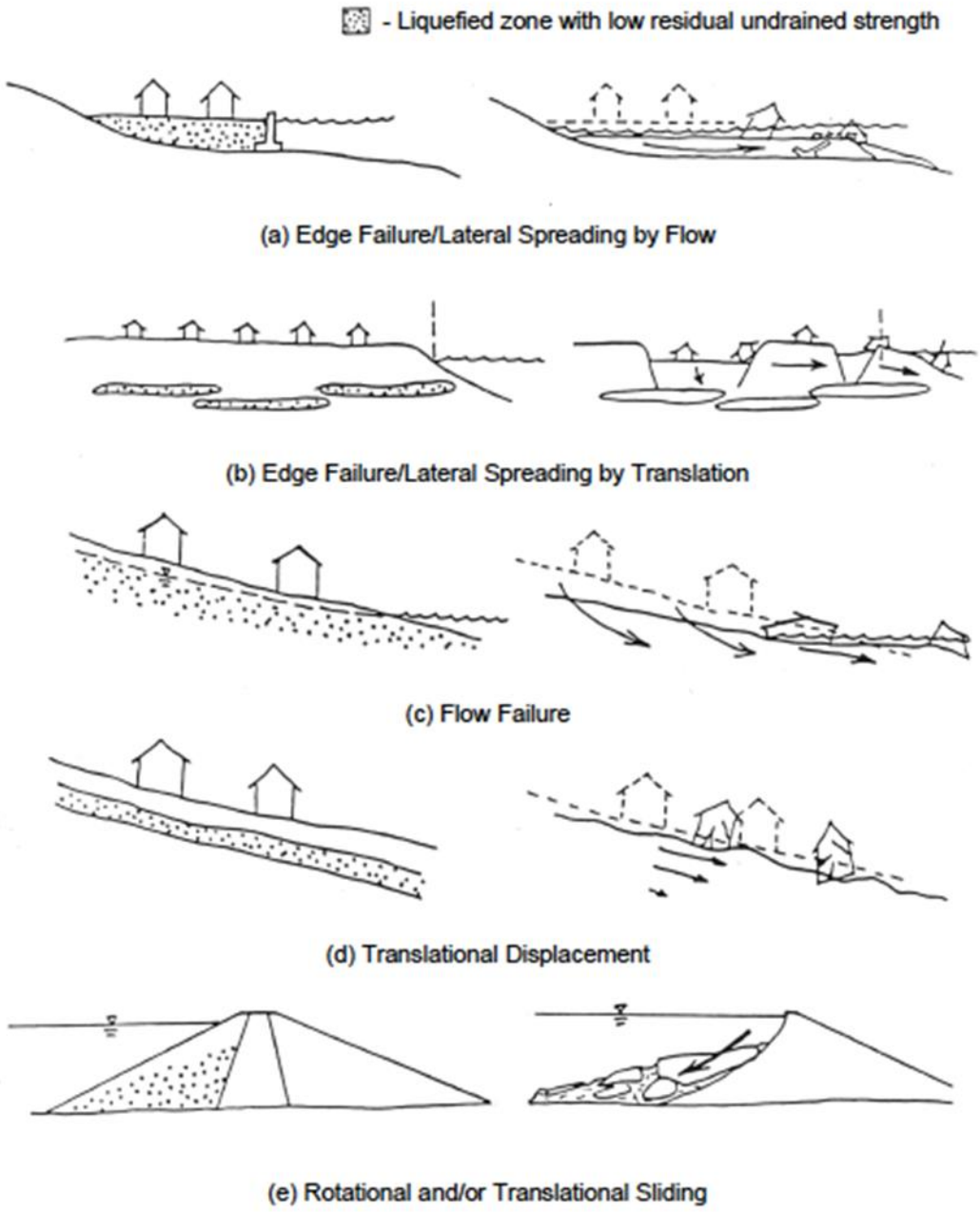

Fig. 44: Schematic Examples of Liquefaction-Induced Global Site Instability and/or "Large" Displacement Lateral Spreading

Figure 2: Examples of liquefaction-induced global site instability from (Seed et al. 2003, with original figure caption included)

