5.2 Landslides

- Seattle has steep hills, wet winters, and geology that is prone to landslides. Landslides occur frequently, especially in the winter and early spring.
- 8.4% of the city's surface is covered by areas identified as slide prone in the city's Environmentally Critical Areas Ordinance. 81% of the slide-prone area is zoned for open space, the right of way, or single-family residential areas. The City of Seattle is the largest owner of landslide-prone slopes.
- The most common landslides in Seattle are shallow (less than 6 – 10 feet deep), fast moving (up to 60 km per hour) slides that occur on undeveloped slopes. Shallow slides can have run-outs that exceed 50 feet.[209] Less common are deep-seated landslides that cover a wider area and have a depth of movement greater than 6 – 10 feet.[210] Small movements of deep-seated slides occur gradually over weeks or months. They can be very destructive to property and infrastructure if this gradual movement is not identified before a large failure of the slope occurs.
- Landslides are more likely to occur when soils are saturated. Many landslides can occur within a few days when Seattle experiences heavy rainfall or rapid snowmelt.
- Response to landslides can be more difficult when they are triggered by an event like a winter storm, which is often associated with other hazards such as widespread flooding.
- Traditional home-owners insurance policies do not cover landslide damage, making property owners extremely vulnerable to economic loss.[211]
- Freight and passenger rail lines run along landslide-prone slopes. Landslides have disrupted or canceled passenger trains along the Puget Sound over 500 times from 2015 – 2018.[212]
- Landslides can trigger secondary hazards like flooding and hazardous materials incidents.
- The City of Seattle has undertaken measures to mitigate vulnerability to landslides. They include inventorying and mapping landslide prone areas, requirements to stabilize building sites during construction, public education, and slope stabilization projects. Mitigation often requires cooperation between private land owners and the city.

5 2.1 Context

Washington state experienced its most deadly landslide in March 2014, when the SR 530 "Oso" Landslide destroyed an entire neighborhood and took 43 lives. Nationally, landslides cause over 25 deaths and cost about $3.5 billion per year in the U.S. Landslides are a common natural hazard in Seattle, but most result in minor consequences to private property.[213]

A landslide is the movement of a mass of soil, rock, or debris down a slope. Landslides occur when the force of gravity on a slope exceeds the strength of the earth materials that compose the slope. The amount of downslope force and/or slope material strength changes with a variety of factors including precipitation, changes in water level, erosion, ground water, earthquakes, prior landslides, or human activity.[214] There is typically more than one cause. The most frequent triggers of landslides in Seattle are human alteration of the slope, groundwater saturation, or a combination of both. For example, a person may cause a pipe to leak and saturate the ground, triggering a landslide. Landslides that occur under water are called submarine landslides.

While landslides do not always fit neatly into a specific category, Seattle experiences four general types:[215]

- Shallow landslides: shallow (less than 6 – 10 ft) and rapid slides on a slope, which may result in a debris flow. These slides can attain speeds of up to 60 km per hour and can have debris runouts that exceed 50 feet.[216] Although they are typically minor, their potential speed and long runout can make them dangerous to humans. Over two-thirds (69%) of all landslides in Seattle are shallow.
- Deep-seated landslides: deep (more than 6 - 10 ft), typically ancient, landslides that have been on the landscape for centuries or longer. People build on them, not recognizing the hazard. Deep-seated landslides may reactivate, often due to months or years of above average precipitation or modification of the slope or other processes. Most deep-seated landslides are slow, allowing people to escape them without issue. However, some can be dangerous if they go undetected, and they can cause considerable damage to buildings and infrastructure. Between 18-19% of all landslides in Seattle.
- High Bluff Peel-off: blocks of soil fall from the high bluffs primarily along the cliffs of Puget Sound. Between 3-4% of all slides.
- Groundwater Blowout: groundwater pressure built up at the contact between overlaying pervious (sand) and underlaying impervious (clay) soil units causes increasing groundwater pressure that may initiate a landslide. Between 5-6% of all slides.

