CASCADIA'S MULTI-HAZARD ENVIRONMENT

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ABSTRACT:

The Pacific Northwest of the United States is exposed to multiple natural hazards, including the severe winter storms and Cascadia Subduction Zone earthquakes and tsunamis. A winter storm in December 2007 caused $250-$300 million (USD) in losses and five fatalities in a small scale disaster in Oregon. Critical infrastructure was damaged, including: 230 kV electrical transmission, telecommunications including 911 emergency communication, 85% of international fiber optical connectivity, and the transportation systems with 366 highway closures. Most of the damage to vulnerable infrastructure (lifelines) and buildings was caused by sustained high winds, flooding and landslides. The response and recovery efforts were slowed in large part due to interdependent infrastructure, such as lack of communication due to power outages. A repeat of the 1700 prehistoric Cascadia earthquake would be a catastrophic disaster with widespread impact. Expected losses in Oregon from a magnitude 9 Cascadia earthquake are over $30 billion (USD) and over 5,000 fatalities.

This paper describes the impact, damage and losses of the 2007 storm in Oregon. It then compares the 2007 storm to projected losses in Oregon from a Cascadia earthquake and tsunami. Recommendations for prioritized mitigation for critical infrastructure and civic infrastructure protection are described for a multi-hazard environment. Especially vulnerable areas require proactive risk reduction measures. For low lying tsunami-prone coastal communities, the construction of tsunami evacuation buildings in high tsunami hazard zones combined with aggressive public education and reliable near-field tsunami warning systems are needed to ensure adequate safety.

KEYWORDS: Cascadia, earthquake, tsunami, storm, hazards, lifelines, infrastructure

1. INTRODUCTION

The Pacific Northwest of the United States is exposed to multiple natural hazards, including the severe winter storms and Cascadia Subduction Zone (CSZ) earthquakes and near-field tsunamis (Figure 1). An extraordinary winter storm in December 2007 hit Oregon and Washington with hurricane force winds, treacherous sea conditions, heavy rain and flooding resulted in a small scale disaster. The most likely catastrophic disaster in the Pacific Northwest is a Cascadia subduction zone (CSZ) earthquake and tsunami.

In the state of Oregon, storm related losses were $250-$300 million (USD) and five fatalities were suffered. Damage and losses in Washington state were considerably higher than in Oregon but are outside the scope of this paper. In Oregon, critical infrastructure was damaged, including: 230 kV transmission, 911 communication, 85% international fiber optical connectivity, and the transportation systems with 366 highway closures. Most of the damage to vulnerable lifelines and buildings was caused by sustained high winds, flooding and landslides. The response and recovery efforts were slowed in large part due to co-located and interdependent lifelines, such as lack of communication due to power outages or blocked roads. A repeat of the 1700 Cascadia earthquake would be a catastrophic disaster. Expected losses in Oregon from a magnitude 9 Cascadia earthquake are over $30 billion (USD) and 5,000 fatalities. This paper describes the impact, damage and losses in Oregon caused by the December 2007 storm. It then compares the 2007 storm to projected losses in Oregon from a future magnitude 9 CSZ earthquake and tsunami.

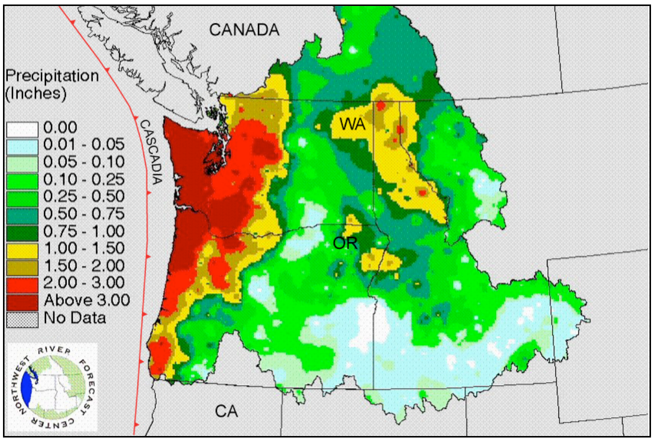

Figure 1. Map of Region showing 2007 storm rainfall and CSZ (Modified from NW River Forecast Center)

In order to be able to recover from disasters, that is, become a disaster resilient region, a CSZ scenario of the critical infrastructure systems is required to determine the interdependencies and vulnerabilities. Then, prioritization and mitigation of the systems is required in order to ensure adequate performance. The paper concludes with lessons learned from past disasters. Preliminary recommendations to improve disaster resilience for prioritized mitigation of critical infrastructure and civic infrastructure protection in a multi-hazard environment are discussed.