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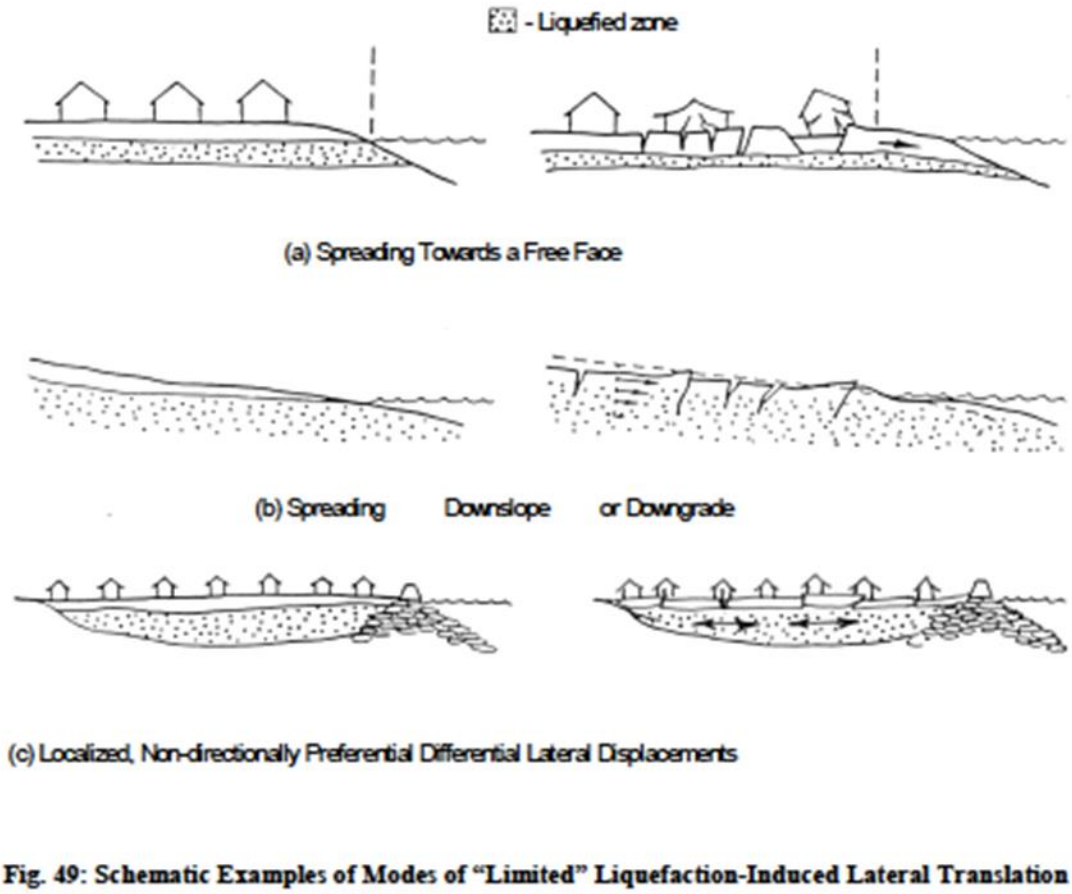

Fig. 49: Schematic Examples of Modes of "Limited" Liquefaction-Induced Lateral Translation

Figure 3 - Examples of liquefaction-induced lateral translation from (Seed et al. 2003, with original figure caption included)