Deep-seated landslides usually occur more suddenly on slopes made of pervious soils, like sand. Slopes with more impervious material like silt and clay, experience gradual movements over weeks to months. There can also be dormant landslides that go unrecognized until they begin to move again. It is believed that there had been smaller landslides at the same location of the 2014 Oso landslide, making the slope more unstable to begin with.[217] When slopes are struck by a sudden event such as an earthquake, heavy rain, or human alteration, landslides can occur.

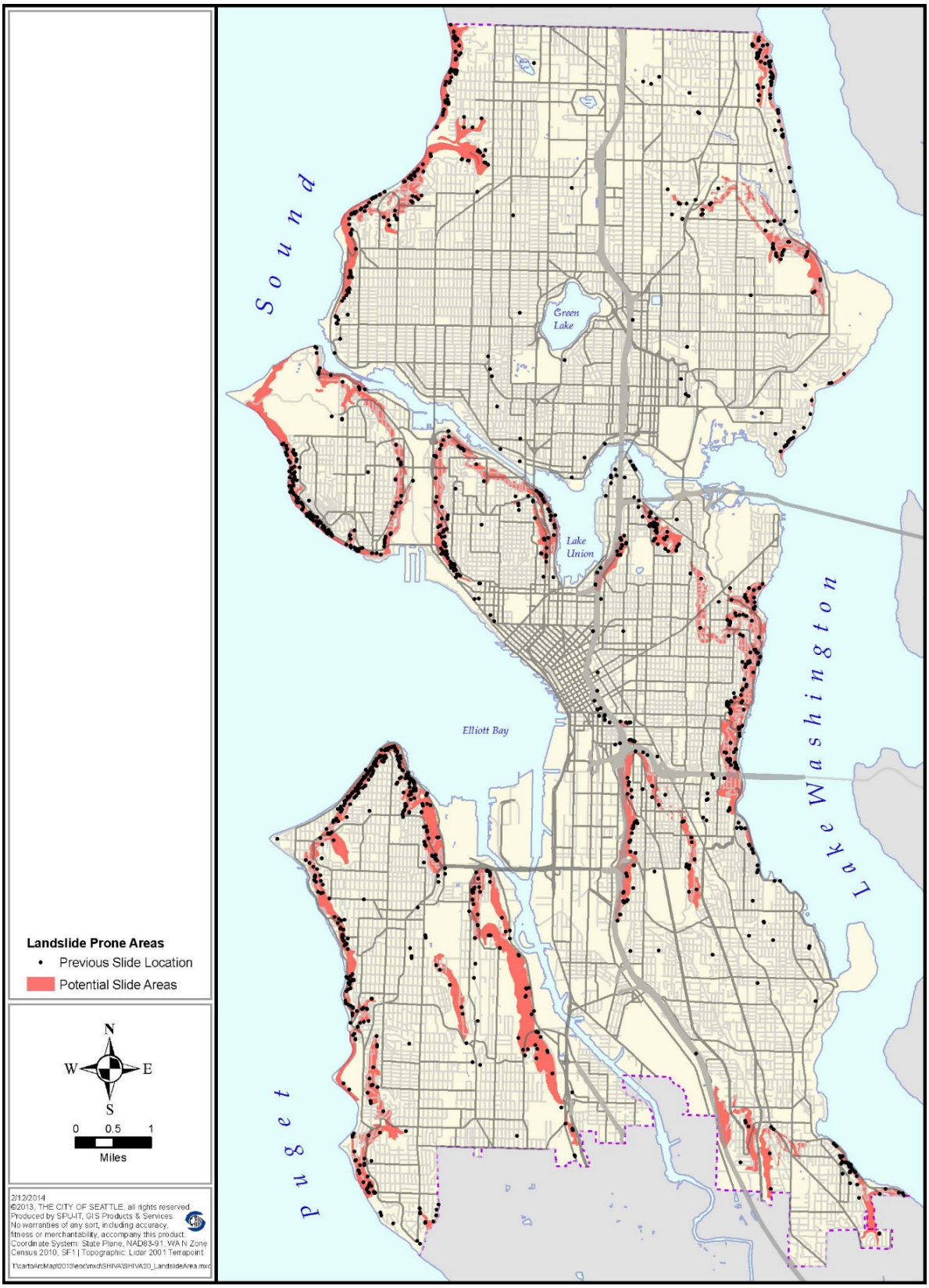
It is difficult to correlate the size of landslides with fatalities. Fatalities have occurred in relatively small slides, many of which happened at construction sites. While deep landslides have caused fatalities when they go undetected, such as with Oso, they are often slower moving, giving people enough time to detect the threat and remove themselves from harm.