2. DECEMBER 2007 SEVERE STORM

A severe winter storm hit the Pacific Northwest in early December 2007. In Oregon, storm waves heights reached 16 m (47 ft), winds gusted up to 206 km/h (129 mph) and rainfall totaled 37 cm (14.5 inches) between December 1st and 3rd. The brunt of the damage was in northwestern Oregon and southwestern Washington, where waves, wind, flooding and landslides caused localized damaged. Roads, highways, bridges and railways, buildings, and some entire small communities were impacted. Transportation between the coastal towns and the Willamette Valley was severely limited for days. Telecommunication and electric power systems sustained extensive damage due to wind, flooding, landslides, and erosion. These critical lifeline services were out in some areas for days. Water and waste water systems, coastal jetties, agricultural and forest lands were damaged. As of July 2008, many systems had not been restored.

The governors of the two states declared a state of emergency and launched response and recovery operations. Federal Emergency Management Agency (FEMA) of the U.S. Department of Homeland Security, Oregon Emergency Management, Federal Highway Administration, Oregon Department of Transportation, Small Business Administration, not-for-profits, and others provided disaster assistance. Many industries were impacted, including: holiday consumerism, tourism, timber, fishing and crabbing, transportation including railway transportation, shipping in the Columbia River waterway, trucking, as well as numerous small businesses. U.S. Interstate 5, the major north-south transportation route was flooded for four days in Washington. The diverted traffic incurred losses estimated at $4 million each day.

2.1 Oregon's Direct Losses

Total direct losses are estimated at $250-$300 million. See Table 2.1 Estimated Direct Losses in Oregon. Five fatalities were suffered. Indirect losses are expected to be on the order of 5 to 10 times the direct losses.

Table 2.1 Estimated Direct Losses in Oregon

Losses (in millions)	**Subject**	**Sources**
$62.5	Infrastructure	FEMA Damage Assessment
$94.1	Housing	FEMA Damage Assessment
$22	Business losses	FEMA Damage Assessment
$2	Private non-profit	FEMA Damage Assessment
$42	Timber losses (private and public lands)	Estimated based on Oregon Department of Forestry data
$15.5	Forest roads (private and public lands)	Estimated based on Oregon Department of Forestry data
$14.5	Transportation system	Data from Oregon Department of Transportation
Not available	Agriculture, including livestock	Oregon Department of Agriculture; Farm Service Agency
Not available; see below discussion	Private utilities	Public Utility Commission

The Technical Council on Lifeline Earthquake Engineering (TCLEE) of the American Society of Civil Engineers (ASCE) conducted an investigation of the storm damage. As part of the TCLEE investigation, the Oregon Public Utility Commission invited private energy and telecommunication companies to meet and discuss loss of critical infrastructure service and their storm impacts. The meeting resulted in a productive exchange of information on damage, some relating co-location issues and upstream and downstream interdependencies among lifelines. The private utilities that reported damage included: PacifiCorp, Portland General Electric, NW Natural, Verizon, Qwest, WCI, Centurytel, Embarq, AT&T and others.

Public electricity providers also sustained damaged including the Department of Energy's Bonneville Power Administration (BPA), Western Oregon Electric Company, Lincoln County Public Utility District and others. The BPA electrical transmission system was damaged, including Timber Substation that flooded and portions of the 230 kV transmission system that sustained wind damage. The most prevalent damage to the electrical systems was incurred by trees that were blown onto transmission right-of-ways. One large provider reported 57,000 customers without electricity during the peak damage period.

Telecommunication services, including both landlines and wireless (cellular), experienced various challenges involving both local and international disruptions to voice and data services. The systems include optical fiber cable toll links including submarine cables, microwave dishes, copper cable toll links, cell sites, satellite services and independent radio operators. Public safety answer point (PSAP) 911 emergency communications were inoperable in areas. Satellite services were unreliable. A telecommunications central office was flooded. Several fiber optic cables were severed due to river bank erosion, debris-laden channel scour and deposition, and tree-damaged electrical towers with co-located fiber lines. A microwave dish and antennas experienced wind damage. Back up power was exhausted at dozens of cellular towers. Ham radio communications maintained reliability. Certain regions were isolated for days, in part due to the lack of geographic redundancy or a system loop configuration. Due to systems configuration, northern and southern Lincoln County and the south coast are inherently vulnerable to isolation. Interruptions in telecommunications can be very costly in terms of human safety and business operations.

