Assessment of Earthquake and Tsunami Threat to the Grays Harbor PUD System

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May 25, 2020

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Acknowledgements

Much of the data presented and analyzed in this report was provided by the Grays Harbor PUD. I would like to thank Schuyler Burkhart, Chris Eide, Daniel Kay, and Jared Zarelli of the Grays Harbor PUD for their help. Additionally, I would like to thank Professor Marc Eberhard, Professor Jeffrey Berman, and Dr. Nasser Marafi for providing guidance on the seismic risk assessment. I would also like to thank Professors Randy LeVeque and Dan Abramson for providing their tsunami inundation maps and related guidance. I offer special thanks to Professor Kirschen for supervising me throughout this project. I also want to thank Professor Kirschen and the engineers of the Grays Harbor PUD for providing valuable feedback on the first draft. Any remaining errors are the sole responsibility of the author.

Executive Summary

Earthquakes and tsunamis pose a great threat to Grays Harbor County because of its location on the Pacific Coast and its proximity to the Cascadia subduction zone. Past events have shown that these disasters can devastate lifelines, including power systems. This research project investigated how these threats would affect GHPUD.

Transmission and distribution lines have generally performed well in past earthquakes, although some minor damage spread across the distribution system is likely. Substations, however, can be quite vulnerable to damage from major earthquakes. The following substation components are the most likely to be damaged:

- Disconnect switches (broken porcelain and misalignment)
- Power transformers/regulators (broken porcelain, bushing seal failure, radiator leakage, sliding, toppling)
- Instrument transformers (broken porcelain)
- Bus connections (broken connections)
- Battery racks (spilled acid and cracked cases)

Many different earthquake scenarios could impact the Grays Harbor PUD. These include earthquakes from nearby faults such as the Canyon River Fault (≤M7.5), Olympia Fault Structure (≤M5.7), and Tacoma Fault (≤M7.1). There is also a threat from deep intraplate earthquakes (≤M7.5), and the Cascadia subduction zone (≤M9). Results from prior studies conducted by the Washington State Department of Natural Resources show that the threat of damage from earthquakes resulting from these faults is low. Some minor damage to substations or distribution is possible, but no outages are expected. However, a major deep earthquake like the 2001 Nisqually Earthquake could cause moderate damage to the GHPUD system if it were to be centered below the county. Deep earthquakes are the most common damaging earthquakes in the Puget Sound region, occurring approximately every 30 years.

The Cascadia subduction zone poses a significant threat to the GHPUD system because of its potential to generate earthquakes up to magnitude 9. A magnitude 9 earthquake would create widespread damage in the county. Damage to the distribution system should be minor, but damage to substations is likely to be severe. For an M9 Cascadia subduction zone earthquake, it is estimated that approximately 27 out of 36 substations will be extensively damaged.

Substation transformers were found to be the most seismically vulnerable component. Approximately half of the GHPUD's field inventory is expected to be damaged by an M9 earthquake. Due to the high cost of transformers and long lead times for replacements, recovering from these failures could be particularly difficult.

The M9 earthquake is expected to cause about $6.6 million in direct damage. The actual damage will vary depending on the characteristics of the earthquake. The cost of direct damage for the 30 scenarios analyzed ranged from $2.5 million to $11 million. This widespread substation damage may cause outages to up to 85% of the GHPUD's customers. An M9 earthquake has a 15% probability of occurring in the next 50 years, and represents the single greatest natural threat to the GHPUD power system.

While the GHPUD substations meet the minimum applicable standards, the analysis in this study shows that this may not yield acceptable performance in an M9 earthquake. Resilience improvements should be considered to protect the utility's investments in power equipment and

limit the potential for prolonged outages and economic damage to the local community. To mitigate the seismic threat the following resilience improvements are recommended:

- Adopt the recommended standards of the "high" equipment qualification level specified by IEEE693
- Anchor existing transformers where possible
- Anchor new transformer installations, or consider installing base isolators for increased performance
- Retrofit buswork with flexible conductors or flexible connectors where possible, following the recommended IEEE1527 standard
- Brace large radiators to reduce moments on pipes that penetrate transformer tanks

A major Cascadia subduction zone earthquake is likely to trigger a tsunami. Tsunami from distant sources are also a significant threat. Based on the "worst-case" scenario maps published by the state, 18 out of 36 substations are vulnerable to tsunami. The substations most at risk are Grayland, Ocean Shores, Oyehut, and Westhaven, due to their coastal proximity. However, the Aberdeen, Hoquiam, and Cosmopolis areas also have a significant risk of inundation, which puts substations like State Street and Scott Street at risk. A major tsunami could also cause damage to the distribution system in coastal areas. It may be possible to protect against tsunami by elevating equipment, waterproofing equipment, constructing levees, or relocating substations. More research would be required to determine the viability of these actions.

This work paints a rather grim picture, but the disasters analyzed are the worst-case scenarios. Additionally, estimates tend to err on the side of caution. While making the system entirely resilient against these scenarios is not practical, seismic performance can be significantly improved through a seismic mitigation program. This work gives a basic overview of the natural dangers the GHPUD faces, but more work would have to be done to arrive at a specific mitigation plan.

1 Introduction

The Grays Harbor PUD (GHPUD) is a public power utility in southwestern Washington serving Grays Harbor County (GHC) along with portions of Pacific, Lewis, Mason, and Jefferson Counties (Fig. 1). The Grays Harbor PUD provides electricity and wholesale fiber to its customers. They operate a distribution system of both overhead and underground lines primarily operating at 12 kV, along with a network of 69 kV and 115 kV lines. The Grays Harbor PUD receives most of its power from connections to the Bonneville Power Administration (BPA).

Electricity is a critical resource in our modern society, and a power outage can have devastating impacts. Hospitals, communications systems, and other critical infrastructure are especially at risk during an outage. Given the impacts of power outages, power utilities strive to build a reliable system to prevent them. Major natural disasters pose a great threat to power systems that are normally reliable. They can cause widespread damage to power lines and substation equipment, resulting in large-scale outages. Power utilities are typically well-equipped to deal with routine hazards, but they are often less prepared for devastating low-frequency events. Resilience is an active area of power systems research that deals with hardening the power system against these threats. A study was carried out to determine the likelihood and impacts of natural threats to the Grays Harbor PUD's electrical and telecommunication systems and to recommend possible actions. The study had the following primary objectives:

- To identify and rank the most significant natural threats to the GHPUD electrical system
- To evaluate the likelihood of these disasters occurring
- To determine the impacts of these disasters on GHPUD facilities
- To determine potential mitigating actions, as well as their costs and benefits

Natural disasters can affect power systems in devastating ways. A detailed overview of the threats to power systems can be found in [16]. The following natural disasters were considered to be the most significant threats to the system of the GHPUD:

- Earthquakes (including induced liquefaction and landslides)
- Tsunamis
- Geomagnetic disturbances (GMD)
- Extreme wind
- Winter storms

The probability and consequence of these disasters was used to guide the direction of this project. While geomagnetic events can cause widespread damage to power systems, very few such events have occurred and methods to assess the vulnerability of a system to GMD are relatively less developed. High winds are a relatively common occurrence in Grays Harbor County, but are generally low-impact, making them less important to research. Similarly, winter storms are generally mild in the County. On the other hand, Grays Harbor County has a unique exposure to earthquakes and tsunamis because of its location on the Pacific Coast near the Cascadia subduction zone. Due to the potential for a high-impact earthquake or tsunami and the sparse history of such recent events in the area, we chose to research these threats in depth.

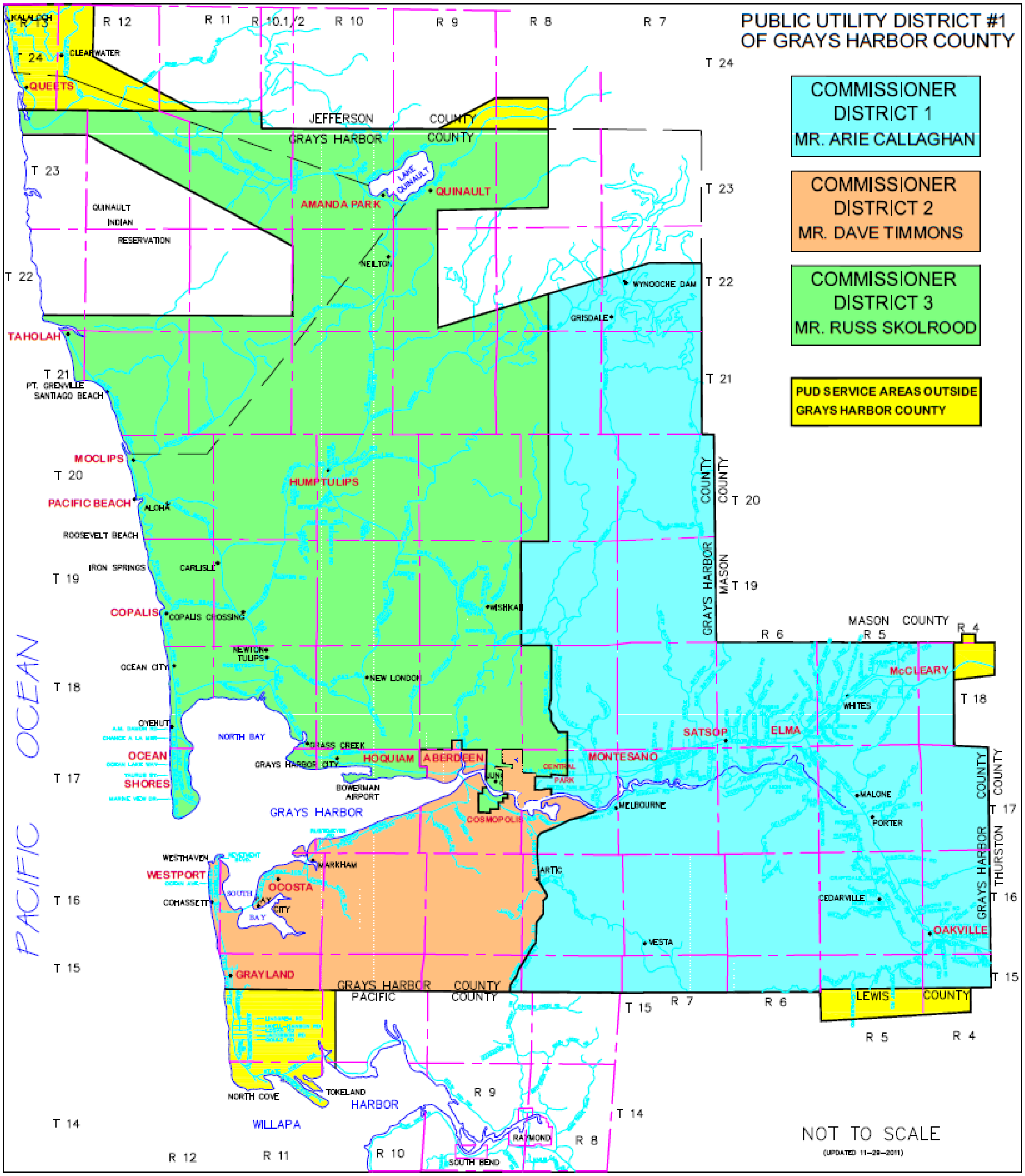

Figure 1: Grays Harbor PUD service area [1]

2 Earthquake Risk Assessment

2.1 Classifying Earthquakes and Ground Motion

Earthquakes can be classified using different scales. Traditionally, earthquakes were classified based on the amplitude of waves recorded by seismographs using the Richter scale. This scale varies logarithmically from 1.0 to approximately 10, so an earthquake of magnitude 6.0 would have ten times the wave amplitude of a magnitude 5.0 earthquake. Earthquakes are now typically measured using the Moment Magnitude (M_W) scale. The Moment Magnitude scale is also logarithmic and values range from 1.0 to approximately 10, but it gives a better indication of the total energy released by the earthquake. Moment magnitude will be used in this work, but most earthquakes give a similar value on both scales. Higher magnitude earthquakes occur with a lower frequency, as given by the Gutenberg-Richter law [17].