Most landslides happen between late October and late March, due to greater levels of precipitation during these months. However, even if the landslide "season" is over, slides can be delayed and occur beyond early spring.[218] According to Tubbs, the probability of sliding rises after a wet, cold winter, especially if a freeze occurs in late winter and early spring.[219] The ground becomes saturated over the winter, and then porous following a freeze, so a subsequent rain will penetrate the surface while the high water table will prevent the ground from absorbing it. The water increases the slope stress by adding weight and increasing pore pressure within the soil.

Landslide Monitoring

The U.S. Geological Survey (USGS) created a tool to help the Seattle public understand when there is a heightened risk for landslides. This tool can be found online at https://landslides.usgs.gov/monitoring/seattle/. It consists of various graphs modeled on historic events and current national weather service data. The graphs show the 15-day cumulative precipitation forecast, the intensity of rainfall in the past 70 hours, a rainfall intensity and duration index for the past 14 days, and a water balance model that shows how wet the soils are. The tool also includes graphs that show real-time data from monitoring instruments located north of Seattle on slopes similar to those in the city. Those graphs include rainfall and soil water content. Most of the graphs have thresholds that can be monitored to see whether there is a heightened real-time or forecasted risk for landslides. This work also produced a map of shallow landslide hazards that shows relative likelihood of shallow landslides (i.e., from low to high).

Figure 5-10. Landslide and Landslide Prone Areas



5 2.2 History

From the time records began being kept in the 1890s to 2000, Seattle has recorded 1,326 landslides. The events listed below were found in newspaper articles and city records. Only the events that required significant city response are included. Most of them happened during winter storms and involved multiple slides incidents throughout the city. Shannon & Wilson indicated that Seattle's three worst years for landslides were 1933/34, 1985/86 and 1996/97.[220]

1921 Six major slides occur during one weekend.[221]

1933/34 More than 400 Seattleites battle slides in ten areas of the city. These slides prompted numerous repair projects.[222]

1941 Several slides occur during December around Sand Point.[223]

1947 Several children die when a slide destroys their home.[224]

1948 Multiple slide events in Magnolia and Yesler Terrace.[225]

1950 Many slides occurred in the spring. They may have been connected with heavy snowfall as the 1997 events were.[226]

1961 Slides occur in many areas of the city during the spring.[227]

1965 SR 520 threatened, one lane closed, Roanoke interchange closed.[228]

1966 A large slide closes Golden Gardens Drive NW to traffic in January. Shannon and Wilson's Landslide Study reports this as a heavy winter.

1969 Large slides occur on Magnolia Bluff.[229]

1971/72 Slides destroy homes in Madrona causing about $1.8 million in damage. These slides were also probably connected with snowfall.[230] Largest number of landslides since 1933/34.

1974 West Seattle experiences multiple slides in the winter. Golden Gardens was also damaged. The mayor authorizes assistance.[231]

1983 Queen Anne slide closes Aurora for a day. Mud travels as far as Lake Union.[232]

1985/86 Shannon and Wilson's Seattle Landslide Study reports this as a heavy winter.

1995/96 A large slump along Perkins Lane in Magnolia destroys five homes (January).

1996/97 Over 100 slides reported in the city (January). These slides and the accompanying snow caused approximately $100 million in damages. More slides occurred in March in a continuation of the wet winter.