Oregon experienced 366 road closures and areas of delay over 1,800 road miles according to the Oregon Department of Transportation. Forty closures were due to landslides and 27 roads were closed due to downed power lines and fallen trees at 115 locations. A number of bridges and roads are under-designed for flood conditions, which led to overtopping of bridges, and flooding, scouring and washouts of roads. Columbia River Bar Pilots, located at the river mouth in Astoria, closed the navigable waterway along the Columbia River for river traffic. Approximately 20 cargo ships were delayed. Also, according to the U.S. Army Corps of Engineers, several coastal jetties were damaged.

2.2 Community Impacts

A Presidential major disaster declaration (FEMA-1733-DR-OR) was issued on December 8, 2007 for the northwestern counties of Clatsop, Columbia, Lincoln, Tillamook, and Yamhill. Additional counties and tribes became eligible for federal assistance as more damage became apparent.

Transportation and infrastructure services along the state highway 30 that parallels the Columbia River and coastal U.S. Highway 101 corridors were impacted or damaged due to landslides, downed trees from wind damage, and flooding. Clatskanie, Woodson, Westport, Astoria, Cannon Beach and many other towns were affected. The dam and water conveyance system was destroyed by stream channel scour and deposition in Westport. As of July 2008, Westport was still on boiled water alert. In an after-action review of Clatsop County, it was reported that the storm and the resulting aftermath affected the county and its citizens in several ways, including:

- Electricity was largely lost throughout the county for up to six days.
- Phone service disrupted throughout the county.
- Cell-phone and satellite phone service disrupted throughout the county.
- Inability to maintain food stores and fuel throughout the county.
- Shelter operation challenged by the widespread need.
- Transportation severely impacted due to downed trees and landslides, isolated 3 days.

- Debris removal and management issues.

In Columbia County, about 800 homes were damaged, of which 200 were insured for floods and 260 were in Vernonia. Vernonia and vicinity (including towns of Mist, Birkenfeld, and Fishhawk Lake) were flooded and hit with landslides. In Vernonia, flood water reached four feet above the 100-yr "base flood elevation" in parts of town. The Nehalem River and Rock Creek flooded businesses, schools, homes and lifelines, including a central office for a telecommunication service provider of 1,800 service lines, the electric substation and headquarters, waste-water ponds, and overtopped the bridge spanning Rock Creek.

Washington elementary school was flooded, including with waste water from overtopped sewage ponds. This 1930s school is subject to severe consequences from even a moderate sized earthquake because the construction is of unreinforced masonry (URM) with a high global collapse potential. The structural system in grossly inadequate by modern standards and has been poorly maintained over the decades. In contrast to floods, occupants will have no warning before an earthquake strikes.

Woodson, Midland, Marshland, and the Clatskanie area experienced flooding and mudslides. The small community of Woodson, which is located on state highway 30, was severely damaged from a debris flow, a fast moving, water-ladened, landslide. Figure 2 shows the debris flow fan, which engulfed the community, state highway 30, the railway, and several lifelines, before entering the Columbia River. The photo shows the highway after the debris was removed. Approximately 50 km of state highway 30 are at risk from channel scour, debris flows and landslides from the adjacent hills to the south in Columbia and Clatsop Counties.

Figure 2. Debris Flow Fan that Inundated a Community and Lifelines

Lincoln County experienced wave, flooding and wind damage. In Tillamook County, extensive damage to the railroad operated by the Port of Tillamook was incurred. Miles of railroad, which includes right-of-ways for three fiber optic lines, were flooded and experienced wash-outs, erosion, flooding and landslides. Portions of the city of Tillamook were flooded, including areas with sewage overflows and U.S. Highway 101.

3. COMPARING 2007 STORM AND CASCADIA EARTHQUAKES & TSUNAMIS

The damage from the 2007 storm was investigated in order to better understand the performance of lifelines due to wave, wind, and flood damage. As part of the investigation, system vulnerability to earthquake hazards was determined where possible as a means for multi-hazard loss reduction. The flooding from the 2007 storm was considered to be about a 40-yr flooding event in the worst flooded areas. In contrast, a magnitude 9 CSZ earthquake and tsunami has a recurrence interval of about 1 in 6 over 50 years. A CSZ is considered to be a low probability, high consequence event.

Direct losses from a CSZ event is estimated to be about two-to-three orders of magnitude higher than the 2007 storm. A CSZ event would result in a catastrophic disaster on national level and have a long term recovery process. Table 3.1 2007 Storm and CSZ Earthquake and Tsunami Damage in Oregon compares the damage in Oregon from the 2007 storm to estimated damage in Oregon from a future magnitude 9 Cascadia earthquake and tsunami.

