MODELING TSUNAMI INUNDATION AT LINCOLN CITY

by

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A THESIS

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Primary Thesis Advisor

The Cascadia Subduction Zone is a 700 mile long fault that runs along the Western Coast of North America. It starts in California and runs through Oregon and Washington before ending in the Southern portion of Canada. Until 1970, scientists did not know this fault existed. Many people outside of the scientific community either do not know about the fault or know very little about it. Those that do know about it tend to give very little thought to the tsunami risks and other effects. This project aims to make our knowledge about the Cascadia Subduction Zone more accessible to the public by modeling the tsunami and specifically how it could affect Lincoln City. To make this project accessible to the public GeoClaw was used for the computations and Google Earth was used for the visualizations.

Acknowledgements

I would like to thank Diego Melgar for all his help and support during this long process, I wouldn’t have found the color bar without him. I would also like to thank David Small for all the early morning meetings where he helped me figure out what I was doing wrong. It was so much fun working with you both. Thank you for welcoming me into your little team.

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Introduction

Each year the Earth experiences around 20,000 earthquakes with about 16 of them being major earthquakes (USGS). These earthquakes occur worldwide and are heavily studied to improve our understanding and preparations. Of the 20,000 earthquakes that occur per year about 1,500 of them are centered around Japan, with minor tremors occurring almost daily. Japan has so many earthquakes because it is situated on four different tectonic plates that move around and create tremors (Israel np). These tectonic plates interact with each other at what are called fault boundaries.

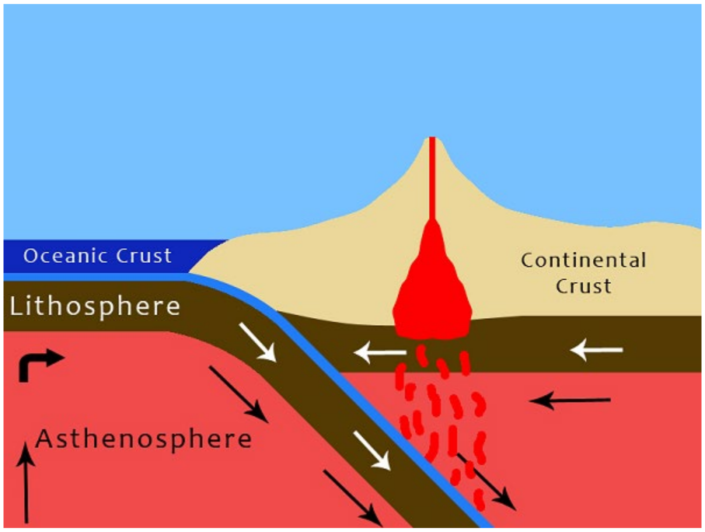

Figure 1: Diagram of a Convergent Fault or Subduction Zone taken from: https://en.m.wikipedia.org/wiki/File:Common_Cross_Section_of_a_Subduction_Zone.jpg

There are three types of fault boundaries: divergent, transform, and convergent. Transform boundaries are where two or more plates slide across each other. Divergent boundaries are where two or more plates move away from each other. Similarly, convergent boundaries refer to two or more plates that move towards each other or converge. Subduction zones are another word for convergent boundaries and are called that because one plate usually subducts or slides beneath the other. Convergent boundaries can occur with both oceanic and continental plates. When oceanic and continental plates converge, the oceanic plate subducts under the continental because the oceanic plate is denser. The Cascadia Subduction Zone is a large convergent fault that lies off the coast of Western North America. It runs for 700 miles starting in Northern California and continuing northward through Oregon and Washington before ending in Southern Canada.