Whereas the magnitude of an earthquake gives an indication of the overall energy released, the ground motion at a particular location has to be measured using a different scale. This is because the energy attenuates with distance from the epicenter. The intensity of motion at any point in time can be described using ground displacement, ground velocity, or ground acceleration. However, these values vary with time throughout an earthquake, so often the peak values are used. Damage to electric power facilities is most strongly correlated with peak ground acceleration (PGA), so this is the measure typically used in this work.

To describe shaking intensity, the Modified Mercalli Intensity (MMI) can also be used. The MMI scale is based on perceived shaking, ranging from I (not felt) to X (extreme). This scale of intensity is more intuitive, so PGA values can be scaled to equivalent MMI values using Table 1 to get a better idea of the severity of shaking. However, PGA will generally be used in this work to compare ground motion between sites as it gives a greater degree of precision.

Table 1: Conversion of MMI to PGA [7]

MMI	I	II-III	IV	V	VI	VII	VIII	IX	X
PGA (%g)	<0.17	0.17–1.4	1.4–3.9	3.9–9.2,	9.2–18	18–34	34–65	65–124	>124
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

2.2 Earthquake Hazards of the Pacific Northwest

The plate-tectonics of the Pacific Northwest make it a seismically active region. Earthquakes vary significantly in their intensity, partly depending on the generation mechanism. There are three types of earthquakes that have the potential to significantly impact Grays Harbor County:

- Deep intraplate
- Crustal faulting
- Cascadia megathrust

Deep intraplate earthquakes occur 30–70 km below the ground where the Juan de Fuca plate is bending beneath North America (Fig. 2). Deep earthquakes are the most common source of damaging earthquakes in Washington [2]. Due to their deeper depth, these earthquakes tend to affect a wider area than crustal earthquakes. However, they also result in less intense ground motion at the epicenter because the energy is distributed over a wider area, and energy is lost as the seismic waves travel through the crust. These earthquakes also tend to produce few aftershocks. The 2001 M_w 6.8 Nisqually earthquake is a recent example of a deep intraplate earthquake in the region. Notably, this earthquake damaged distribution circuits as far away as Seattle, although damage to substations was very minor and restoration efforts were completed within 28 hours [18]. Deep intraplate earthquakes have historically occurred in the Puget Sound region about every 30 years, and the USGS estimates that there is an 84% chance of another M_w 6.5 or greater deep earthquake in the next 50 years [2].

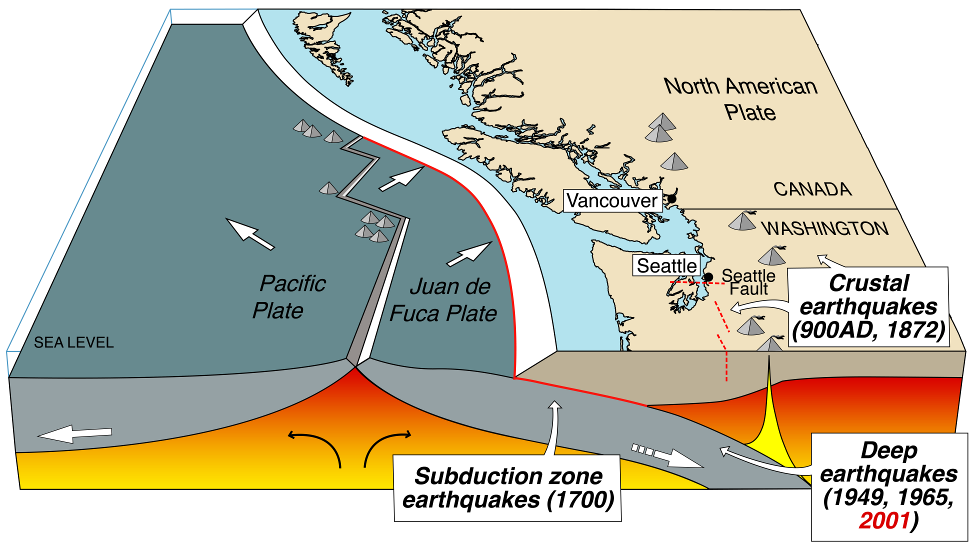

Figure 2: Earthquake sources in the Pacific Northwest [2]

Crustal earthquakes occur on fault lines in the Earth's crust. The maximum possible size of an earthquake from a fault generally increases with the size of the fault. Because the energy is released near the surface, ground motion tends to be intense near the fault, but affect a smaller area. Major aftershocks are relatively common for these earthquakes.

Several active faults could impact Grays Harbor County (Fig. 3). Additionally, there are potential hazards from undiscovered active faults, and faults that have not been extensively studied. One significant nearby fault is the Canyon River–Saddle Mountain Fault Zone (CRSMFZ), a 30 km long rupture between Lake Wynoochee and Lilliwaup [8]. The Washington State Department of Natural Resources (DNR) has simulated earthquake scenarios for this fault and several others using Hazus [19]. Table 2 summarizes the relevant results from these studies.

While the total economic damage to power systems from the crustal earthquake scenarios studied by the DNR range from tens to hundreds of millions, these losses are for the entire study area, i.e. the state of Washington. Most of the significant damage would be concentrated near the epicenter of the earthquake. The economic damage is not broken down county by county, but it can be inferred that the loss to the GHPUD would be minor for each of these scenarios based on the estimated zero customers without power in Grays Harbor County. The WA DNR has also published

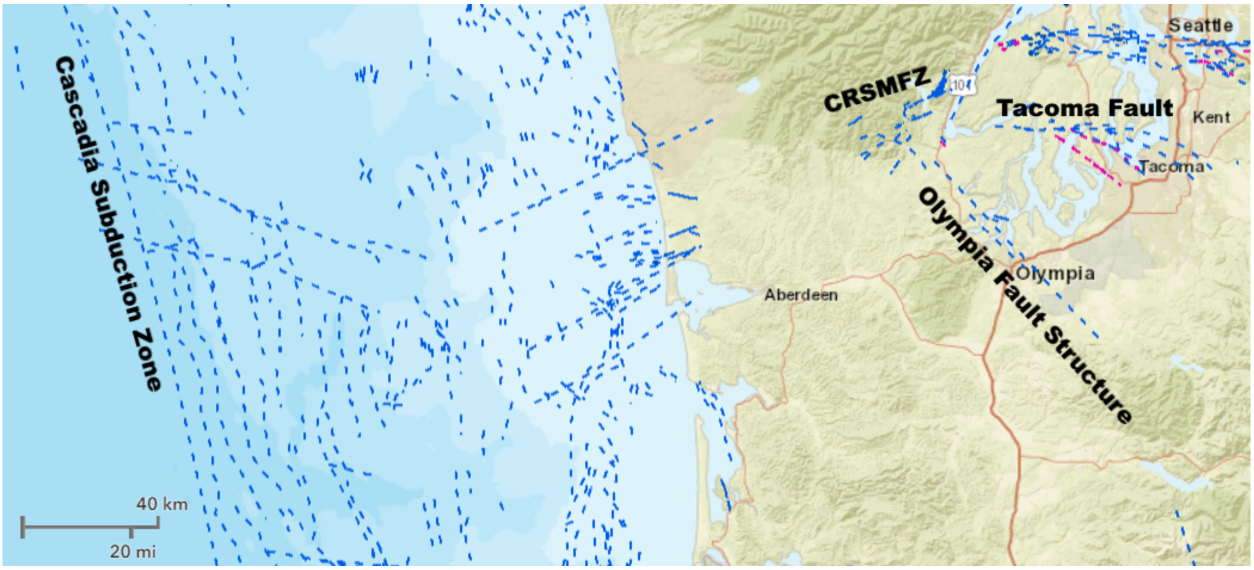

Figure 3: Known active seismological faults in the vicinity of Grays Harbor County [3]

earthquake scenarios for additional earthquake scenarios such as the Seattle Fault, although these earthquakes would be more distant and should result in a lesser impact to the GHPUD than the scenarios listed in Table 2. Based on these reports, we conclude that the threat of these faults to the GHPUD is low. However, for cities such as Olympia, Tacoma, and Seattle, which are located upon major faults, crustal earthquakes are a significant threat.

Table 2: Summary of WA DNR seismological fault and deep earthquake studies [8–11]

Fault location	Magnitude	PGA* (%g)	Economic loss to power Systems† (millions)	Households without power*
Canyon River	7.5	3.4–18	$97.01	0
Nisqually	7.2	3.9–34	$397.63	0
Olympia	5.7	1.4–9.2	$54.42	0
Tacoma	7.1	3.9–18	$283.24	0

*In Grays Harbor County
†Statewide

The third and largest earthquake threat to the region is the Cascadia subduction zone (CSZ), where the Juan de Fuca Plate is subducting below the Pacific Plate, as shown in Fig. 2. The Cascadia subduction zone stretches over 1,000 km from Vancouver Island to Northern California. It is capable of producing megathrust earthquakes of magnitude 9.0, the last of which took place in 1700 [20]. The CSZ has an average recurrence interval of about 500 years for earthquakes of approximately magnitude 9, and the USGS estimates a 14% probability of a magnitude 9 earthquake in the next 50 years [20]. The WA DNR also simulated two CSZ scenarios using Hazus: an M9 CSZ earthquake and an M8.3 Northern CSZ earthquake. The results of these studies are summarized in Table 3.

Table 3: Summary of WA DNR CSZ earthquake studies [12,13]

Scenario	Magnitude	PGA* (%g)	Economic loss to power systems† (millions)	Households without power by day*			
				1	3	7	30
Cascadia subduction zone	9.0	34–65	$679.72	7%	4%	1%	0%
Cascadia North	8.7	18–34	$184.65	0	0	0	0

*In Grays Harbor County
†Statewide

2.3 Substation Site Conditions and Liquefaction Susceptibility

Local ground motion during an earthquake depends heavily on the soil conditions, as loose soils can result in site amplification. ASCE 7-16 provides definitions for six site classes based on the hardness of the soil. Hard rock is given a site class of “A”, Rock a site class of “B”, Very dense soil and soft rock “C”, stiff soil “D”, soft clay soil “E”, and liquefiable soils, peat, and high plasticity clay are given a site class of “F” [21]. A substation at a location with a site class of “D” or “E” is generally more at risk of strong ground motion and permanent ground deformation from an earthquake than a substation a at a site of Class “B” or “C”. Site classes according to this scale were collected for each substation from [3], as shown in Table 4. This data gives some indication of which substations are most susceptible to earthquakes.

Liquefaction susceptibility data was also collected from [3] and is shown in Table 4. It should be noted that the liquefaction susceptibility is primarily based on the site class, so the two are strongly correlated. Additional factors influencing liquefaction are the groundwater content of the soil and intensity of ground motion. This data shows that 21 out of 36 substations have a moderate to high susceptibility to liquefaction. Liquefaction can result in severe ground deformation that can damage equipment. To assess more accurately the threat of liquefaction, site visits with geotechnical investigations would be required. For an example of an investigation on the liquefaction susceptibility of several of BPA’s transmission river crossings, see [22].

2.4 Seismic Vulnerability of Equipment

Distribution circuits have generally performed well in past earthquakes, so their overall contribution to system vulnerability is low [15]. However, since there are so many distribution circuits and occasional seismic damage does occur, it is likely that some distribution outages will occur during a major earthquake.

