# Coseismic Landslide Risk Assessment of the Carbon River Valley near Orting, WA

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## Abstract

Landslides are a prevalent hazard in areas with steep slopes and heavy rains. This hazard risk increases with the presence of ground shaking caused by earthquakes. The goal of this project was to determine the coseismic landslide risk along a section of the Carbon River Valley near Orting, WA. The online software Scoops3D was used to find the Factor of Safety of the river valley walls and a Newmark Analysis was conducted using those results as well as peak ground acceleration values found using the USGS Unified Hazard Tool. The results of the Newmark Analysis fit the upper portion of the Weibull curve from Jibson et al. (2000), showing that there is a high probability for landslides in this area, even without the presence of ground shaking. The highest peak ground acceleration values would create the biggest hazard.


<u>Coseismic Landslide</u>:
Landslide caused as a direct result of an earthquake

## Research Question

**What peak ground acceleration (PGA) would create the most significant landslide risk along the area of the Carbon River Valley (Fig. 1) east of Orting, WA?**

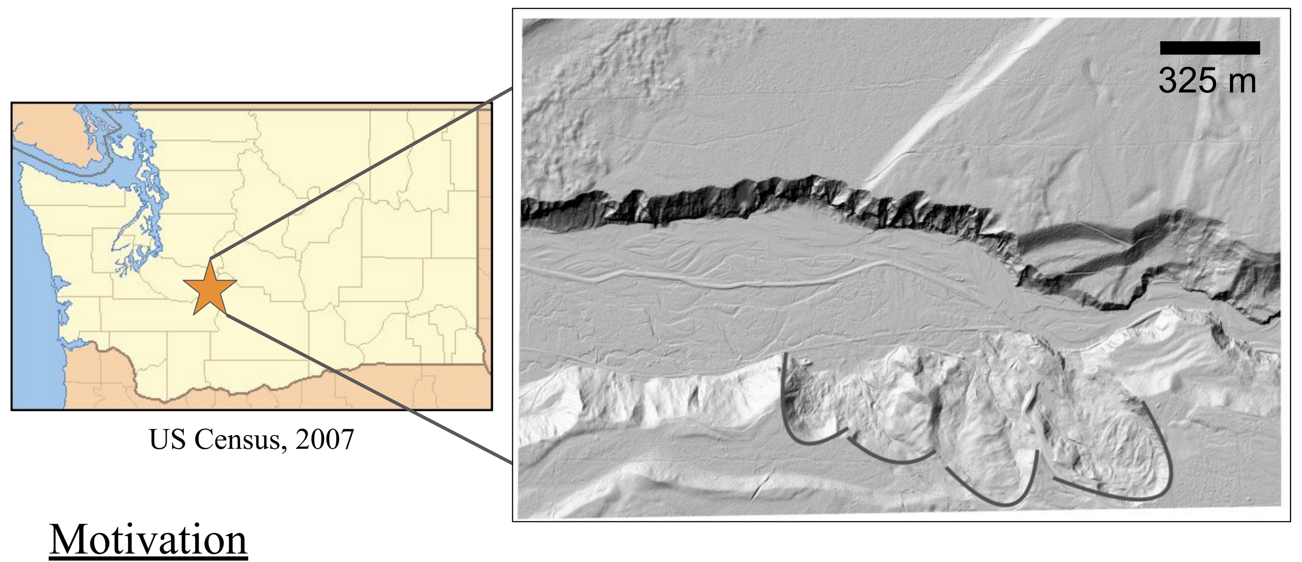


**Figure 1.** Map of WA state (left) and study site along the Carbon River (right). Previous landslide scarps outlined. LiDAR image from Pierce DTM (2011).

<u>Motivation</u>

- Evidence of past slides can be observed along the Carbon River Valley near Orting, WA (Fig. 1)
- Slopes that have failed once are prone to reactivation
- Coseismic landslide risk analysis allows likelihood of future events to be quantified and applied to safety measures for populations that live in/along the river valley

## Hypothesis

The highest coseismic landslide risk will be attributed to earthquakes with the highest peak ground acceleration values

## Background

*<u>Washington and Earthquakes</u>*

- Washington state sits above an active subduction zone (Driedger, 2012)
  - Convergence of North American and Juan de Fuca plates
- This type of plate boundary produces several different types of earthquakes (Fig. 2)
- Deep earthquakes have the shortest recurrence interval (30-50 years) and are the most likely to occur again in the next 50 years (Cascadia Subduction Zone, pnsn.org)
- Most recent WA earthquake was the 2001 Nisqually event (Cascadia Subduction Zone, pnsn.org)