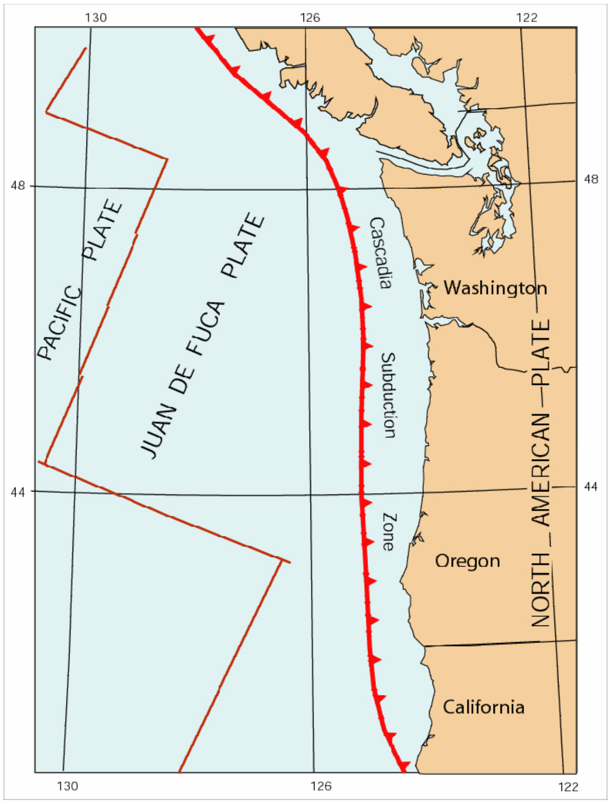

Figure 2: A Map of the Cascadia Subduction Zone taken from: https://serc.carleton.edu/eet/tsunamiinseaside1/case_study.html

What Evidence Do We Have of the Cascadia Subduction Zone

Most faults like the ones in Japan create hundreds of smaller earthquakes each year. Unlike other subduction zones, Cascadia does not create minor earthquakes. In fact, it has not had any major earthquakes that we know of since the beginning of the 18th century. On January 26, 1700, the Cascadia Subduction Zone ruptured, triggering an earthquake estimated at 8.7–9.2

magnitude (Schulz np). The January earthquake also triggered a tsunami that hit both the West Coast of North America and Japan. Because it has not had any recorded major earthquakes in modern times, the earthquake that occurred in 1700 was discovered through deduction. Scientists studying the Ring of Fire (a series of volcanoes and places of seismic activity around the Pacific Ocean) realized that it ran along the Western North American Coast and therefore a fault must exist there. Their next step was to prove that it existed. They did this by using sediment layers, ghost forests, and Japan's historical records. They found salt marshes that had thick layers of sand. The salt marshes used to be higher but during the earthquake they dropped and later got covered in sand and mud when the tsunami came in (AMNH np).

By looking at what are known as 'ghost forests' in Oregon and Washington, scientists were able to narrow the earthquake's timeframe to between August 1699 and May 1700. These 'ghost forests' are large areas where trees all died off at the same time when the ground was quickly lowered into the tidal zone by the earthquake. They know the earth lowered quickly because of the sediment records, where mud mixes with sand. The ghost trees lie on this mud, and all have an outermost growth ring correlating to the year 1699, the last growing season before the January earthquake. These 'ghost forests' also have tree stumps that are under the ocean's surface and are only exposed during low tide (Schulz np).

There are no written records of the Cascadia earthquake, but Japan has been keeping records of its earthquakes dating back to 599 AD (Ishibashi 1). Japan's records documented an 'orphan tsunami,' or a tsunami without any known causes. By matching up the 'orphan tsunami' with other evidence like the ghost forests and sediment layers, scientists managed to pinpoint the exact time of the earthquake to 9 pm January 26, 1700 (Schulz np).

The Effect of Limited Knowledge

The Japanese records and other data have given scientists the ability to better prepare for disasters like the 2011 Tohoku earthquake and tsunami. Even with the knowledge of these earthquakes, the 2011 disaster resulted in over 20,000 dead or missing people and over $360 billion in damages (Reid, np). Unlike Japan, the Cascadia Subduction Zone has not had centuries of recorded knowledge to build on (Sullivan np).

Since the Cascadia Subduction Zone was not discovered until scientists deduced it existed, the state of Oregon did not have a seismic code until 1974. Because of this an estimated 75% of buildings in Oregon are not designed to withstand any major earthquake. The Federal Emergency Management Agency (FEMA) has calculated that around 1 million buildings in Oregon will collapse or be compromised in the earthquake. After the earthquake, a tsunami will strike the coast. When an earthquake hits, people have an estimated 10-30 minutes to get to higher ground before the wave reaches them. But hotels and businesses are not required to post evacuation routes or provide evacuation training. And while it has been illegal to build hospitals, schools, and firehouses in inundation zones in Oregon since 1995, those that have already been built remain in inundation zones (Schulz np).

To prepare for the eventual disaster, scientists are creating computer models and simulations. By running different simulations, we can better predict how the earthquake and subsequent tsunami will affect the Pacific Northwest coast. The more we know about the possible effects of an earthquake and tsunami the more we can tailor our response systems. The models can help us better understand where the water from a tsunami will reach and therefore where the tsunami warning and evacuation signs should be placed.