Transmission towers over 66 kV historically have performed well enough in past earthquakes that their contribution to overall system vulnerability is negligible [15]. For this reason the study did not attempt to model risks to the GHPUD 69 kV and 115 kV system. However, some transmission structures can fail, especially if they are located in landslide zones [15].

Substations face the greatest seismic risk, especially those operating at high voltages. Higher voltage substations generally have larger insulators and bushings, which if made of ceramics are prone to damage during a major earthquake [23]. Large unanchored equipment like transformers and regulators can be at risk of tipping or sliding during an earthquake [24]. Extreme shear forces can cause anchorings to fail, so even anchored equipment can fail during a major earthquake. Moderate voltage substations (33–100 kV) have typically performed well in past earthquakes, given that equipment is of the appropriate seismic ratings and anchored [15]. In general, new seismic designs for 115 kV equipment should be reasonably rugged for ground shaking up to 0.5 g [15]. However, moderate voltage substations with unanchored equipment may face a significant risk of

Table 4: Substation site classes and liquefaction susceptibility

Substation	NEHRP site class	Liquefaction susceptibility
Adams Street	D-E	Moderate to high
Cosmo Fiber 13 kV	D-E	Moderate to high
Cosmo Fiber 4 kV	D-E	Moderate to high
Cosmopolis	D-E	Moderate to high
Electric Park	D-E	Moderate to high
Harding Road	D-E	Moderate to high
Harpo	D-E	Moderate to high
Highlands	D-E	Moderate to high
Hoquiam Plywood	D-E	Moderate to high
Junction City	D-E	Moderate to high
Mayr Brothers	D-E	Moderate to high
Monroe Street	D-E	Moderate to high
Pacific Veneer	D-E	Moderate to high
Quinault	D-E	Moderate to high
Scott Street	D-E	Moderate to high
State Street	D-E	Moderate to high
Grayland	D	Moderate to high
Ocean Shores	D	Moderate to high
Westhaven	D	Moderate to high
Westport	D	Moderate to high
Bernard Creek	C	Moderate to high
Montesano	D-E	Low
Cedarville	C-D	Low
South Elma	C-D	Low
Central Park	C-D	Very low
Copalis Crossing	C-D	Very low
Crane Creek	C-D	Very low
Elma	C-D	Very low
Moclips	C-D	Very low
Oyehut	C-D	Very low
Powell Road	C-D	Very low
Promised Land	C-D	Very low
Satsop Park	C-D	Very low
Axford Prairie	C	Very low
East Hoquiam	C	Very low
Valley	B	Very low

damage when subjected to strong ground motions. The seismic vulnerability of this equipment was modeled using the NIBS loss estimation methodology [15], and the vulnerability of whole substations was modeled using the methods of Hazus [6], as described in Appendix A.

2.5 Magnitude 9 Scenario

New data from the University of Washington M9 group was analyzed to get more accurate estimations of damage for an M9 CSZ earthquake [20], the worst-case earthquake scenario. This data predicts more intense ground motion than what was used in the previous studies by the Washington State DNR that were summarized in Table 3. Sets of synthetic seismograms were used from thirty different equally likely M9 scenarios. Each seismogram contains simulated time histories of ground motion at sites in a 20 by 20 km grid. Peak-ground acceleration was extracted from the acceleration time histories, and the PGA was adjusted by the site class according to the site coefficients from [25]. Failure probabilities for individual components at each substation were calculated using the methods described in Appendix A. The outcomes of the 30 different M9 scenarios were then averaged to get the expected outcome for an M9 earthquake.

Fig. 4 shows the expected PGA at each substation for an M9 CSZ Earthquake. These expected values were calculated as the mean of the PGAs from the 30 scenarios. This plot shows that the substations along the coast generally receive the most severe shaking, as they are closest to the subduction zone. This includes Moclips, Crane Creek, Powell Road, and Copalis Crossing, among others. The substations farthest inland such as Montesano and South Elma have expected ground motion almost half of that on the coast. Some of the variation in PGA between substations is also due to the difference in site classes. Valley substation, for example, has the lowest mean ground motion partly because it is the only substation on class “B” hard rock, which reduces site amplification.

Among the 30 M9 CSZ scenarios there is much variation in the ground motion at each site. This is due to the variations in rupture parameters between the scenarios, such as the hypocenter location. To illustrate the range in intensity, Fig. 5 shows a histogram of the PGA at Moclips substation for the 30 scenarios. The PGA ranged from 0.34 g to 1.36 g, with a mean of 0.82 g. Fig. 6 shows a similar histogram for Montesano substation in the East side of Grays Harbor County. For Montesano, the PGA ranged from 0.27 g to 0.66 g with a mean of 0.40 g. According to the MMI scale, the motion at Montesano can be classified as “very strong” to “severe” and the motion at Moclips can be classified as “severe” to “extreme”.

Fig. 7 shows the number of substations expected to be in each damage state after an M9 CSZ earthquake. Almost all substations will be damaged to some extent, and approximately 27 out of 36 substations will have extensive damage or greater. Fig. 8 shows the probability of each substation entering each damage state. It can be seen that for each substation the probability of at least minor damage is above 90%. The most seismically vulnerable substations are shown at the top of this graph. The probability of “complete” damage is above 50% for Moclips substation, and there are fourteen substations where this probability is above 25%. This indicates that the substation damage from a magnitude 9 earthquake is likely to be quite devastating.

As a worst-case estimate, the widespread substation damage from an M9 earthquake may cause outages to 34,482 customers, which is 85% of the GHPUD’s total customers. This includes 30,361 residential customers, 3,823 commercial customers, and 298 industrial customers. However, this estimate is overly conservative because it neglects the redundancy in the system, as described in Appendix A. A previous WA DNR study [12] predicted 7% of customers without power in Grays Harbor County. This study used slightly lower estimates for the ground motion, and used a default inventory to represent the GHPUD system. However, the methodology used for estimating customers without power is more accurate, so the actual number of customers without power is likely to be much lower than the 85% worst-case scenario.

Figure 9 shows the probability of damage for each component at Electric Park substation. Table 5 shows the number of substation components expected to be damaged across the entire

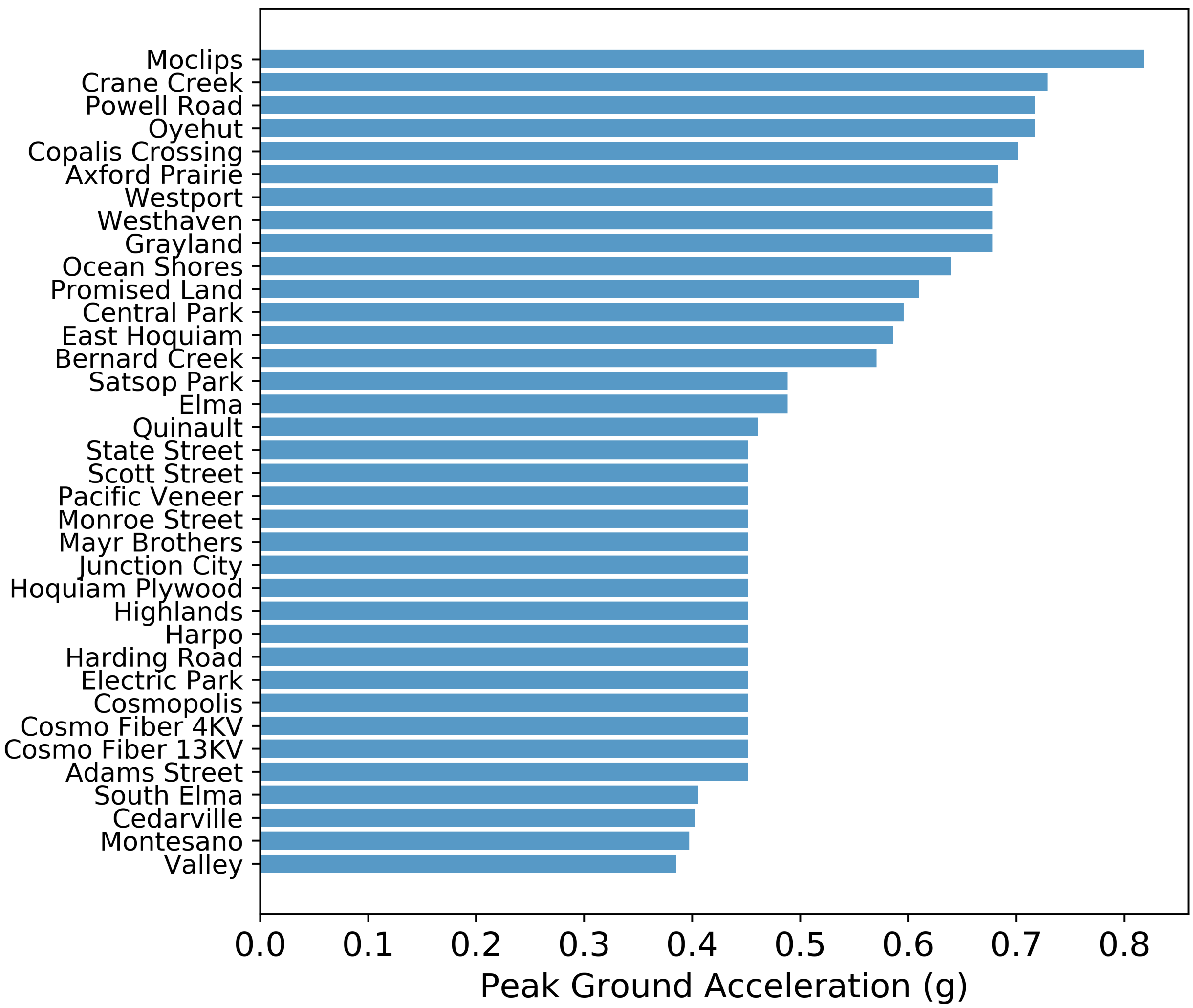

Figure 4: Expected PGA at each substation for an M9 CSZ earthquake

system. This data shows that transformers are the most vulnerable, with nearly half expected to sustain damage. Considering the high cost and long lead times for transformer replacements, this represents a major system vulnerability. Regulators and instrument transformers have a similarly high likelihood of damage. Only a small percentage of circuit breakers are expected to be damaged, however.

Financial loss for each M9 scenario was estimated using the computed probabilities of damage and the repair costs in Appendix B. Fig. 10 shows a distribution of the predicted financial loss. The expected cost is \$6.6 million and the range of the 30 scenarios is from \$2.5 million to \$11 million. This estimate only includes the direct cost of damage based on equipment that was modeled. Additional damage to other equipment and facilities may result in a greater loss. Indirect costs like value of lost load were not considered.