Table 3.1: 2007 Storm and CSZ Earthquake and Tsunami Damage in Oregon

	2007 Storm	**CSZ quake/tsunami**	**Factor Difference**
Cost (in USD)	$250-300 million	$30 billion	100x
Fatalities	5	over 5,000	1000x
Damage Zone (sq km)	3,000	60,000	20x

The 2007 storm hazards included large coastal waves, high velocity and sustained winds, flooding, erosion in the vicinity of drainages, and landslides over a relatively small geographic region. The National Weather Service provided storm warning information. In contrast, hazards from a CSZ event would impact a broad region including several states and no forewarning would be issued. CSZ hazards include strong ground shaking rich in low frequency waves for several minutes, amplification of shaking in soft soils, liquefaction, landslides, and tsunami inundation along the coastline. Research suggests possible directivity effects in Portland, Oregon, and basin effects in the Willamette Valley, Oregon, which is a geologic forearc basin characteristic of subduction zone settings. Shaking in the east-west direction may be stronger than the north-south direction due to the north striking orientation of the CSZ and the east-dipping fault plane and associated east-west slip.

4. RECOMMENDATIONS BASED ON LESSONS LEARNED

All too often, older infrastructure is not adequately maintained or upgraded. During disasters, vulnerable infrastructure fails and is repaired and strengthened as part of disaster recovery. Perhaps the most important lesson from this investigation is that civic infrastructure (such as schools and emergency facilities) and critical infrastructure (such as the energy sector, telecommunication, and transportation) require a higher level of robustness to ensure public safety in the case of severe natural disasters. Particularly in terms of seismic hazards, many facilities were built long before modern understanding of seismic engineering. Much of it should be reevaluated then mitigated to ensure adequate public safety. Being pro-active by implementing cost-effective pre-disaster mitigation measures can greatly minimize the impacts from disasters. On the other hand, if prudent corrective actions are not taken, then it is likely that society will continue to be hit with costly and worsening disasters.

By applying lessons learned from recent disasters, we can increase the effectiveness of risk reduction measures, thereby reducing potential losses. The following recommendations are provided to help manage natural disaster risks. They were developed from research findings and lessons learned from this storm as well as from worldwide earthquakes.

- Civic infrastructure including schools, emergency management centers, fire stations, police stations, and hospitals, especially those on poor soils or zones prone to flooding, landslides, or earthquake-induced liquefaction or amplification, or in storm surge, should meet modern building codes and should be able to withstand strong storms and earthquakes. Any existing important facilities and communities at high risk, including with high tsunami hazards, should be mitigated before disaster strikes.

- Critical facilities and lifelines facilities that contain significant hazardous materials, that serve important functions to society (e.g., energy facilities), or that have other sensitive parameters should meet modern building codes and should be able to withstand severe storms and major earthquakes. Those facilities co-located or interdependent with other lifelines should require special performance considerations to avoid multiple or cascading failures. Any existing critical facilities and major lifelines at high risk should be mitigated before the disaster and have adequate safeguards for the public.

- Redundancy of important lifelines, both in terms of geographic diversity of network links and technology diversity, can help increase resiliency and adequate performance of the systems. Adequate redundancy should be available in important lifeline systems, such as loop configured systems for fiber optical toll systems for voice and data transmission.

- Expect and prepare for damage after major natural disasters. Knowledge of vulnerabilities determined from risk assessments is vital for pre-disaster preparations. Having post-disaster emergency funds is needed for efficient response and recovery.

5. RECOMMENDED TASKS

Regions need to have reliable critical and civic infrastructure. Recommended tasks for prioritized mitigation for critical and civic infrastructure protection are discussed. Most regions are exposed to multiple natural hazards, such as floods, earthquakes, tsunamis, windstorms, dust storms, wildfires, drought, coastal erosion, volcanic hazards, and landslides. It is not feasible to eliminate damage from all natural hazards. However, it is prudent to understand the existing hazards and the probability of those hazards occurring. It is recommended to understand the exposed infrastructure and its vulnerability in order to evaluate the impact of the event and to manage the risk. Risk management of critical and civic infrastructure includes these five elements: hazard identification, risk assessment, engaging stakeholders, prioritization and cost effective mitigation.

- Evaluate and mitigate critical infrastructure, including energy systems, telecommunication systems, levees, dams, water systems, waste water systems, and sites with hazardous materials. Critical infrastructure should have defined performance standards in which to meet.

- Evaluate and mitigate priority transportation routes for use during disasters. These may include airports, ports and harbors, navigable waterways, highways, bridges, and railways.

- Evaluate and mitigate high risk civic infrastructure. These may includes schools, hospitals, fire stations, police stations, emergency operation centers, 9-11 call centers, and ambulance services.