Chapter 1: Modeling Methodology

FakeQuakes

Scientists simulate earthquakes using a program called FakeQuakes. FakeQuakes is a computer modeling software that maps, in this case, the Cascadia Subduction Zone, and splits the fault into 963 triangles (Figure 3). The model then picks a random point on the fault to rupture and randomly chooses how big of a split it should be based on a chosen magnitude. Then the model calculates how big the downdip or uplift each triangle experiences (Melgar np).

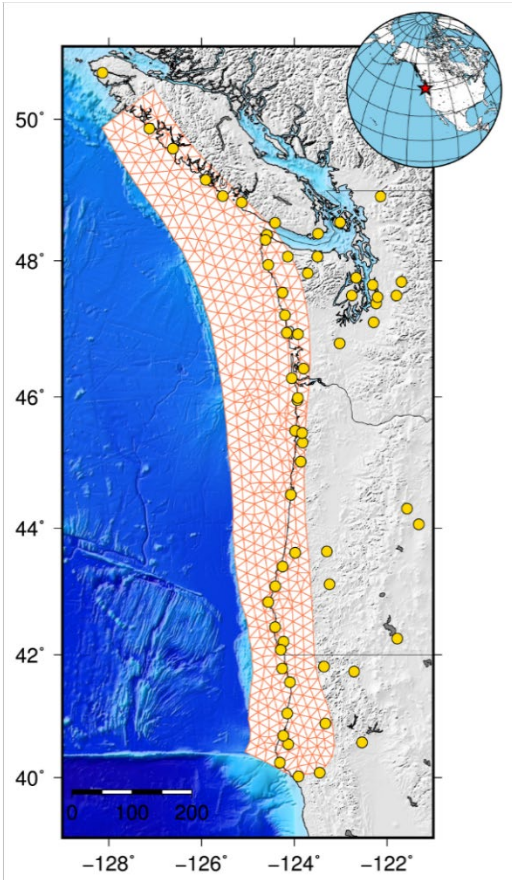

Figure 3: Fault discretization (triangles) and station distribution used for the synthetic data (circles) of FakeQuakes

After calculating the downdip and uplift, we use that data to synthesize waveforms at the selected stations in Figure 3 (Melgar np). The scientists then rerun the model 1300 times at different magnitudes to better compute what could happen during the earthquake (Melgar). They found that there is some built-in variability. For example, one of their 8.66 magnitude models had more slip than one of the 8.91 magnitude. However, the 8.91 event had a longer length and larger high slip area than the 8.66 event (Melgar np).

FakeQuakes simulates earthquakes as well as seismic waves, but it does not simulate anything related to tsunamis or the ocean. To simulate tsunamis, I used the first part of the FakeQuake simulation, the earthquake simulation. Then I ported it into GeoClaw to use that to simulate the tsunami. Since I am focused on tsunami simulation, the seismic wave simulation is irrelevant, so I did not run that part of the FakeQuake simulation.

Tensor Processing Units (TPU)

A team at Standford University recently tested an alternative to GeoClaw using Google's new Tensor Processing Units (TPU) along with 2D non-linear shallow water equations to model the Cascadia Fault Zone (Madden 6). "TPUs are a new class of hardware accelerators developed by Google with the primary objective of accelerating machine learning computations" (Madden 3). They chose to use a TPU because it is more easily accessible, as they are available through the Google Cloud Platform, and do not require any specific tools to use (Madden 3). Their goal was to create a program that anybody could theoretically boot up and receive results. They ran their model through both TPU and GeoClaw (another heavily used modeling program) and compared the results. TPU was much faster, only taking 17 minutes, compared to GeoClaw's 10.5 hours (Madden 14). But TPU sacrificed accuracy for speed: as demonstrated in Figure 4 TPU has been smoothed out in comparison to GeoClaw. To be able to produce results so quickly, TPU had to sacrifice some processing power and as such the longer the model runs the less accurate it is (Madden 14).