2014 A deep landslide occurred the morning of March 22 near the city of Oso in Snohomish County. Three weeks of heavy rainfall preceded the event. It was the deadliest landslide in the history of the U.S. with 43 fatalities and several injured. Forty-nine homes and structures were destroyed,[233] and State Route 530 was closed for more than two months. The state estimated capital losses of at least $50 million.[234]

A study of 50 landslides in Seattle found that hillside excavation for roadcuts and other construction activities contributed to 40% of the slides.[235] During the construction of Interstate 5, and newspaper accounts document several landslides along Beacon Hill and Capitol Hill during this time.

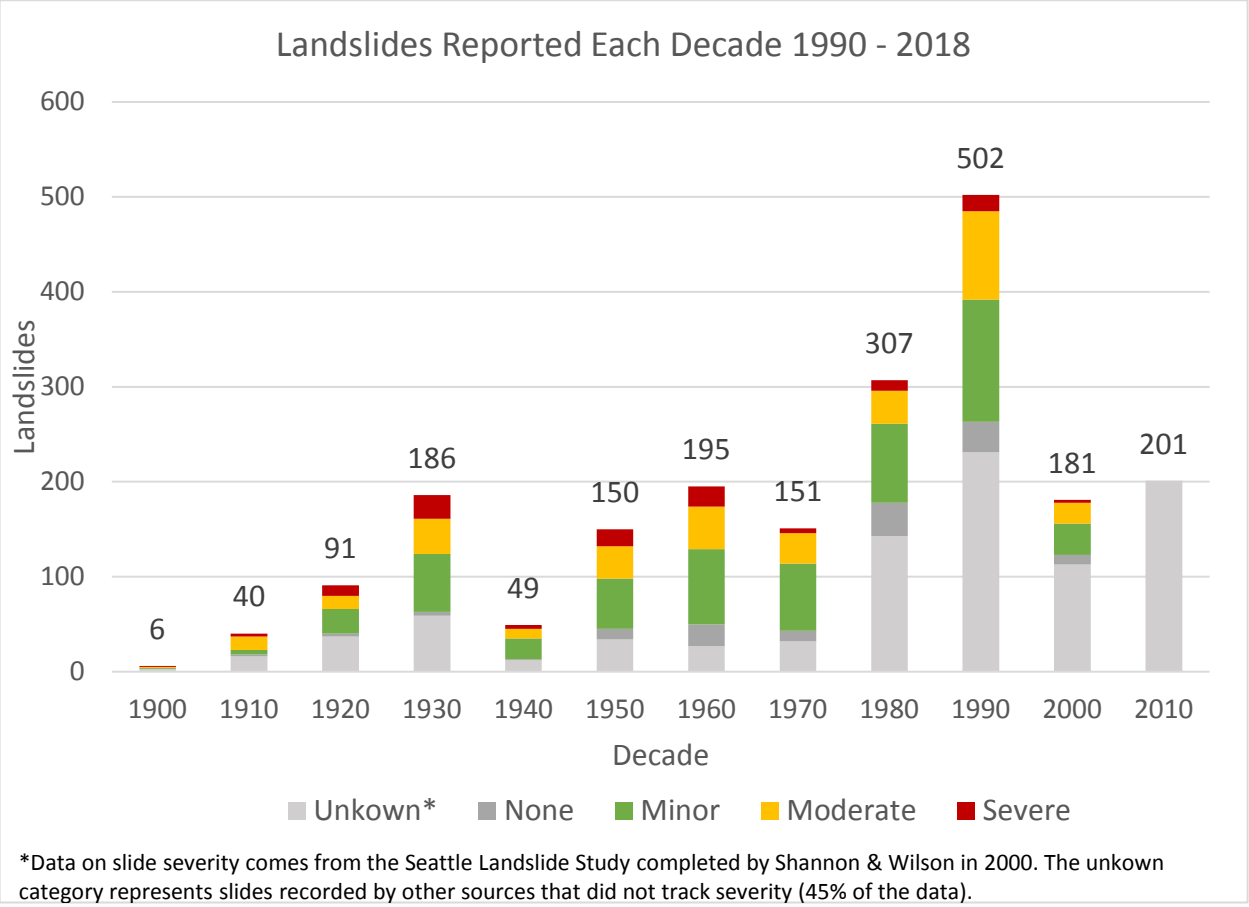
Urban development has the potential to reduce risk but can also expose more people to the consequences of a landslide. When impervious materials like concrete are added to a slope, water is diverted, and soils are less likely to become saturated. Seattle's modern construction codes have specific engineering requirements in slide-prone areas to increase structural safety and reduce the amount of