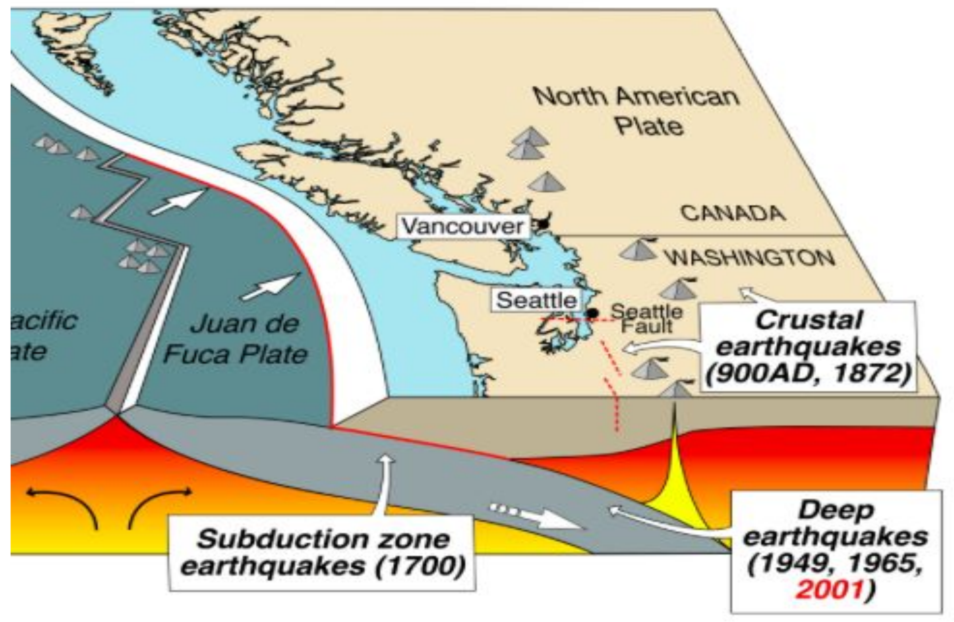


**Figure 2.** Potential locations of earthquakes (white text boxes) along the Cascadia Subduction Zone. Earthquakes occur in the shallow crust, at plate margins, or deep along the subducting plate (Cascadia Subduction Zone, pnsn.org)

*<u>Washington and Landslides</u>*

- General prerequisites for slope failure:
  - **Steep slopes, unconsolidated weak sediments, and high precipitation rates**

*<u>My Study Site</u>*

- Tall valley walls steepened by bank undercutting
- Coarse outwash gravel found in terrace deposits left behind by glacial lake Puyallup (Crandell, 1963)
- 38 inches of rain per year (NOAA, 2017)
- Recent earthquakes with deep foci (Fig. 2)

## Methods

**<u>NOTE:</u>**
FoS values <1 indicate slope instability, but the value used for Eq. 1 was >1 (1.5057) because otherwise the result would be negative. Jibson et al. (2000) also used FoS values >1 in their analysis.

- **Scoops3D** (Reid et al., 2015)
  - Software program that computes slope stability of a landscape when provided with a digital elevation model (DEM) of an area
  - <u>**Important Output**</u>: Factor of Safety (**FoS**) of individual DEM cells (FoS = resisting forces / driving forces)
  - Output (Fig. 3) is based on DEM and user parameter values, all of which in Table 1 were held constant
- **Newmark Analysis** (Jibson et al., 2000)
  - Mathematical model of the dynamic behavior of coseismic landslides on natural slopes
  - <u>**Important Outputs**</u>: Potential Displacement (cm) of a slope (Eq. 2) AND Proportion of Landslide Cells Affected by Ground Shaking (Eq. 3)
  - Used **Equation 1** to find the critical acceleration (how much ground shaking) required to overcome shear resistance and initiate sliding of a topographic slope
  - Then used **Equation 2** to find the **potential displacement** (cm) of the hillslope during a seismic event
    - Max. or peak ground acceleration (PGA) found using the Unified Hazard Tool on USGS.gov
  - **Equation 3**, modeled after a Weibull function that indicates probability density, was then used to find the spatial density of coseismic landslides (**P(f)**)
    - When plotted, this equation can be used to directly estimate probability of slope failure as a function of displacement (Fig. 4)
  - Jibson et al. (2000) used coefficients based on data from the 1994 Northridge earthquake and its resulting landslides (Eqs. 2&3), results may be skewed due to this
  - <u>**Equations:**</u>

1 g = 9.8 m/s²

1) $a_c = (FoS - 1)g\sin\alpha$

$a_c$ : Critical Acceleration (g)
g : Gravitational Acceleration (g)
$\alpha$ : Slope Angle (values in Fig. 3)

2) $\log D_n = 0.215 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.341}\left(\frac{a_c}{a_{max}}\right)^{-1.438}\right] \pm 0.510$