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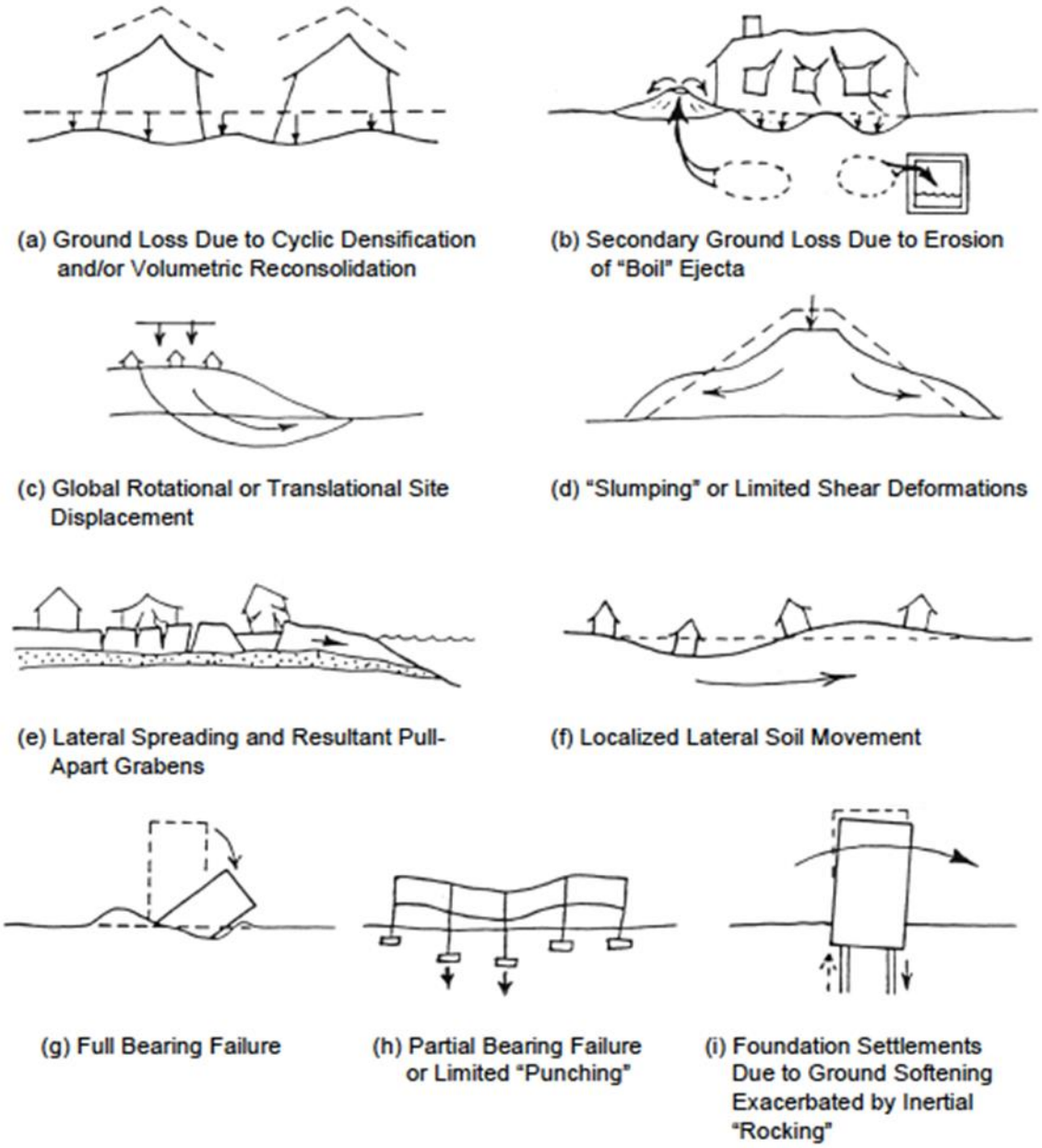

Fig. 50: Schematic Illustration of Selected Modes of Liquefaction-Induced Vertical Displacements

Figure 4 - Examples of liquefaction-induced vertical settlements (Seed et al. 2003, with original figure caption included)

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V. SEISMIC RISKS ASSOCIATED WITH INDUSTRIAL FACILITIES

18. Million of gallons of crude oil will be stored at the proposed Tesoro-Savage Project Site. As noted in the previous sections, the project site has a high seismic hazard and a high liquefaction hazard. Taken individually, these hazards each pose a significant risk to the facility; however, when acting together (as they would be expected to in a seismic event), these hazards can combine and result in a large-scale cascading-type failure. Such "cascading" or chain-reaction-type events are a hallmark of large-scale engineering system failures initiated by earthquakes and other extreme events. Moreover, as these types of failures are the result of an extreme event, they occur at times when emergency response services are most taxed and least able to respond to a crisis. A well-known recent example of a cascading-type failure of an engineering system is the Fukushima nuclear disaster that was initiated by the 2011 Tōhoku, Japan Earthquake. At the Tesoro-Savage site, the seismic hazard concerns are further amplified by the toxic nature of the impounded crude oil. Moreover, consequences of a failure at the facility would be severe in light of the economic and cultural importance of the Columbia River and the vulnerability of the local ecosystem.