water that can penetrate the slope.[236] A decrease in landslides in some areas, like the southwest side of Yesler Hill, is presumably a result of its transformation into a dense urban neighborhood. Additionally, some slopes such as the west side of Beacon Hill have benefited from large public works projects, such as construction on I-5 in the 1960s that added concrete reinforcements and drainage.[237]

5 2.3 *Likelihood of Future Occurrences*

The number of landslides recorded by the city increased dramatically from the mid-1900s to the end of the century (Figure 5-11). This increase likely reflects a combination of development on landslide prone-slopes and more frequent reporting. In the past, landslides on undeveloped property were underreported. Once developed, property owners in these areas probably reported slides to the city more frequently. The large spike in the 1990s also reflects the extreme number of slides that occurred during the 1996/97 winter. Since the 90s, the number of landslides recorded has decreased to about 190 slides per decade.

Figure 5-11. Landslides By Decade

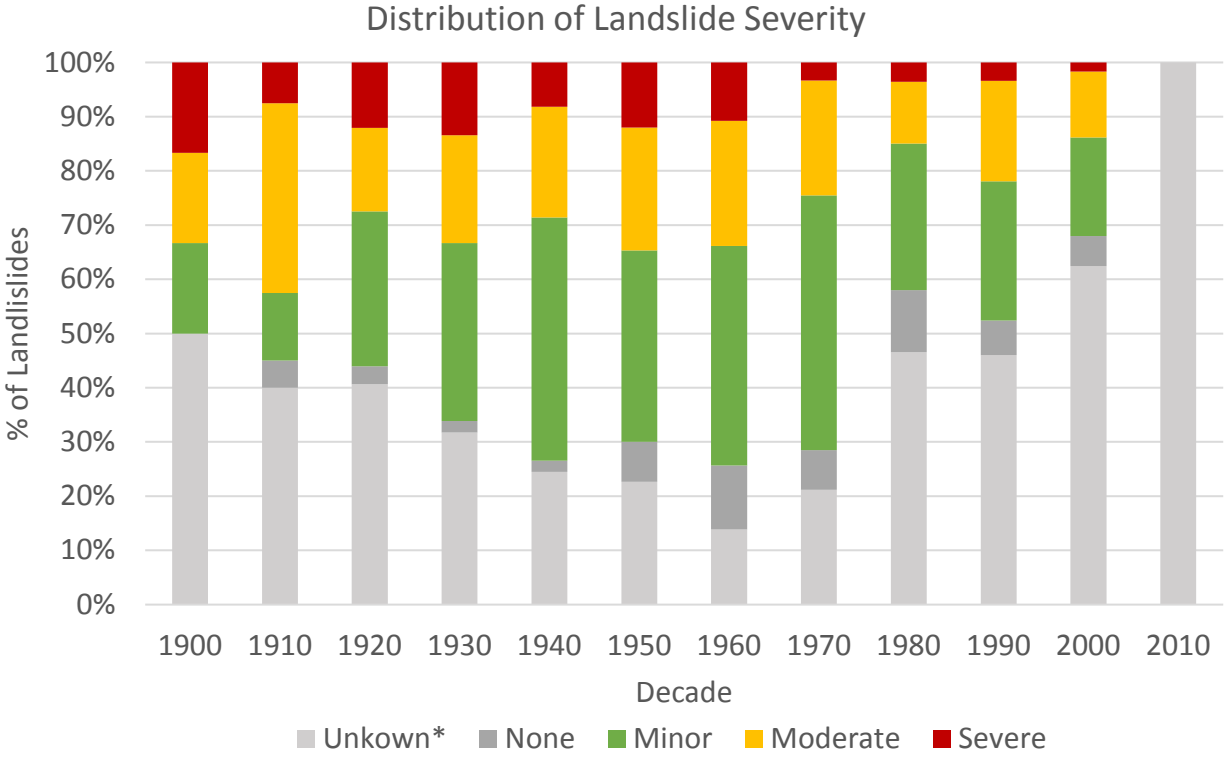


*Data on slide severity comes from the Seattle Landslide Study completed by Shannon & Wilson in 2000. The unkown category represents slides recorded by other sources that did not track severity (45% of the data).

The number of landslides that have severely damaged property decreased between 1980 to 2000 (Figure [Distribution of Landslide Severity by Decade]). While it has not been formally studied, stricter building codes for properties in slide-prone areas could have contributed to the decrease in property damage. Shallow landslides made up a growing proportion of slides from 1950 onward, with deep seated landslides becoming less common (except for the 1990s).

The tragic Oso landslide caused concerns around the risk of a massive landslide occurring in a more densely populated area, like Seattle. A recent study analyzed and dated 25 deep-seated landslides, including the Oso landslide, in the North Fork Stillaguamish River (NFSR) Valley, about 60 miles north of Seattle. The results revealed that deep-seated landslides from our current geologic age (roughly the past 12,000 years) have an average frequency of one slide every 140 to 500 years in the NFSR Valley.[238] The NFSR Valley has different topography and is much less developed than Seattle. However, the soil structure that makes the slopes in the Valley landslide prone, are similar to soil structures in Seattle.

Figure 5-12. Distribution of Landslide Severity by Decade



*Data on slide severity comes from the Seattle Landslide Study completed by Shannon & Wilson in 2000. The unkown category represents slides recorded by other sources that did not track severity (45% of the data).