$D_n$ : Potential Displacement (cm)
$a_{max}$ : Peak Ground Acceleration (g)

3) $P(f) = 0.335[1 - \exp(-0.048 D_n^{1.565})]$

P(f) : Proportion of Landslide Cells that are affected by seismic event

**Table 1.** Break down of important parameters used by Scoops3D and how they affect Factor of Safety outputs. Definitions from Reid et al. (2015). First two values from Perkins et al. (2017). Other values from calculations made with observed data.

| Variable | Definition | Value Used |
|---|---|---|
| Cohesion ($c$) | The sticking together of particles of the same substance (i.e. how well sediment stays together on a hillslope) | **5 kPa** |
| Angle of Internal Friction ($\varphi$) | A measure of the ability of a unit of rock or soil to withstand a shear stress. It is the **angle** ($\varphi$), measured between the normal force (N) and resultant force (R), that is attained when failure occurs in response to a shearing stress | **30°** |
| Unit Weight | total unit weight ($\gamma_t$) for a layer of earth material | **10.1 kN/m³** |
| Volume Maximum | the maximum volume limit for potential failure masses to be analyzed, given in volume units consistent with the length units of the DEM | **77871 m³** |
| Volume Minimum | the minimum volume limit for potential failure masses to be analyzed, given in volume units consistent with the length units of the DEM | **29 m³** |

## Results

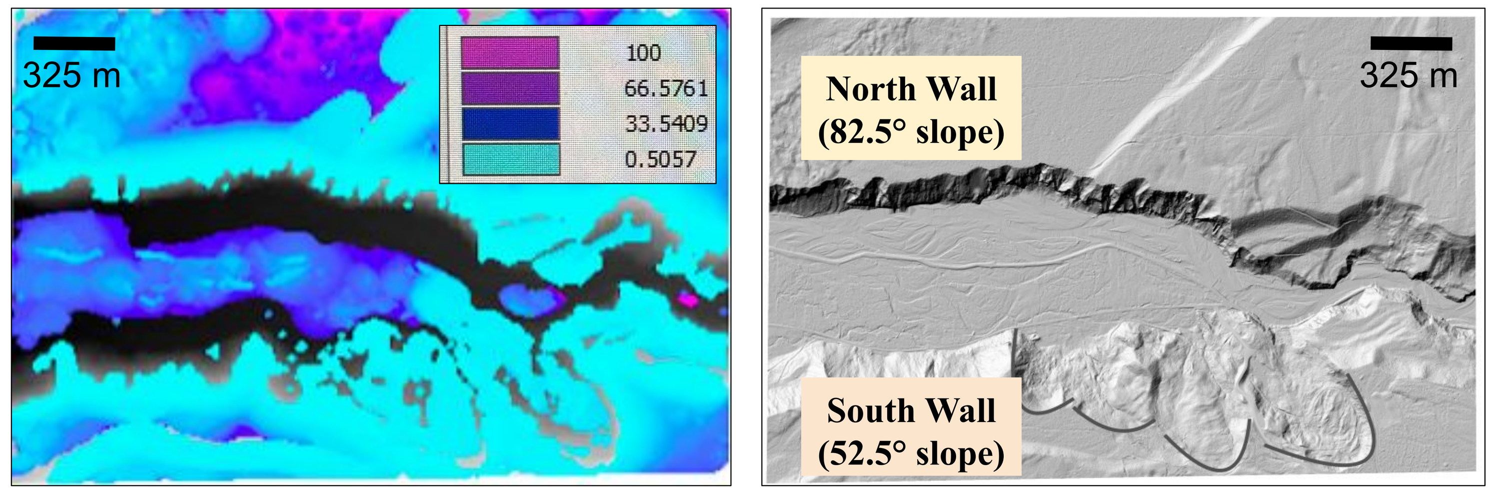


**Figure 3.** Factor of Safety output layer from Scoops 3D (left) and hillshade of study site (right). LiDAR image from Pierce DTM (2011). Light blue indicates a Factor of Safety range of 0.5057-10, lowest values in this range used for the Newmark Analysis. Differences in slope indicated.

- Low factor of safety by the valley walls or areas that have steeper slopes (Fig. 3)
- High factor of safety where there is little change in slope (i.e. flat) (Fig. 3)

| Probability of Occurrence in 50 years | Critical Acceleration (g) | Maximum Acceleration or PGA (g) | Displacement D (cm) | Proportion/P of Landslide Cells Affected |
|---|---|---|---|---|
| 10% | 0.04 | 0.284 | 27.21* | 0.334* |
| 5% | 0.04 | 0.397 | 44.19 | 0.334 |
| 2% | 0.04 | 0.556 | 72.06 | 0.335 |
| 10% | 0.055 | 0.284 | 17.01* | 0.329* |
| 5% | 0.055 | 0.397 | 27.87* | 0.334* |
| 2% | 0.055 | 0.556 | 45.48 | 0.334 |

**Table 2.** Results from each Newmark Analysis equation (yellow-red scale indicates low-high PGA values). Earthquake scenarios indicated by Occurrence Probabilities and PGA values found with Unified Hazard Tool on USGS.gov. Differences in crit. acceleration values come from different slope values (Fig. 3).Values with an asterisk plotted on Fig. 4.