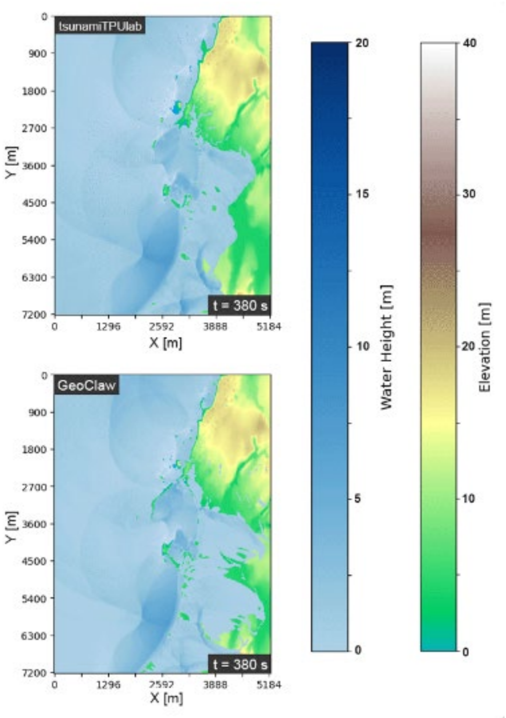

Figure 4: A TPU and GeoClaw comparison at time 380s

The fact that TPU's results are smoothed out is fine for a program that is supposed to be able to be implemented without specialized equipment, but since I only inundated one city, I chose GeoClaw because while it takes longer it is much more accurate than TPU.

Relative Tsunami Hazard

The amount of damage a tsunami can do depends on many different factors. One factor that can determine the amount of damage is the layout of the coastline. Amir Salaree et al. created simulations focused on the Pacific Northwest. They found that regardless of origin, any earthquake along the Cascadia Subduction Zone that has a magnitude of 8.5 or above will create comparable tsunamis along the US West coast (Salaree et al. np). These different magnitude earthquakes "can create similar tsunami amplitudes at a given location depending on the position of the hypocenter" (Salaree et al. np). This occurs because of the concave nature of the West Coast, which concentrates the effects between 44° and 45°N, or around Newport, Oregon

(Salaree et al. np). This effect can be seen in Figure 5, where Salaree et al ran a tsunami simulation where they assumed that the ocean floor was completely flat in order so that they could model the effect of the coastline without interference. In Figure 5 the pink lines are the tallest towards the center of the curve. Lincoln City is within that higher hit area, lying at 44.96°N. This means that it will most likely be one of the harder hit cities.

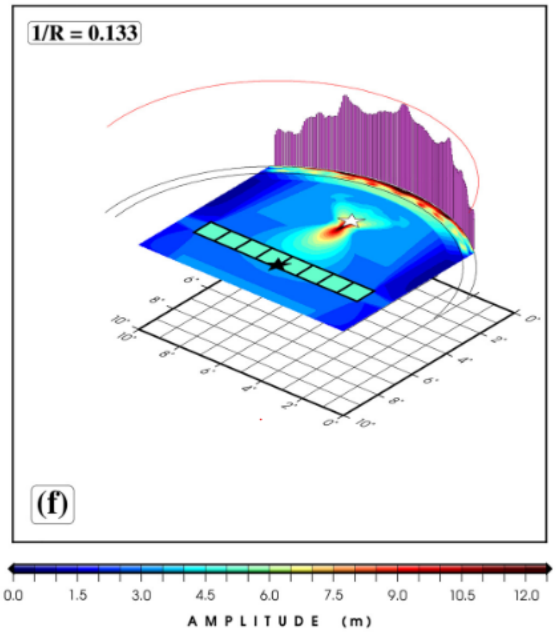

Figure 5: Maximum coastal tsunami amplitudes are represented by the vertical pink lines. Black and yellow stars show the center of curvature and focal point of the curved coastline, respectively.

Validating Velocities in GeoClaw

Simulations of tsunamis are only useful if we can be sure that the simulations are done accurately. A paper by M. E. M. Arcos and Randall J. LeVeque compared the data from the 2011 Tohoku Tsunami to simulations given by GeoClaw both to test the accuracy of GeoClaw but also to better understand flow velocities and accelerations (Arcos and LeVeque 2). They tested results from 10 different stations around Hawaii. The stations were at varying depths from less than 25 meters to 150 meters below the ocean's surface. They chose their stations because often damage from a tsunami “was not the result of high flow depth or long inundation distances, but rather due to the strong currents generated in harbors and along coastlines” (Arcos and LeVeque 1).

From the results they found that “the agreement seen between the GeoClaw simulations and the observations at most of the stations studied provides significant additional validation of the model beyond what has been achieved by past studies.” Nevertheless, there is still room for improvement (Arcos and LeVeque 11). While most of the simulations of the separate stations were fairly accurate, station HAI1123 information did not correspond with the given data. But the precise location of that station during the tsunami is unknown and by moving the estimated location to the east slightly the information matches much closer (Arcos and LeVeque 9). Station HAI1126 also had the lowest agreement between the observed data and GeoClaw’s simulations. The station was in shallow water near the wall making the flow more turbulent and maybe “too complex to be adequately modeled by the shallow water equations in this harbor” (Arcos and LeVeque 10).