19. In a recent review article, Pidgeon (2012) cites a series of safety-oriented practices to employ when addressing the possible failure of complex systems. Practices relevant to the Tesoro-Savage Project evaluations include: (i) open communication and deference to expertise (at all levels) to help identify, address, and respond to potential failures, (ii) avoiding incomplete or inaccurate representation of problems, which can influence an organization's belief about what is and what is not regarded as a "hazard," (iii) failure to recognize limitations and uncertainty in codes and standards, even when it is possible that triggering events that may exceed established professional guidelines and/or legal remit. Antonioni et al. (2009) go beyond these general practices and offer a systematic procedure for assessing "Na-tech" risks—that is

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risks posed to technical systems by natural hazards. Their guidelines were established for chemical facilities, however, it is my opinion that they are also relevant to this project. Their procedure encompasses:

- Characterization of the external event(s);
- Identification of susceptible equipment;
- Identification of damage states and reference scenarios;
- Estimate of the damage probability;
- Consequence evaluation for the reference scenario;
- Identification of credible combinations of events;
- Frequency/probability calculation for each combination;
- Consequent calculation for each combination; and
- Calculation of risk indexes.

20. Because of the complex nature of the industrial facilities and the storing of a large quantity of hazardous materials, I regard Tesoro-Savage Project as a special facility that requires careful assessment and scrutiny to ensure the safety of the local community and environment. Overall, it is also my opinion that multiple hazards at the site together with the severe consequences of failure combine in a manner that poses a high risk to the local region.

VI. ANALYSIS OF THE TESORO-SAVAGE TERMINAL

A. Liquefaction Is Expected at the Tesoro-Savage Site.

21. As part of my evaluation, I reviewed an independent, comprehensive assessment of seismic hazards at Tesoro-Savage included in the DEIS. Geotechnical test borings presented in the assessment report and the Geotechnical Investigation (GRI, 2013) indicate that the on-shore portions (Areas 300 and 500) of the site are underlain by approximately 20 feet of sandy

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fill located over a ~10-foot layer of soft silts and clays. These, in turn, overlie sands extending to the top of a deep, stiff gravel deposit. Analyses indicate that the lower sand layer is susceptible to liquefaction, which is expected to cause several feet of lateral deformation of the ground surface. Along the near-shore portions of the site (Area 500), an approximately 15-foot layer of granular fill is found over a thick deposit of sand. The lower sand layer is susceptible to liquefaction, which is expected to result in significant ground settlement (~10 inches) and large lateral deformation (~10 feet) of the ground across this portion of the site.

22. Based on my experience, I anticipate that liquefaction at the Tesoro-Savage Project Site would result in significant horizontal and vertical differential movement of the ground surface. This ground movement could cause significant damage to containment protection structures such as berms and/or walls and thus, reduce or negate their ability to contain spills. Based on the above, it is my opinion that a very high liquefaction hazard exists at the project site for Tesoro-Savage.

B. Liquefaction Would Damage Structures at Tesoro-Savage.

23. Liquefaction during past earthquakes has caused extensive damage to industrial structures, infrastructure, and operation systems at ports. For example, the recent study "*Vulnerability of Industrial Components to Soil Liquefaction*" (Lanzano et al., 2014) concluded that "this phenomenon represents a crucial issue for the risk assessment of industrial components under seismic actions." Examples liquefaction-related damage to industrial port facilities can be found in recent earthquakes. For instance, a study conducted by the Japan Society of Mechanical Engineers Research Committee on the (2011) Great East Japan Earthquake Disaster (Fujita et al. 2013) found that liquefaction-induced soil deformation was observed at many industrial facilities. This resulted in damage to pipeline systems (Figure 5a) and associated facilitates (Figure 5b). The study concluded that during the earthquake significant damage occurred to

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machinery and pipes due to soil deformation caused by soil liquefaction. Similarly, liquefaction damage to tanks located at the Port of Kobe, Japan resulted in an accidental release of gas that required the neighboring community to evacuate after the earthquake (INCEDE 1999). Other damage port facilities in the earthquake included tilting and deformation of storage tanks resulting from liquefaction-induced ground deformation and severing of valves and pipes at tank connections (Figure 6).

Figure 5a (left) and 5b (right) - Liquefaction-induced soil deformation observed at port industrial facilities in the 2011 earthquake. 5a: Uplift of a pipe support base due to ground subsidence, and 5b: Pipes fractured at the connection point of the building and soil.