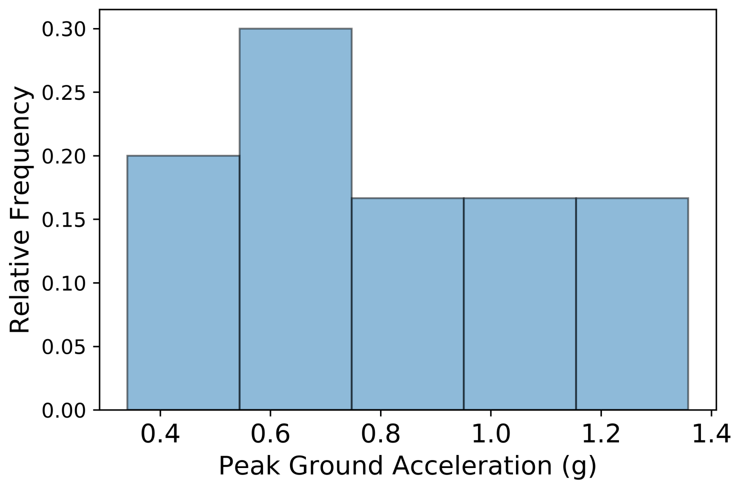

Figure 5: Histogram of PGA at Moclips substation for 30 M9 scenarios

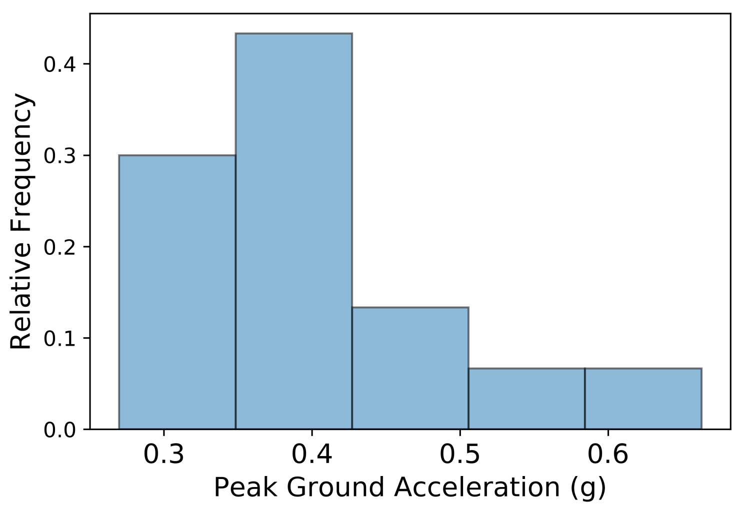

Figure 6: Histogram of PGA at Montesano substation for 30 M9 scenarios

2.6 Earthquake Resilience Improvements

The GHPUD should consider implementing a seismic mitigation program to protect its investments in power equipment and to limit the potential for prolonged outages and economic damage to the local community. While the GHPUD system does meet the minimum applicable requirements as is, the analysis in this study shows that this may not yield acceptable performance in an M9 earthquake scenario.

Most of the GHPUD substation facilities were built to the standards of Uniform Building Code Zone 3, which was the applicable standard at the time of construction. However several major earthquakes in the 1970s and '80s revealed that these general building codes do not yield satisfactory seismic performance for substation equipment. In response to this, the IEEE has developed recommended standards on the seismic design of substation equipment and buswork [26,27], and the ASCE has released a guide on improving substation seismic performance [28]. The application of these standards through new construction or retrofit can greatly improve the seismic

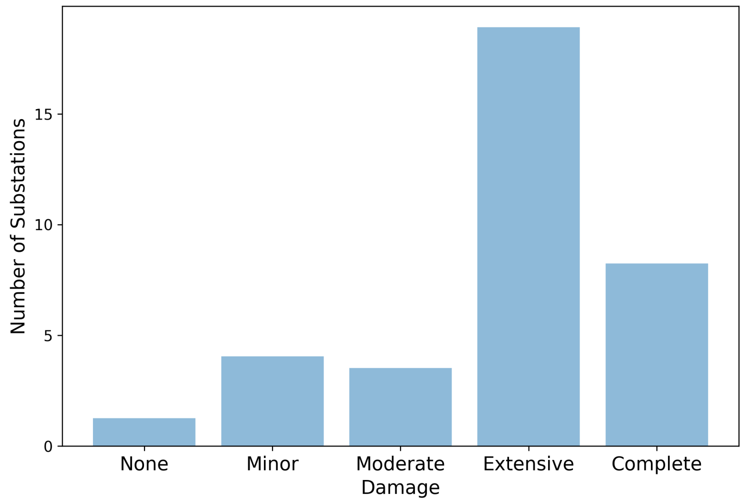

Figure 7: Number of substations expected to be in each damage state after an M9 earthquake

Table 5: Count of substation components damaged in M9 scenario

Component	Quantity damaged	Percentage of field inventory damaged
115-69 kV transformers	2	50%
Other transformers	19	50%
12 kV regulators	4	40%
Current transformers*	5	31%
Potential transformers*	12	29%
Bus structures	12	20%
Disconnect switches	33	20%
Lightning arrester*	9	19%
Circuit breakers	1	2.2%

*Set of 3

resilience of the GHPUD system. IEEE693 specifies three qualification levels for equipment: low, moderate, and high. The high qualification level should be used due to the >0.5 g PGA that is likely to occur at most sites during an M9 CSZ earthquake. Equipment rated to the moderate qualification level would bring improved performance, especially for the more likely but less intense deep earthquakes, but would be more likely to fail during an M9 CSZ earthquake.

During an earthquake, buswork conductors can transfer significant forces between connected pieces of equipment. Therefore, the design of buswork can greatly affect the performance of substation equipment [27]. Buswork can either be rigid, rigid with flexible connections, or flexible. The buswork currently used by the Grays Harbor PUD is rigid or rigid with flexible connections. Improvements to seismic performance may be possible by using flexible buswork where possible, and rigid buses with flexible connections otherwise. Adequate slack in conductors is also important. More detail on recommended practices for the design of buswork can be found in IEEE1527 [27].

For transformers, making flexible connections to bushings can improve their performance [28]. Seismically robust bushings should also be considered. Additionally, large radiators should be

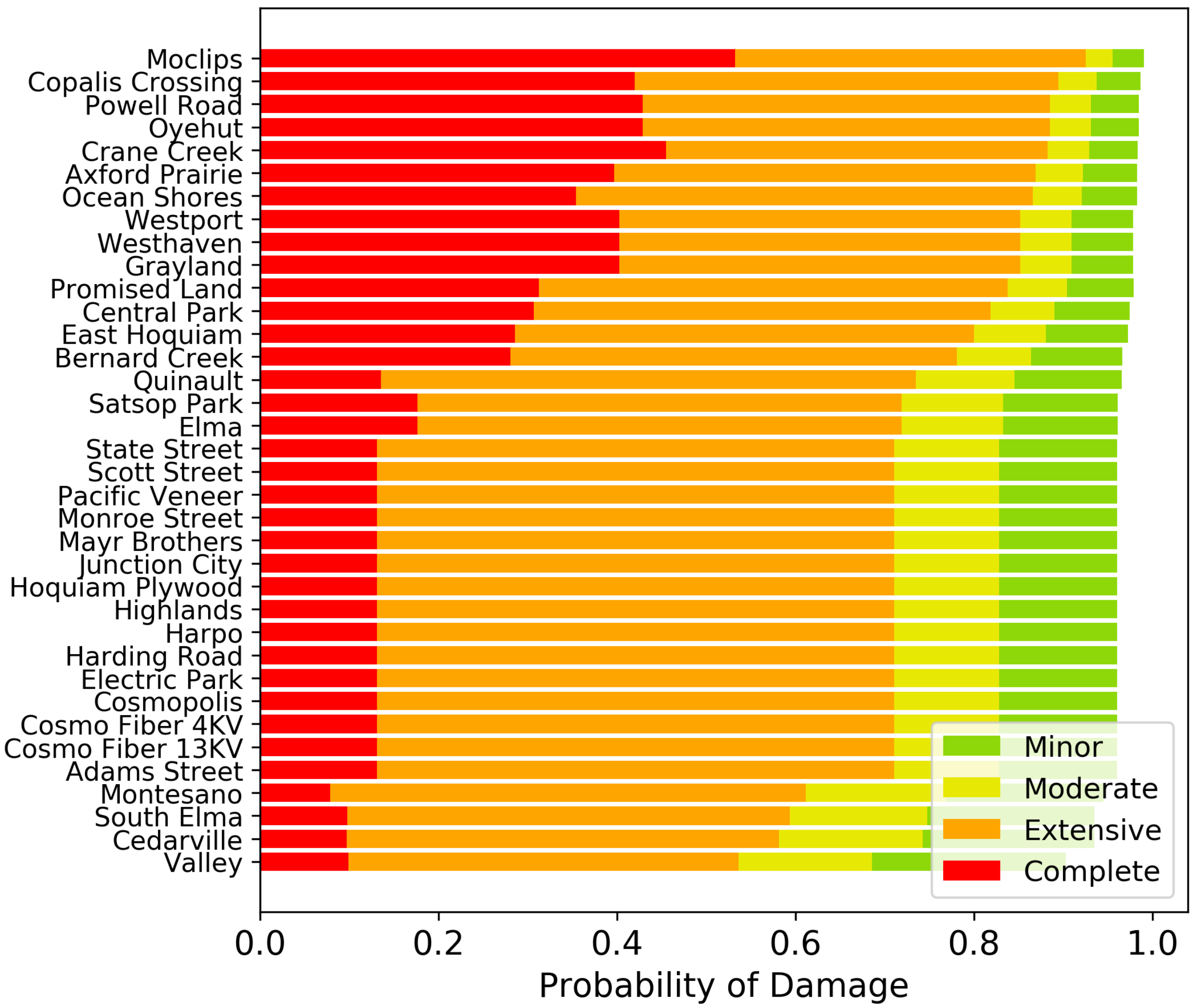

Figure 8: Probability of each damage state by substation for M9 earthquake

braced to reduce moments on pipes that penetrate the transformer case [28].

Since transformers and regulators have a high risk of sliding or tipping during strong earthquakes, modern guidelines recommend that this equipment be anchored [26, 28]. However, the GHPUD currently has this equipment unanchored. Adding anchoring has been cited as being a cost-effective way to improve the seismic performance of substation equipment [26]. Therefore, it is recommended to retrofit substation transformers with anchoring where possible. Guidelines on anchoring can be found in [29] and [26]. However, retrofitting transformers with anchoring may not always be practical due to space or attachment constraints.

As an alternative to anchoring, seismic isolation systems can be constructed below transformers. Base isolation is achieved by inserting flexible supports, called isolators, between the structure and its foundation (Fig. 11). This decouples the structure from the ground motion, and can reduce PGA by as much as 75% [30]. Base isolation is not a new technology and has been used in bridges and buildings for at least the last 30 years, although adoption in the power industry has been slow. BPA was the first in the U.S. to base-isolate an existing transformer [30]. BPA estimates that their existing transformers could be retrofitted with isolators for under $100,000 [4]. Seattle City Light

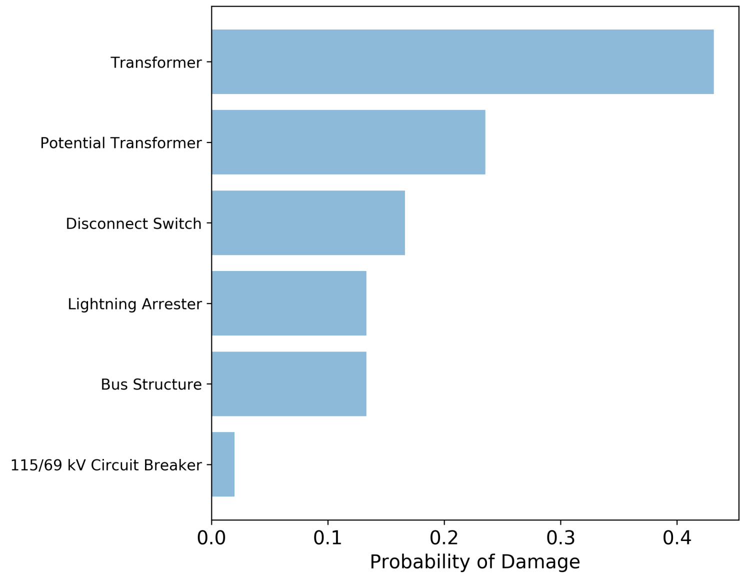

Figure 9: Probability of damage from M9 earthquake for components at Electric Park substation

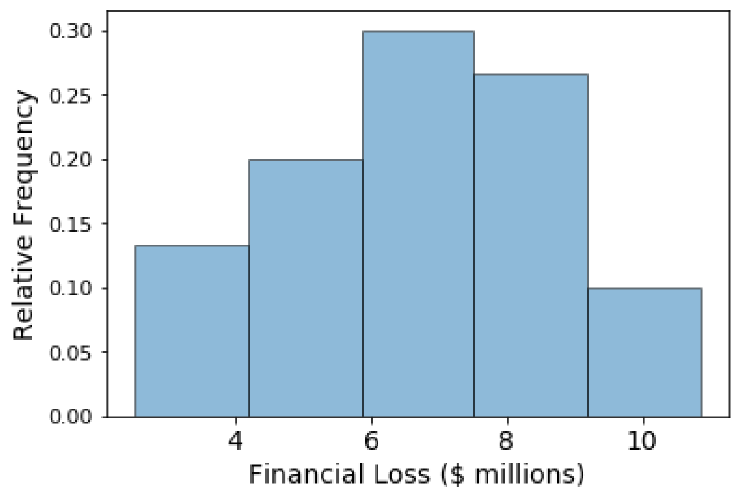

Figure 10: Distribution of expected financial loss for M9 earthquake

(SCL) was the first US utility to install a new high-voltage (120 kV) transformer on an isolated base, and found that foundation costs only increased by 20–30% compared to traditional design [31]. SCL plans to isolate all new transformers as part of its seismic program. We recommend that the GHPUD consider fitting new substation transformers with isolators. However, retrofitting existing transformers with base isolators may not be as cost-effective as anchoring.