5 2.4 *Vulnerability*

Eighty-eight percent of the documented landslides in Seattle have occurred either within a steep slope area or potential landslide area already mapped by the City of Seattle (see Figure 21 [Landslides and Landslide Prone Areas]).[239] The map reflects slopes where landslides are prone to start. However, it does not account for the potential runout of a slide, which can extend further than 50 feet.[240] The homes that were destroyed in the Oso landslide were not in landslide-prone areas but were reached by the massive debris flow that occurred as a result of the slide. Additional research is needed to understand the potential length of runout for different types of slides. The areas that have had the greatest number of landslides in Seattle are along Alki Avenue in West Seattle and Perkins Lane North in Magnolia, with over 100 documented landslides each. Other areas with large numbers include Beach Drive Southwest, Pigeon Point, Madrona, Rainier Avenue S.E., Interlaken, Magnolia and Northwest Seattle.[241] Human alteration of the slope was at least a partial cause in 84% of landslides in Seattle in the 20th century.[242]

Landslides in certain parts of Seattle are increasing, most notably along the slopes along northwest and northeast Seattle, Perkins Lane, and the Duwamish Head. A few areas, such as the areas around southwest Yesler Hill and the slope along the west side of Beacon Hill, are having fewer landslides.

Deep-seated landslides have been located in Southwest Magnolia, Northwest and Southwest Queen Anne, East Queen Anne, Alki, Admiral Way, West Beacon Hill, Interlaken, Madrona and Pigeon Point.[243]

Nearly one third of the area designated as landslide prone is single family residential (33%). As the amount of vacant property dwindles in the city, more people are willing to build on landslide-prone slopes. Additionally, many of these areas are desirable for their proximity to the water and views. The City of Seattle cannot stop people from building their home in a landslide-prone area, but it does require a more intensive geologic assessment and mitigation work to eliminate risk to the home and neighboring properties. Common mitigation measures can include special foundation designs or pipes that divert water from the slope. Nevertheless, there is always a risk of danger when building on a slope. A home built underneath a bluff on Bainbridge Island was buried in a landslide in 1997, tragically killing a family of four. It is unclear how many older properties conform to current standards. Furthermore, mitigation is usually designed to prevent loss of life and not property loss, which is typically uninsured.