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Tanks on Liquefied Ground

These photos from the 1995 Kobe earthquake in Japan illustrate various effects of liquefaction on tanks and their foundations.

This tank farm was located on reclaimed land along the waterfront. The cohesionless fill materials liquefied during the earthquake, and many tanks experienced excessive settlements or bearing failures.

The large blue tank in the middle of the photo tilted excessively due to liquefaction of the foundation soils.

[Accompanies above slide]
The tank foundation punched into the ground on one side. Notice that the numerous pipelines connecting the tanks were heavily damaged as well.

This set of tanks, also near the waterfront and on reclaimed land, experienced excessive settlements due to liquefaction. Notice that the walkway across the top of these two tanks has been torn away from the larger tank. Cracks in the ground are visible near the base of the large tank.

Figure 6 - Examples of earthquake-induced damage to port facilities in the Kobe, Japan, earthquake (Source: Univ. of Calif. Davis, see: https://research.engineering.ucdavis.edu/gpa/earthquake-hazards/liquefaction-tanks/)

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24. The Tesoro-Savage site faces a very high liquefaction hazard, which may result in similar damage to the facility. Based on my experience, I anticipate that liquefaction-induced horizontal and vertical deformation of the ground surface would cause significant damage to tanks, connectors, pipelines, and/or containment systems, releasing oil into the environment.

C. Tesoro-Savage's Mitigation Options Are Insufficient To Remove Risks.

25. An independent seismic assessment of the project revealed significant technical deficiencies with the Tesoro-Savage seismic mitigation plan. These concerns, which are detailed in Appendix C of the DEIS, notably include the following.

26. The foundation soils underlying the secondary containment berm surrounding the storage tanks ("Area 300") are subject to liquefaction, which could severely damage the berm and make it inoperative. This ground failure hazard is not mitigated in the proposed Tesoro-Savage project plan.

27. The portion of Tesoro Savage proposal near the dock and adjacent pipeline ("Area 400") has a high risk of liquefaction-induced lateral spreading and ground deformation, which could severely damage the transfer pipeline infrastructure and result in the release of oil. In addition, the proposed ground improvement measures do not fully penetrate the liquefiable soils and therefore, will not mitigate the lateral spread risk.

28. The proposed deep soil mix panels proposed for Area 400 are not a well-established liquefaction mitigation technology, and additionally, their design is not supported by sufficient engineering analyses.

29. Ground improvement in the tank-to-shoreline pipeline area ("Area 500") does not fully penetrate liquefiable soils leaving the ground failure hazard unmitigated. Ground failure at this location could damage the pipeline system and cause a release of oil.

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30. Having reviewed Appendix C and the Tesoro-Savage application, I concur with these critiques of the Tesoro-Savage seismic mitigation plan. Vancouver Energy's January 22, 2016 comment letter on the DEIS objects to the findings of the DEIS based on a preliminary (rather than comprehensive) assessment of the liquefaction hazard and concludes that mitigation measures are unwarranted in some areas and that earthquake damage to the facility will be later repaired. However, relying on post-event repair is a reactionary approach that does not protect the environment from an initial spill or release of hazardous materials. Preventative rather than reactionary measures are needed. The comment letter also opposes the suggested use of modern numerical engineering analysis and design methods (e.g. programs FLAC or PLAXIS) over highly simplified "pseudostatic-type" engineering models, which the current project design is based upon. Modern numerical models are reliable and provide a significantly more accurate prediction of geotechnical engineering performance in earthquakes (Boulanger, et al. 2015). Taken together, these concerns suggests that the liquefaction hazard will not be adequately assessed or mitigated. Nevertheless, even if this mitigation plan is later modified or enhanced, it should be recognized that there are no mitigation measures capable of completely eliminating geologic risks at the facility.

31. In summary, the risks posed to the Tesoro-Savage project from liquefaction are significant and may result in severe damage to the oil storage tanks, containment systems, and other equipment, resulting in the release of large quantities of oil into the environment, and Tesoro-Savage's mitigation plans are inadequate to counter those risks.

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I declare under penalty of perjury that the foregoing is true and correct to the best of my knowledge.

Executed this 16th day of May, 2016, at Seattle, Washington.

JOSEPH WARTMAN, Ph.D.

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