Seismic hardening of each substation should start with a seismic walkdown by a team including structural engineers, mechanical engineers, electrical engineers, communication engineers, and substation operators. They should walk through the substation and assess equipment for adequate anchorage, bracing, flexibility of connections, and seismic vulnerability [32]. A list of all identified vulnerabilities should be developed. A hardening option and estimated cost should then be developed for each vulnerability. Substations and equipment can be prioritized based on their relative

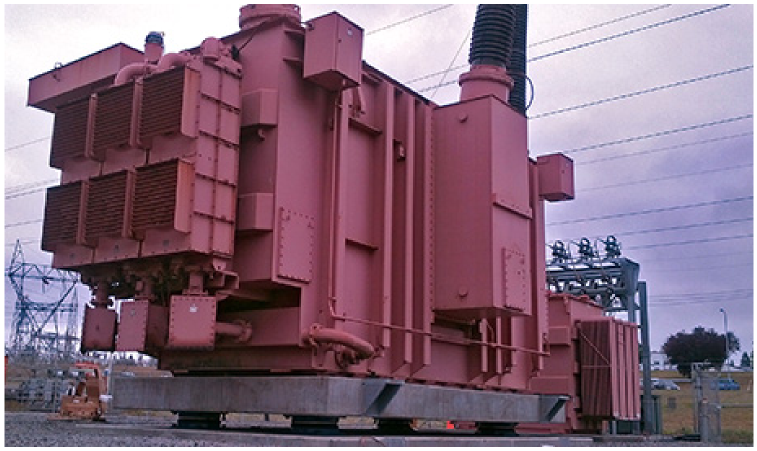

Figure 11: Transformer retrofitted with base isolation [4]

vulnerability and importance to the system. The most prudent actions can then be selected based on cost-benefit analysis.

2.7 Summary of Earthquake Risk

Various kinds of earthquakes can impact Grays Harbor County, including crustal earthquakes from nearby faults and deep earthquakes. Crustal earthquakes pose a low risk to the GHPUD system, and deep earthquakes are a moderate risk. A M9 Cascadia subduction zone earthquake is the greatest seismic hazard, and was examined in-depth. Peak ground acceleration between 0.65 and 1 g (MMI IX) is likely at many substations sites, especially the coastal ones. This is expected to cause extensive damage to about 75% of the GHPUD's substations. The GHPUD's unanchored transformers are particularly vulnerable, with nearly half expected to be damaged. An M9 earthquake is expected to cause about $6.6 million in damage, and impact up to 85% of the GHPUD's customers. To reduce the threat of damage to transformers, it is recommended that they be anchored and have large radiators braced. Additionally, it is recommended that new equipment be qualified to recommended standard IEEE693. It is also recommended that flexible buswork be used where possible. Following these basic guidelines should significantly improve the system's seismic resilience and reduce the financial damage and outages resulting from a major earthquake.

3 Tsunami Risk Assessment

Tsunamis can be classified into two main categories based on their source: local and distant. Distant tsunamis are generated by distant earthquakes and travel across the ocean, impacting a wide area. Local tsunamis are generated by local mechanisms such as earthquakes or landslides at sea. The largest risk of local tsunamis is a Cascadia subduction zone earthquake. All of the tsunami scenarios shown in this report are based on CSZ earthquakes of varying magnitude.

3.1 Equipment Vulnerability to Tsunami

Very little information was found on correlating tsunami inundation or current with damage to power system equipment. For this study, it was assumed that if the water level reaches the elevation of a sensitive piece of equipment, then that equipment is at risk of damage. This was used because sensitive electronics like those inside substation control buildings would most likely be destroyed by exposure to water. Equipment like transformers may be more resilient, but mechanical failure is possible considering that waist-high surges can cause currents strong enough to float cars and small buildings [33]. Table 6 provides a list of what we considered to be the most at risk equipment and their typical elevations. Equipment not listed in Table 6 was considered to be less vulnerable to tsunami, although high inundations may make this assumption invalid. More rigorous models could be developed to more accurately estimate component damage from tsunami.

Table 6: Substation equipment and typical elevations

Equipment	Elevation (ft)
Control building	2
Switchgear building	2
Circuit breakers	3
Power transformer	3

3.2 Tsunami Inundation Data

For our study, tsunami inundation maps published by the Washington State Department of Natural Resources were used [14], along with unpublished inundation maps from University of Washington researchers [5]. These maps cover scenarios for various tsunamis resulting from a CSZ earthquale.

The tsunami scenarios are divided into “T-shirt” sizes based on [34]. A small (SM) scenario has a recurrence interval of approximately 300 years, a Medium (M) scenario has a recurrence interval of approximately 525 years, and a Large (L) scenario has a recurrence interval of approximately 800 years [34]. These translate to a 0.33% annual probability for the SM scenario, 0.19% annual probability for the M scenario, and a 0.13% annual probability for the L scenario. It is worth mentioning that extra-large and extra-extra large scenarios are also defined, but they are unlikely so the state has chosen to use the L1 scenario as the “worst-case” for planning purposes. Each “T-shirt” size has multiple ways it can occur, which are given different numbers. The L1 scenario is the most likely of the many possible L scenarios, and corresponds to CSZ rupture zone earthquake of approximately M_w 9.0. Similarly, the M1 scenario and SM1 scenario correspond to CSZ earthquakes of approximately M_w 8.9 and 8.7, respectively [34]. This information is summarized in Table 7. When the next major CSZ earthquake occurs, inundation is almost certain to meet the

SM1 scenario, and there is approximately an 80% chance of meeting the M1 scenario, but only a 20% chance of meeting the L1 scenario [5].

Tsunami scenario	Recurrence interval (yr)	Annual probability	Estimated earthquake magnitude (M_w)
SM1	300	0.33%	8.7
M1	525	0.19%	8.9
L1	800	0.13%	9.0

Table 7: Definitions of CSZ tsunami scenarios

Table 8 shows the inundation at each substation for the "worst-case" L1 tsunami. Based on the criteria specified in Section 3.1, 18 out of 36 substations have equipment vulnerable to tsunami. It should be noted that some substations not located near the coast, such as Valley substation and Mayr Brothers substation, are still at risk because of river run-up. At risk are 10 control buildings, 5 switchgear buildings, 17 circuit breakers, and 23 substation transformers, including 2 of the more expensive 115/69 kV voltage class. Assuming complete loss of the vulnerable equipment and buildings, an L1 tsunami may cause $23.1 million in direct damage to substations. This ignores any damage to the distribution system, and any indirect losses.

In total, there are approximately 24,000 customers normally served by these substations who would be at risk of an outage after an L1 tsunami. This represents 60% of the GHPUD's customers, and includes 21,260 residential customers, 2,667 commercial customers, and 221 industrial customers. Many of these customers are also located in areas that may be inundated, however.

The outcome of the L1 tsunami is particularly devastating, so it would be useful to examine other scenarios that are more likely but less severe, such as the CSZ SMl and M1 scenarios. Unfortunately, there is no published data for these scenarios available at the county level, but a set of unpublished maps for the Aberdeen area were obtained from a group of University of Washington researchers. It should be noted that the state only officially supports using the "worst-case" L1 scenario from [14] for planning purposes. The data for the other tsunami scenarios shown in the LeVeque maps is unofficial, and there is much uncertainty associated with it. However, the maps are useful here for comparison.

Figs. 12, 13 and 14 show the expected inundation in Aberdeen for SM1, M1, and L1 tsunamis, respectively. Fig 15 shows these three scenarios combined probabilistically. The data collected from these maps is summarized in Table 9. Inundation data for the SM1 and M1 scenarios is only available for Electric Park, Harpo, and State Street substations. From these maps we see that all three of these substations are likely to be safe from an SM1 tsunami. However, State Street substation is inundated in the M1 scenario, and all three substations are inundated in the L1 scenario.

3.3 Tsunami Resilience Improvements

Little research has been done on reducing the threat of tsunamis to substations. However, much applicable research is available on protecting substations against flooding. The main possible ways to protect substations against tsunami would be by elevating equipment, waterproofing equipment, constructing levees, or relocating the substation. Due to the extreme forces of the tsunami, bracing and anchoring of yard equipment may also be beneficial.

For Grayland, Monroe Street, Ocean Shores, Oyehut, Pacific Veneer, Scott Street, State Street, Valley, and Westhaven substations, the inundation depth for the L1 tsunami is high enough that

Table 8: L1 tsunami inundation depth and vulnerable components at coastal substations [14]

Substation	Inundation depth (ft)	Count of vulnerable equipment			
		Control buildings	Switchgear buildings	Circuit breakers†	Power transformers†
Oyehut	40	1	0	0	1
Moclips	N/A*	1	0	0	2
Ocean Shores	14	1	0	0	2
Westhaven	14	1	0	0	1
Grayland	13	1	0	0	1
Scott Street	13	1	0	0	1
Valley	13	0	1	2	1
Pacific Veneer	12	0	0	0	1
State Street	9	0	1	0	1
Monroe Street	8	1	0	0	1
Mayr Brothers	6	0	0	0	1
Cosmo Fiber	5	1	0	0	2
Harpo	5	0	0	0	1
Electric Park	4	1	2	12	4
Hoquiam Plywood	4	0	0	0	1
Westport	4	0	1	1	1
Cosmopolis	3	1	0	0	1
Junction City	3	0	0	2	0
Adams Street	1	0	0	0	0
Bernard Creek	1	0	0	0	0
Harding Road	0	0	0	0	0
Highlands	0	0	0	0	0
Powell Road	0	0	0	0	0

*Inundation data not available, but assumed to be high based on [35]
†Only includes equipment of 69 kV and 115 kV class

Substation	Inundation (m)			Inundation probability
	SM1	M1	L1	
Electric Park	0	0	1–1.5	25%
Harpo	0	0	1–1.5	25%
State St.	0–0.5	1–1.5	2–3	100%

Table 9: Inundation at Aberdeen substations for three CSZ tsunami scenarios [5]

severe damage to the substation is probably unavoidable without relocation. However, these substations are the most vulnerable to smaller tsunamis, so they should be the first to consider making mitigation measures to. The number of impacted customers at each substation should also be considered.

The L1 tsunami inundation at Cosmopolis, Electric Park, and Westport substations is low enough that they could likely be made resilient to tsunamis through equipment elevation or levees.