Transportation / Right of Way

Public right of way, such as roads, railways, and trails, accounts for one-quarter of the land within landslide prone areas. Landslides can either go over the right of way, undermine it, or both.

The most vulnerable right of way is that which is parallel to a slope. Seattle has many such locations, importantly, the railroad tracks running along Puget Sound in north Seattle, I-5 along parts of Beacon Hill and Capitol Hill, and SR 99 Aurora along Queen Anne. It is estimated that landslides have disrupted or canceled passenger train service along Puget Sound over 540 times between 2015 and 2018.[244] Since 2011, two trains have been derailed by landslides in the Seattle-Everett corridor. BNSF requires that passenger trains suspend service for 48 hours after a landslide, but this rule does not apply to freight trains. In late 2013, BNSF and the State of Washington began a $16 million, multi-year project to mitigate landslides in this corridor. They are building retaining walls, improving drainage systems, and conducting erosion control in six different areas.[245] They have also installed slide detection fences, which act like a trip wire and automatically send an indicator to train conductors when a slide occurs.

Usually, a landslide going over a right of way does not damage it and the debris can be cleared in a matter of hours. Exceptions occur if crews are unavailable or complications like downed power lines are present.

Landslides that undermine a right of way take longer to repair and cost more. Bridges and other roadway structures are especially vulnerable. In 1996, a landslide destroyed a support of the Magnolia Bridge causing it to remain closed for months. The I-5/I-90 and I-5/Spokane Street Viaduct interchanges are on landslide prone slopes as are ends of the West Seattle Bridge, Ballard Bridge, and I-5 Ship Canal Bridge.

Utilities

Utilities, especially those underground, are vulnerable to landslides. Because drainage systems are close to slopes by necessity, they are most frequently damaged. About 8% of reported landslides have damaged the city's drainage infrastructure. Another 4% have been associated with water leaks, with the leak sometimes causing the landslide and not the reverse.

Seattle's water, power, and sewer lines all cross landslide prone areas. The sewer system is the most exposed to landslide hazards because it has main lines that run parallel along the base of many landslide prone hill sides, especially in West Seattle, the east side of Queen Anne Hill, and in Carkeek Park. Sewer

mainlines cross landslide prone slopes in more than seven locations. Seattle water supply lines cross landslides prone areas in three locations: southeast Seattle, the north end of Beacon Hill, and the Interlaken area of Capitol Hill. Power transmission lines cross landslide prone areas in southeast Seattle.