## Results cont'd.

- Critical acceleration increases with an increase in FoS and slope angle
  - Tested several different FoS values that were slightly greater than 1 to observe this trend, but only showed results for FoS = 1.5057 because (1.5057-1 = 0.5057) which was the lowest FoS value on the Scoops3D output
- Potential displacement decreases if there is an increase in the critical acceleration
- Higher PGA leads to a higher potential displacement value
- The proportion of landslide cells that are affected increases with an increase in potential displacement

## Interpretations

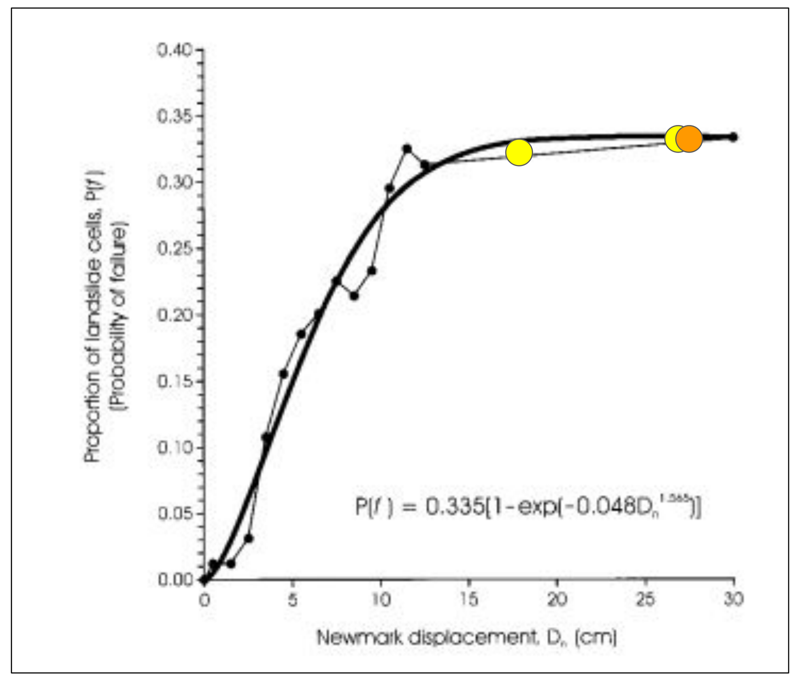


**Figure 4.** Weibull curve of Eq. 3 from Jibson et al. (2000). Demonstrates probability of slope failure as a function of Newmark displacement. Upper portion of curve indicates high probability of slope failure. Yellow and orange points are my results from Table 2 that were able to fit on the chart.

- My critical acceleration results were low (0.04g and 0.055g) which reveals that this study site will be susceptible to all tested PGA values (0.284, 0.397, 0.556 g) because the PGA values are much greater than the critical acceleration values
- In the study completed by Jibson et al. (2000), points plotted along the upper portion of the Weibull curve (Fig. 4) indicated their maximum probability of coseismic failure in the study of the 1994 Northridge seismic event
- My results either plot along this upper portion or are greater than the scale of the chart and could not be plotted
- This indicates that my study site has a high probability for coseismic failure when compared to Jibson et al. (2000) results
- Highest coseismic landslide risk will be due to earthquakes with high PGA values because they have the largest displacement values for the largest spatial extent (0.334 = 33.4% of space is affected)
- Tested PGA value that will create the most significant landslide risk = 0.556 g

## Conclusions & Future Work

- My study area has a high landslide risk even without the presence of high ground acceleration values because landslides have occurred without earthquakes in the past
- The highest risk scenarios would likely be a result of the highest possible PGA (0.556g) that is associated with seismic events that have a 2% chance of occurring in a 50 year span
- This could lead to a significant landslide hazard that would block the river from flowing, affecting the populations that live down and upstream
- Monitoring efforts should be strengthened in this area because there is a significant landslide risk being posed
- Future studies with this type of experiment may benefit from a study area that has a landslide database associated with it, in order to find coefficients that fit the desired location instead of using values from the 1994 Northridge event
- In the future, time permitting, there would also be the chance to use GIS for the Newmark Analysis calculations to receive a wider range of results

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