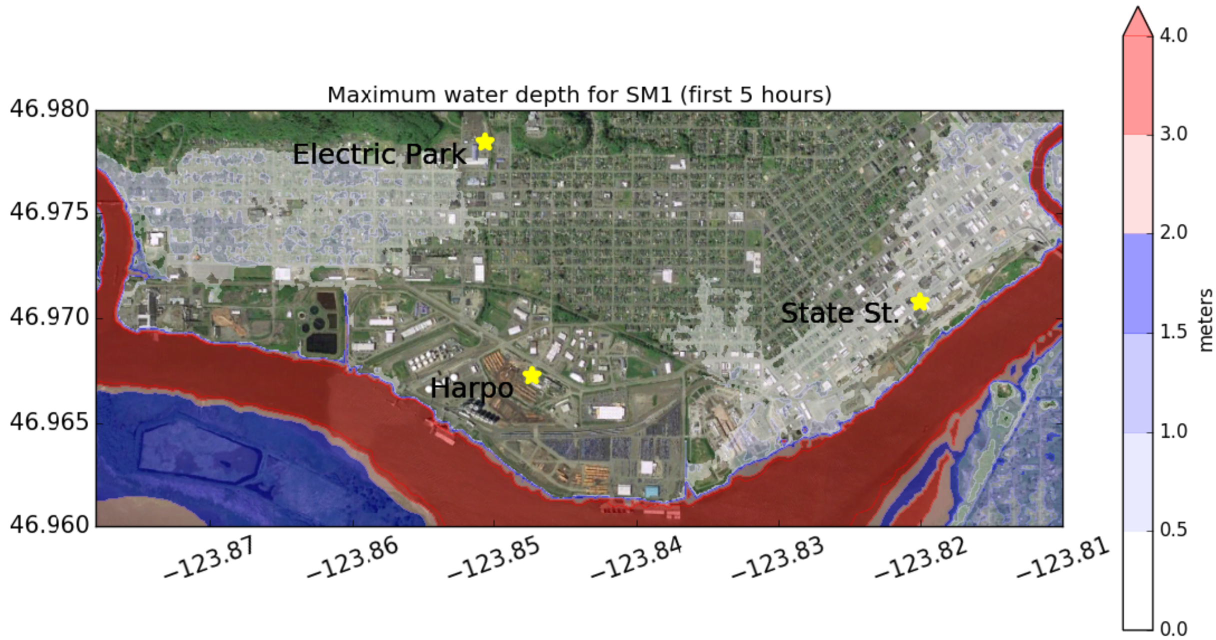

Figure 12: Aberdeen, WA inundation map for SM1 CSZ tsunami [5]

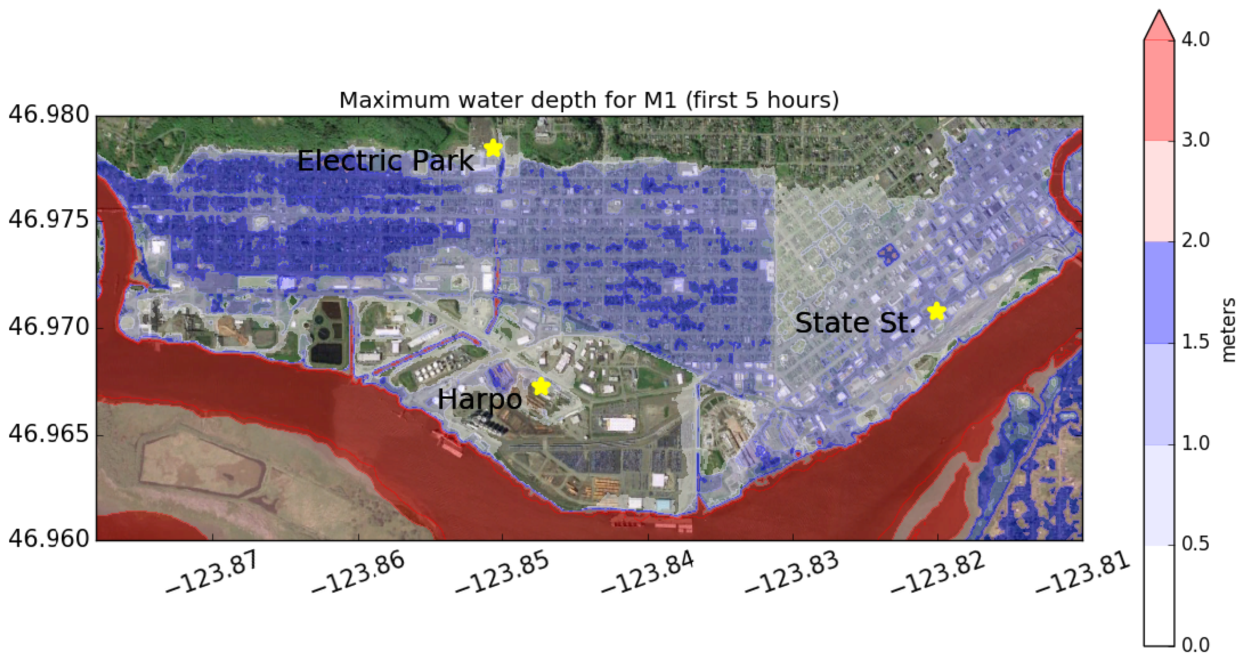

Figure 13: Aberdeen, WA inundation map for M1 CSZ tsunami [5]

These substations are likely to have customers whose residences are not destroyed by the tsunami, so there could be benefit in protecting these substations. However, the 0.13% annual probability of the L1 tsunami may not be enough to justify a significant expenditure.

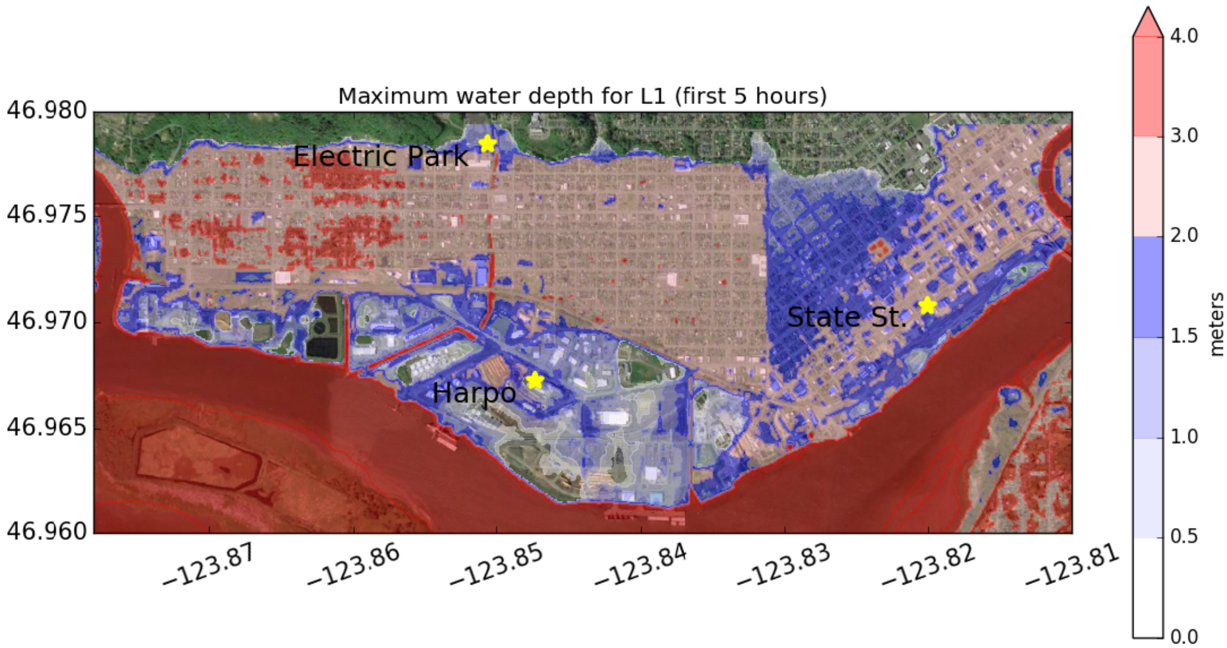

Figure 14: Aberdeen, WA inundation map for L1 CSZ tsunami [5]

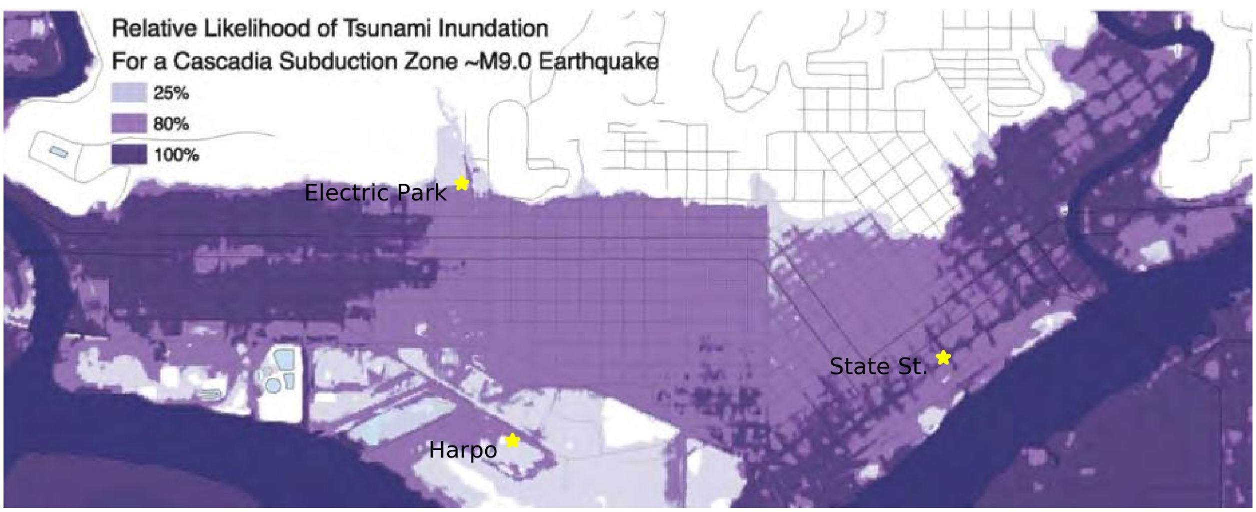

Figure 15: Aberdeen, WA probabilistic inundation map for CSZ tsunami [5]

3.4 Summary of Tsunami Risk

Tsunamis from both distant sources and local sources can impact Grays Harbor County. A Cascadia subduction zone earthquake is the greatest tsunami threat, and the worst-case L1 tsunami can cause inundation over 40 ft in many coastal areas. Half of the GHPUD's substations were found to be vulnerable to tsunami. The L1 tsunami is estimated to cause $23.1 million in damage and impact 60% of the GHPUD's customers. Additional data would be needed to examine the threat posed by smaller tsunami. Elevating equipment in vulnerable substations would be the most practical way to mitigate this risk.

4 Future Research Opportunities

This work could be expanded upon in many ways. For example, there are additional hazards that could be examined. Geomagnetic disturbance would be an interesting topic, although the methods are less developed. There are also human threats such as cyber attack and physical attack that could be considered.

System resilience could also be evaluated at other levels. For example, operations could be examined to determine how effective the response would be after an earthquake, and to assess potential shortcomings such as a lack of crews or insufficient spare parts.

For the seismic risk analysis, site inspections by an expert could be done to assess system vulnerabilities, especially in regards to equipment anchorage and seismic interaction. More extensive geotechnical investigations could also be done on particular substation sites to more accurately assess site amplification of ground motion and liquefaction susceptibility. A network analysis could be used to more accurately estimate outages after an earthquake.