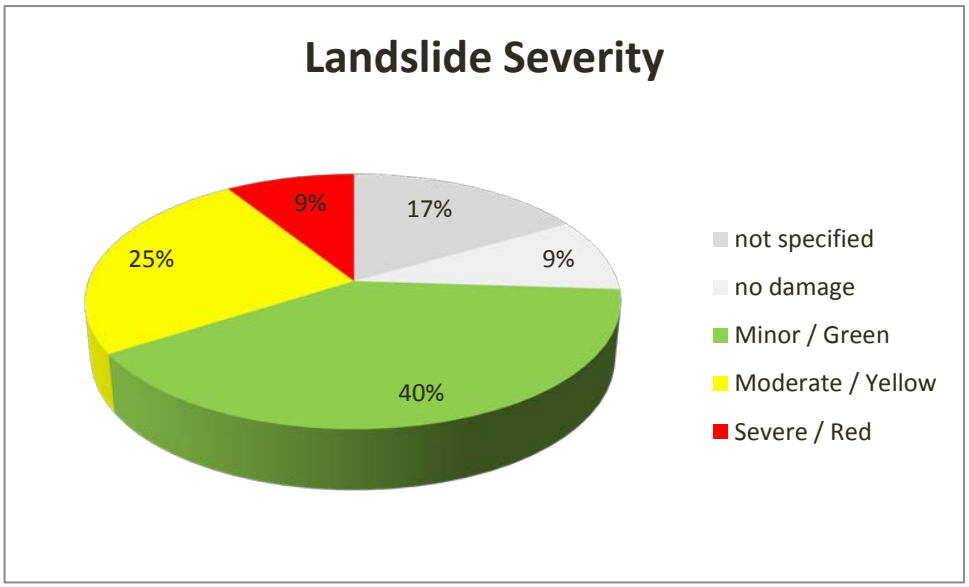
5 2.5 Consequences

Landslides will continue to be a threat to property and public safety. Property damage is the most common consequence of landslides, but the 2014 Oso landslide tragedy and the 1997 deaths of a Bainbridge Island family underscored the human costs.

Property damage from the flurries of landslides in 1974 and 1997 was shared roughly equally by the public and private sectors. However, little can be drawn from two occurrences, and this distribution should be studied further. It may reveal trends in property damage pattern that could help prepare the city for future events.

Most of the land in or immediately adjacent to the City's mapped landslide prone areas is residential so it is to be expected that most future property damage will be private residential. Historically, this has been the case. There is little information about severity (i.e., how many homes were destroyed and how many were only damaged). Newspaper articles making frequent reference to "destroyed homes" yield only anecdotal evidence.

Figure 5-13. Landslide Severity Summary



Other significant impacts could include the interruption of lifeline services such as water, sewer, and transportation. The city's water, gas, sewer, and power lines all cross areas prone to landslides, particularly in Highline, the east side of Beacon Hill, and the east side of West Seattle. Of these areas, Highline is generally the most critical because many of the utility networks have trunks that run through the area. All of the Cedar River water pipelines enter the city in this area.

Transportation corridors could very well be blocked by future slides. Both I-5 and I-90 run through a large landslide area around Beacon Hill. Aurora has been blocked by landslides along the east face of Queen Anne Hill several times. Since each one of these routes handles thousands of vehicles every day, landslides around them have the potential to disrupt large parts of the city.

Landslides often happen in groups over a period of days or even weeks. They usually have the biggest impact in residential areas where they can displace whole blocks of households. Less commonly, they

threaten commercial buildings and facilities that host critical services. Their economic impact comes when they block transportation routes or force businesses to vacate their premises. By blocking roads and damaging lifelines they also inhibit the City's ability to deliver critical services to impacted neighborhoods.

Landslides can induce other disasters. Landslides can cause flooding by blocking rivers, streams, and storm drains, and lead to releases of hazardous materials by destroying waste and storage sites, or derailing freight trains. These trains are increasingly carrying Bakken crude oil, a highly flammable oil that has been known to explode when impacted. Hazardous materials are housed or transported close to potential slide areas in West Seattle, Interbay, and along the Burlington Northern tracks running through the Golden Gardens area.

Future research should look into the potential effects of submarine landslides in water bodies such as Lake Washington. Seattle can also be affected by landslides in other parts of the state. Landslides, rock fall, and avalanches have closed I-90, Washington's main east-west corridor and SR20, which provides access to Seattle City Light facilities in the North Cascades.

Cumulative Hazard

Landslides are a hazard that can best be analyzed by looking at cumulative impacts. While the majority of landslides are insignificant and would not constitute an emergency, their relatively high frequency and their tendency to occur in swarms can compound consequences over time.

5 2.6 Conclusions

Landslides are a common, complex and growing problem in Seattle. There is substantial evidence that landslide losses are growing as more property is developed in landslide prone areas. One bright spot is that safety measures seem to be working. Complicating response is the fact that landslides are often secondary to other hazards, such as earthquakes and storms. Following the major slides of 1996/97, the City convened an Interdepartmental Landslide Team to address the problem. Since then, several structural and non-structural mitigation measures have been taken. In addition, USGS monitoring of rainfall and soil conditions and availability of new landslide susceptibility maps add greater accuracy to the city's predictive ability.