For the above three recommendations, establishing institutionalized funded mitigation programs will ensure adequate progress. These programs may include non-seismic aspects, such as deferred maintenance, sustainable practices, energy efficiency, modernization, renovation, expansion, and more. Encourage emergency generators and adequate emergency power at prioritized facilities for use during a disaster. Those could include cellular towers, gas stations, banks, food supplies, movable bridges, security gates, traffic control equipment, and more.

Determine less costly mitigation solutions as a means to be cost efficient. Establish mutual aid and cooperative agreements with other entities as part of the mitigation solutions (e.g. utilities, counties). Encourage pre-planned staging areas throughout the region.

5.1. Tsunami Evacuation Buildings (TEBs)

Low lying coastal communities along the Pacific Northwest are at-risk of near-field tsunami inundation generated by CSZ earthquakes. Certain communities were developed long before scientists understood the existing tsunami hazards. As such, about 100,000 people are in the tsunami inundation hazard zone each day in Oregon. Some of these 100,000 people are in the high hazard portion of the inundation zone nearest to ocean and river channels with long travel distances to safe, higher elevation land.

Low lying tsunami-prone coastal communities require proactive implementation programs, such as aggressive education, tsunami evacuation buildings (TEB) and reliable near-field tsunami warning systems. People who cannot safely evacuate the tsunami inundation zone should be able to evacuate to a TEB within 500 to 1,000 m. An estimated dozen or more TEBs should be available in Oregon alone. TEBs may be reinforced concrete structures with deep scour-resistant foundations and a minimum of two stories. The lowest story should be open space on the ground floor to allow for water and debris passage. Or, the lowest floor should be designed to be sacrificial, such as with break away walls. The elevation of the bottom of the second story should be higher than the anticipated tsunami inundation elevation. The roof may be designed for general purposes, such as for parking or recreation space. It may also be designed for emergency purposes, such as for evacuees, heliport, emergency storage of food or medical supplies, emergency generator, emergency vehicles and so on. TEBs may be designed with energy dissipation or deflection structures facing the ocean to allow water to flow past the structure. In addition, TEB design should accommodate rapid ingress by foot traffic during tsunamis and be readily identifiable to evacuees. TEBs should allow for a minimum of 1 sq m per evacuee. Because tsunamis are rare, TEBs should serve a daily purpose.

Figure 3 is a schematic design of a hypothetical two story concrete TEB with deep foundations and rooftop parking. Floor 1 includes a tsunami education center and other community functions, which would be sacrificed during a tsunami. Floor 2 includes office space and is elevated above the tsunami inundation elevation. The top floor is for parking, emergency supply storage, and has a readily identifiable TEB beacon and siren for evacuees. Two vehicular ramps and two staircases, which are located away from the ocean, allow for mass emergency ingress including wheelchair access.

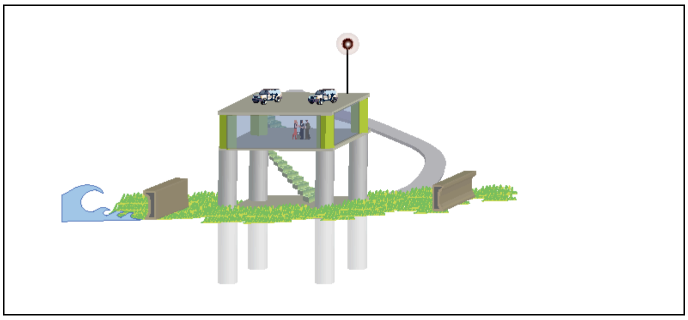

Figure 3. Schematic Design of Tsunami Evacuation Building (TEB)

6. CONCLUSIONS

Not until society invests in its aging infrastructure will we achieve disaster resilience-- the ability of recover from disasters. In order to increase investments towards disaster resilience of infrastructure and reliable infrastructure services, awareness by decision makers must be improved so that it becomes a funding priority.

The most likely catastrophic disaster in the Pacific Northwest is a CSZ earthquake and tsunami. This region is currently not prepared for a future magnitude 9 earthquake and near-field tsunami. A first step towards minimizing future disasters and building a disaster resilient region is to conduct a CSZ scenario of the critical infrastructure to determine their interdependencies and vulnerabilities. After that, prioritization and cost effective mitigation of critical paths is required to ensure adequate performance for our societal needs. Certain areas prone to hazards require special consideration, such as near-field tsunamis, major landslides, regional liquefaction and permanent ground deformation, and flooding. Areas that may require special preparedness measures include communities in high hazard tsunami zones, hazardous material sites, industrial areas, major airports and other sites. *Our society should refocus from disaster response and recovery to pro-active disaster reduction.*

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