The seismic hazard analysis could also be improved by performing a full probabilistic seismic hazard analysis. This would require using a portfolio of many earthquake scenarios, of different magnitudes and sources, and examining the predicted performance of the system under each scenario. The data could then be analyzed using Monte Carlo simulations to create probability distributions of outcomes like component failures, power outages, and financial impacts. This was done to some extent with a portfolio of 30 Magnitude 9 CSZ earthquakes, but other earthquake scenarios were ignored other than what could be inferred from the USGS site-specific hazard curves and the WA DNR Hazus earthquake reports.

It has also become apparent that several areas need more research before being applied to a practical study. It appears that there is a need for more fragility curves to be developed for equipment of the 115 kV and especially the 69 kV voltage classes. Past research has focused on higher-voltage equipment because of its greater susceptibility and value, but these curves if applied to lower voltage equipment are overly conservative. Ideally, fragility curves should be developed for each particular piece of equipment, based on manufacturer ratings, data from earthquakes, shake-table tests, or structural analysis. However, this is difficult to accomplish in practice because of the wide variety of equipment available.

The threat of tsunamis to power systems is one area that could use more research. There seems to be no general methodology for performing a probabilistic analysis of tsunami hazards, or models for estimating substation damage based on tsunami inundation. More research on these topics would be beneficial for this kind of study. Inundation maps for other tsunami scenarios would also be useful. This study was limited to the "worst-case", along with a small number of other maps specific to the Aberdeen area. With probabilistic data or maps for many tsunami scenarios, a probabilistic assessment could be done to better examine the risk posed by tsunamis. In many ways, the worst case may be too catastrophic to prepare for, but it could be more beneficial to harden the system against less severe scenarios that are more likely to occur. Without specific data on these scenarios, this is difficult to assess.

More detailed research can be done on the potential mitigating actions for these natural threats. A cost-benefit analysis would also be an important step before deciding on any course of action to prepare for these events.

5 Conclusions

The report discusses the threat of earthquakes and tsunamis to the Grays Harbor PUD. In particular, a magnitude 9 Cascadia subduction zone earthquake and an L1 tsunami scenario were analyzed in detail. These represent the worst-case disasters that could affect the region. Fragility curves were used to model the expected damage to substation equipment during an earthquake. Damage overall was found to be quite severe for the M9 earthquake.

While the threat of earthquakes to distribution lines and transmission lines is minor, some substation equipment can be very vulnerable. This includes power transformers, regulators, bus connections, disconnect switches, instrument transformers, and battery racks. Substation transformers were found to be the most seismically vulnerable component. Due to the high cost of transformers and long lead times for replacements, transformer failures could be particularly difficult to recover from.

Based on the results of prior studies conducted by the Washington State Department of Natural Resources, it was determined that the threat from nearby crustal faults is low. This includes the Canyon River Fault, Olympia Fault Structure, and Tacoma Fault. Some minor damage to substation components or distribution feeders is possible from these earthquakes, but there are predicted to be no outages in Grays Harbor County for these scenarios. However, there is a threat of moderate damage from deep intraplate earthquakes, which can be up to approximately M7.5 and occur throughout the region. However, these scenarios were not examined.

The Cascadia subduction zone poses a significant threat to the GHPUD system because of its potential to generate earthquakes up to magnitude 9. A magnitude 9 earthquake would create widespread damage in the county. For such an earthquake, we estimate that approximately 27 out of 36 substations will be extensively damaged, at a cost of about \$6.6 million in direct damage. This scenario has a 15% probability of occurring in the next 50 years, and represents the single greatest natural threat to the GHPUD power system.

To reduce the risk of damage from the magnitude 9 earthquake several actions are recommended.

- Adopt the recommended standards of the "high" equipment qualification level specified by IEEE693
- Anchor existing transformers where possible
- Anchor new transformer installations, or consider installing base isolators for increased performance
- Retrofit buswork with flexible conductors or flexible connectors where possible, following the recommended IEEE 1527 standard
- Brace large radiators to reduce moments on pipes that penetrate transformer tanks

A tsunami can be expected following a Cascadia subduction zone earthquake. There is also a risk of tsunami from distant sources. Based on the "worst-case" scenario maps published by the state, we believe that 18 out of 36 substations are vulnerable to tsunami. The substations most at risk are Grayland, Ocean Shores, Oyehut, and Westhaven substations. A major tsunami could also cause damage to the distribution system in coastal areas. It may be possible to protect against tsunami by elevating equipment, waterproofing equipment, constructing levees, or relocating substations.

This work paints a rather grim picture for resilience. However, the cases analyzed are worst-case scenarios, and the estimates erred on the conservative side. While making the system entirely resilient against these scenarios is not practical, measures can be taken improve system performance, especially for less catastrophic but more likely events. This has the benefit of protecting the utility's investments in power equipment and limiting the potential for prolonged outages and economic damage to the local community.

References

[1] Grays Harbor PUD, "Service areas." Accessed on: May 9, 2019. [Online]. Available: https://ghpud.org/about-us/service-areas.

[2] Pacific Northwest Seismic Network, "Deep earthquakes." Accessed on: Mar. 29, 2020. [Online]. Available: https://pnsn.org/outreach/earthquakesources/deepearthquakes.

[3] Washington State Department of Natural Resources, "Washington geologic information portal." [Online]. Available: https://geologyportal.dnr.wa.gov/.

[4] Bonneville Power Administration, "BPA's ground-shaking research could better protect power transformers in quake." [Online], December 2013. Available: https://www.bpa.gov/news/newsroom/Pages/BPAs-ground-shaking-research-could-better-protect-power-transformers-in-quake.aspx.

[5] R. LeVeque and D. Abramson, "Aberdeen, WA Cascadia subduction zone tsunami simulation results." unpublished, 2016.

[6] Federal Emergency Management Agency, *Earthquake Model: Hazus-MH 2.1 Technical Manual.* Federal Emergency Management Agency Mitigation Division, 2013.

[7] D. J. Wald, B. C. Worden, V. Quitoriano, and K. L. Pankow, *ShakeMap Manual.* United States Geological Survey, 2006.

[8] Washington State Department of Natural Resources, "Modeling a magnitude 7.4 earthquake on the Canyon River–Saddle Mountain fault zone in Mason County," 2012.

[9] Washington State Department of Natural Resources, "Modeling a magnitude 7.2 earthquake on the Nisqually fault zone near Olympia, Washington," 2012.

[10] Washington State Department of Natural Resources, "Modeling a magnitude 5.7 earthquake on the Olympia fault in Thurston County," 2012.

[11] Washington State Department of Natural Resources, "Modeling a magnitude 7.1 earthquake on the Tacoma fault zone in South-Central Puget Sound," 2012.

[12] Washington State Department of Natural Resources, "Modeling a magnitude 9.0 earthquake on the Cascadia subduction zone off the Pacific coast," 2012.

[13] Washington State Department of Natural Resources, "Modeling a magnitude 8.3 earthquake on the Cascadia subduction zone along Washington's outer coast," 2012.

[14] D. W. Eungard, C. Forson, T. J. Walsh, E. Gica, and D. Arcas, "Local tsunami hazards in the Pacific Northwest from Cascadia subduction zone earthquakes," tech. rep., Washington State Department of Natural Resources, 2018.

[15] J. M. Eidinger and D. Ostrom, *National Institute of Building Sciences Earthquake Loss Estimation Methods: Electric Power Utilities.* G & E Engineering Systems Inc., June 1994.

[16] B. L. Preston, S. N. Backhaus, M. Ewers, J. A. Phillips, C. A. Silva-Monroy, J. E. Dagle, A. G. Tarditi, J. Looney, and J. Thomas J. King, "Resilience of the U.S. electricity system: A multi-hazard perspective," 2016.

[17] B. Gutenberg and C. F. Richter, “Magnitude and energy of earthquakes,” *Annali di Geofisica*, vol. 9, pp. 1–15, 1956.

[18] J. Park, N. Nojima, and D. A. Reed, “Nisqually earthquake electric utility analysis,” *Earthquake Spectra*, vol. 22, no. 2, pp. 491–509, 2006.

[19] Federal Emergency Management Agency, “Hazus.” Available: https://www.fema.gov/hazus.

[20] A. Frankel, E. Wirth, N. Marafi, J. Vidale, and W. Stephenson, “Broadband synthetic seismograms for magnitude 9 earthquakes on the Cascadia megathrust based on 3D simulations and stochastic synthetics, part 1: Methodology and overall results,” *Bulletin of the Seismological Society of America*, vol. 108, pp. 2347–2369, November 2018.

[21] American Society of Civil Engineers and Structural Engineering Institute, *Minimum Design Loads for Buildings and Other Structures*, 2016. ASCE 7-16.

[22] M. Beaty, S. Schlechter, M. Greenfield, J. Bock, S. Dickenson, L. Kempner, and K. Cook, “Seismic evaluation of transmission tower foundations at river crossings in the Portland-Columbia River region,” in *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute: Anchorage, AK, July 2014.

[23] J. Wilcoski and S. J. Smith, “Fragility testing of a power transformer bushing,” Tech. Rep. 97/57, 1997.

[24] H. H. Hwang and J.-R. Huo, “Seismic fragility analysis of electric substation equipment and structures,” *Probabilistic Engineering Mechanics*, vol. 13, no. 2, pp. 107–116, 1998.

[25] National Institute of Building Sciences, *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*, vol. I. Federal Emergency Management Agency, 2015.

[26] *IEEE Recommended Practice for Seismic Design of Substations.* No. 693-2018, New York, USA: IEEE, 2018.

[27] *IEEE Recommended Practice for the Design of Buswork Located in Seismically Active Areas.* No. 1527-2018, New York, USA: IEEE, 2018.

[28] *Guide to Improved Earthquake Performance of Electric Power Systems.* No. 96, Reston, VA: American Society of Civil Engineers, 1999.

[29] *Substation Structure Design Guide.* No. 113, Reston, VA: American Society of Civil Engineers, 2008.

[30] K. Oikonomou, M. C. Constantinou, A. M. Reinhorn, and L. Kempner, *Seismic Isolation of High Voltage Electrical Power Transformers.* No. MCEER-16-0006, Buffalo, NY: Multidisciplinary Center for Earthquake Engineering Research, 2016.

[31] O. J. Lynch, “Seismic base isolation of a high voltage transformer,” in *Electrical Transmission and Substation Structures 2015: Technical Challenges and Innovative Solutions in Grid Modernization*, pp. 413–425, American Society of Civil Engineers, 2015.

[32] L. Kempner, “Seismic mitigation options for high-voltage electrical transmission substations,” in *Structures 2001: A Structural Engineering Odyssey*, pp. 1–6, 2001.

[33] National Tsunami Hazard Mitigation Program, "Seven principles for planning and designing for tsunami hazards," 2001.

[34] R. C. Witter, Y. J. Zhang, K. Wang, G. R. Priest, C. Goldfinger, L. Stimely, J. T. English, and P. A. Ferro, "Simulated tsunami inundation for a range of Cascadia megathrust earthquake scenarios at Bandon, Oregon, USA," *Geosphere*, vol. 9, pp. 1783–1803, November 2013.

[35] T. J. Walsh, C. G. Caruthers, A. C. Heinitz, E. P. M. III, A. M. Baptista, G. B. Erdakos, and R. A. Kamphaus, "Tsunami hazard map of the southern Washington coast: Modeled tsunami inundation from a Cascadia subduction zone earthquake," Tech. Rep. GM-49, Washington State Department of Natural Resources, 2000.

[36] K. Porter, "A beginner's guide to fragility, vulnerability, and risk," 2019. Available: http://spot.colorado.edu/ porterka/Porter-beginners-guide.pdf.

[37] T. Anagnos, "Development of an electrical substation equipment performance database for evaluation of equipment fragilities," 1999.

[38] R. J. Budnitz, G. S. Hardy, D. L. Moore, and M. K. Ravindra, "Correlation of seismic performance in similar SSCs (structures, systems, and components)," Tech. Rep. NUREG/CR-7237, Office of Nuclear Regulatory Research, 2017.

[39] J.-R. Huo and H. Hwang, "Seismic fragility analysis of equipment and structures in a Memphis electric substation," Tech. Rep. NCEER-95-0014, National Center for Earthquake Engineering Research, 1995.

Appendices

Appendix A Modeling Seismic Damage to Equipment

Fragility curves were used to assess the vulnerability of the equipment to shaking damage from earthquakes. A fragility function is a mathematical model that expresses the probability of failure or damage to a component versus some environmental excitation, which in our case is PGA [36]. Fragility curves can alternatively be keyed to other parameters such as the spectral acceleration at the natural frequency of a structure. PGA is often used for power system equipment because it tends to give the best correlation with damage. Fig. 16 shows an example set of fragility curves. Fragility curves can be empirically derived by fitting a function to observed data, analytically derived using structural analysis, or judgment-based using expert opinion [36]. Unfortunately, little historical data from earthquakes has been collected and analyzed to create fragility functions for relevant substation equipment. A database of earthquake performance for primarily 230 kV and 500 kV transmission equipment was created for Pacific Gas & Electric [37], but little published seismic performance data exists for 69 kV and 115 kV equipment, likely because of the lower capital cost and the lower risk of damage. Likewise, a few analytically derived fragility curves exist for 400+ kV equipment, but none seem to exist for 69 kV and 115 kV.

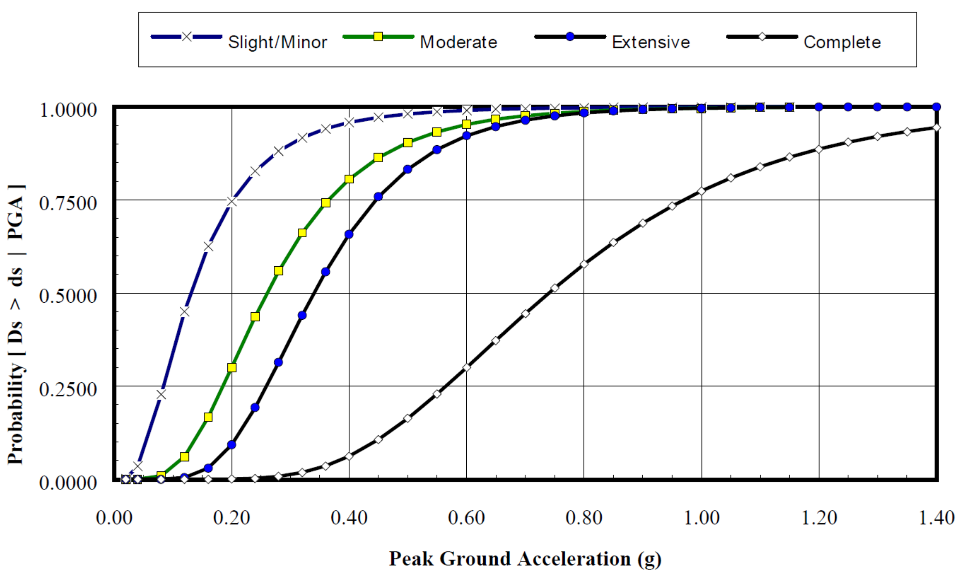

Figure 16: Fragility curves for low-voltage substations [6]

Fragility curves primarily from the National Institute of Building Sciences Earthquake Loss Estimation Methods Technical Manual were used [15] to model equipment vulnerability. The fragility functions are log-normal cumulative distribution functions of the form

$$F_d(x) = \Phi\left(\frac{ln(x/\theta_d)}{\beta_d}\right), \tag{1}$$

where $\Phi(s)$ is the standard normal cumulative distribution, θ_d is the median PGA for failure, and β_d is the standard deviation of the natural logarithm of the PGA. [36]. Table 10 shows the fragility parameters for each piece of equipment. These fragility curves are valid for for 100–165 kV equipment, but they were also used to model the GHPUD's 69 kV equipment due to a lack of published data for the lower voltage class. This results in damage estimates for 69 kV equipment that are overly conservative, but a reasonable approximation for this study.

The failure of each sample of a particular piece of equipment was assumed to be independent, as is the typical practice for a portfolio risk analysis [36]. In some cases the seismic performance of co-located and identical pieces of equipment can be strongly correlated, especially if they are mounted on the same foundation and thus subjected to the same ground motion [38]. However, a lack of data in the literature makes assigning correlation coefficients difficult, so full independence of component fragility was assumed.

Table 10: Fragility curves for 100–165 kV substation equipment [15]

Equipment	Damage factor	θ (g)	β
Transformer - unanchored	0.60	0.50	0.70
Transformer - anchored	0.40	0.75	0.70
12 kV regulator	0.60	0.55 [39]	0.47 [39]
Instrument transformer	0.50	0.75	0.70
Disconnect switch - rigid bus	0.50	0.90	0.70
Disconnect switch - flexible bus	0.10	1.20	0.70
Lightning arrester	1.00	1.00	0.70
Bus structure - rigid	0.15	1.00	0.70
Bus structure - flexible	0.05	2.00	0.70
Dead tank circuit breaker	0.40	2.00	0.70
Other yard equipment	0.50	1.00	0.70

Whole-substation fragility curves (Table 11) from Hazus that model the probability of damage for an entire substation were also used [6]. Five damage states of increasing severity are defined, with an approximate percentage of the components damaged, expected repair cost as a fraction of substation value, and parameters θ and β for the log-normal fragility curves. The expected repair time of each damage state is assumed to follow a normal distribution, with the mean and standard deviation σ given in Table 11.

Table 11: Fragility curves for 34.5–115 kV substations [6]

Damage state	% damage	Repair cost ratio	Mean restoration time (days)	σ	θ (g)	β
None	<5%	0%	0	N/A	N/A	N/A
Minor	≥5%	5%	1	0.5	0.13	0.65
Moderate	≥40%	11%	3	1.5	0.26	0.50
Extensive	≥70%	55%	7	3.5	0.34	0.40
Complete	≥80%	100%	30	15	0.74	0.40

Restoration times assume the following [15]:

- Weather permits

- Spare parts are available
- There is a sufficient number of crews available
- Power demand after an earthquake does not exceed the substation's capacity (this is likely to be a valid assumption because power demand typically drops after an earthquake)

The fragility curves used only model damage based on ground shaking. Damage due to ground failure, such as such as liquefaction, landsliding, and surface fault rupture was neglected. For a more accurate assessment of seismic risk these additional damage modes should be considered.

When estimating customer impacts it was assumed for simplicity that all customers normally serviced by a substation would experience an outage if that substation sustained moderate damage or greater. A substation with minor damage would likely still be operable due to the redundancy in equipment. This is methodology is still likely to be overly conservative due to the equipment redundancy, however. Additionally, outages due to distribution system damage was neglected. More accurate outage estimates would consider distribution system damage and redundancies in the system at each level. However, the results in this study should provide a reasonable approximation for the worst-case scenario.

Appendix B Equipment Inventories and Capital Costs

An estimated inventory of the equipment in each substation was provided by GHPUD and is shown in Table 12. This inventory is not comprehensive, although it contains most of the major equipment contained in the substations for which we were able to find suitable fragility curves to model. Some of these counts may not be exact, as typical values were assumed for some substations. The capital costs shown in Table 13 were used when calculating financial loss. These are rough estimates that include the cost to purchase the item and labor, but they may not be accurate in every case. It is expected that much of the damaged equipment can be repaired, rather than replaced. This was accounted for by multiplying the capital cost by the damage factor that is given with the fragility curve. This damage factor is the ratio of the expected repair cost to the replacement cost. In reality, the actual repair cost will vary depending on the severity of damage, but these figures represent averages based on past earthquakes. The same costs were assumed for 115 kV and 69 kV equipment.

Table 12: Substation equipment inventory

Substation	Distribution circuits	115/69 kV transformer	115/12 kV† transformer	115 kV† circuit breaker	Disconnect switch	Bus structure	Current transformer*	Potential transformer*	Lightning arrester*	12 kV regulator	Control building	Switchgear building
Adams Street	4	0	1	2	8	2	0	2	1	0	0	1
Axford Prairie	2	0	1	1	7	3	0	1	1	0	1	0
Bernard Creek	2	0	1	0	1	2	0	1	1	1	1	0
Cedarville	3	0	1	0	1	2	1	1	2	1	1	0
Central Park	4	0	1	0	1	2	0	1	2	1	1	0
Copalis Crossing	2	0	1	0	1	2	1	1	1	1	1	0
Cosmo Fiber 13 kV	1	0	1	0	1	0	0	0	1	0	0	0
Cosmo Fiber 4 kV	1	0	1	0	1	0	0	0	0	0	1	0
Cosmopolis	3	0	1	0	1	2	1	1	2	1	1	0
Crane Creek	0	0	1	0	1	0	0	0	0	0	0	0
East Hoquiam	3	0	1	0	1	2	1	1	2	0	1	0
Electric Park	7	2	2	12	46	6	0	2	2	0	1	2
Elma	5	0	2	2	6	2	2	3	3	0	1	0
Grayland	3	0	1	0	1	2	1	1	1	0	1	0
Harding Road	4	0	1	2	5	2	0	1	1	0	1	1
Harpo	1	0	1	0	1	0	0	0	0	0	0	0
Highlands	0	2	0	9	26	4	0	3	0	0	2	0
Hoquiam Plywood	1	0	1	0	1	0	0	0	0	0	0	0
Junction City	1	0	0	2	2	0	1	1	0	0	0	0
Mayr Brothers	2	0	1	0	1	0	0	0	2	0	0	0
Moclips	3	0	2	0	1	2	0	1	1	0	1	0
Monroe Street	2	0	1	0	1	2	1	1	1	0	1	0
Montesano	6	0	2	2	8	2	1	4	5	1	1	0
Ocean Shores	5	0	2	0	2	2	1	2	5	1	1	0
Oyehut	3	0	1	0	1	2	1	1	2	1	1	0
Pacific Veneer	1	0	1	0	1	0	0	0	1	0	0	0
Powell Road	0	0	0	5	13	2	0	4	0	0	1	0
Promised Land	1	0	1	0	1	0	0	0	0	0	1	0
Quinault	3	0	1	0	1	2	1	1	2	1	1	0
Satsop Park	4	0	2	2	6	2	0	2	1	0	0	1
Scott Street	4	0	1	0	1	2	1	1	2	0	1	0
South Elma	0	0	0	4	6	1	0	1	1	0	1	0
State Street	5	0	1	0	1	2	0	0	1	0	0	1
Valley	4	0	1	2	5	2	0	1	1	1	0	1
Westhaven	2	0	1	0	1	2	1	1	1	0	1	0
Westport	4	0	1	1	3	2	1	1	2	0	0	1

*Set of 3

†Also includes 69 kV equipment

Table 13: Capital costs of equipment

Item	Value (thousands)
115/69 kV autotransformer	$1,200
Switchgear building†	$950
115/12.5 kV‡ transformer	$600
12 kV regulator	$280
Control building†	$250
Transmission bus structure	$80
Distribution bus structure	$60
115 kV‡ circuit breaker	$50
Current transformer	$35
Potential transformers*	$30
15 kV circuit breaker	$20
Lightning arresters*	$9
Gang-operated switch	$6
Disconnect switches*	$2

*Set of 3

†Includes equipment inside

‡Also used for 69 kV equipment