Possible Impacts

By using these simulations and other data, scientists have managed to estimate the potential impacts and damages of a Cascadia earthquake and tsunami. For example, the Oregon Department of Geology and Mineral Industries completed a Statewide Seismic Needs Assessment. The study surveyed public schools and public safety buildings and found that of the 2,193 public school buildings examined half had a high or very high potential for collapse, as did a quarter of the public safety buildings (OSSPAC 40). Another reason for the high amount of damage is that, unlike other disasters, an earthquake and tsunami will damage power, natural gas, petroleum lines, and more all at the same time. Then to restore communication services we would first need to restore electricity, which would require the roads and bridges to be repaired and so on (OSSPAC 40).

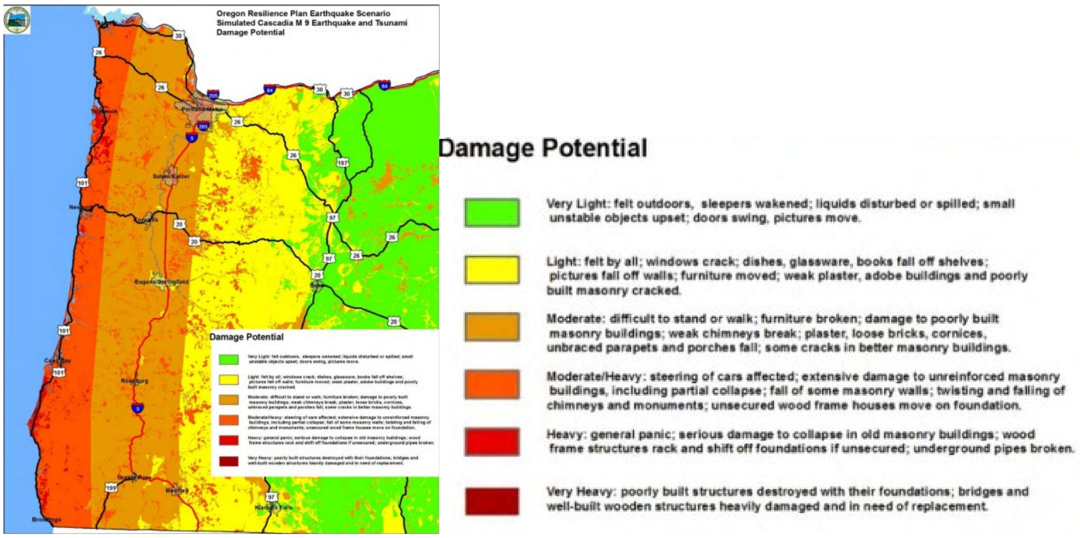

Figure 6: Oregon's damage potential and zoomed in Legend

There are four distinct impact zones when modeling the damages of the Cascadia earthquake: tsunami, coastal, valley, and eastern shown by Figure 6. "Within the tsunami zone, damage will be nearly complete (OSSPAC 40). The coastal zone will experience severe shaking, liquefaction, landsliding, and damage. In the valley zone, the damage will be less severe but shaking will still be strong, and liquefaction and landsliding still common. The eastern zone will have the lightest damage, with mild shaking, and sporadic landslides and liquefaction (OSSPAC 40).

Although exact statistics are impossible to predict, the impacts of the earthquake and tsunami in Oregon alone, have been estimated at 1,250 to 10,000 deaths, 24,000 buildings completely destroyed, with another 85,000 needing extensive repair, approximately $32 billion in economic losses, 27,600 displaced households, and almost 10 million tons of debris to clean up (OSSPAC 40). After the earthquake, it could take 1 month to 3 years to restore drinking water and sewer service, 6 to 12 months to partially restore highways, 18 months to 3 years to restore healthcare services, and finally 1-6 months to restore electricity (OSSPAC 40). All these estimates depend on what zone they are in, with the greater timeframes corresponding to the coastal areas.

Currently, there are not many models that show how exactly a tsunami will affect the West Coast of America. There's the team at Stanford that worked with Google's TPU but their paper was focused on the scientific details rather than the impact of a tsunami. There has even been a simulation that focused on modeling the 1700 earthquake. It shows the tsunami wave amplitude as it makes its way across the globe (Atwater et al).

Chapter 2: Building the Simulation

Why Lincoln City?

I modeled one city along the Western North American Coast with a program called GeoClaw. By keeping this project limited to one city, I produced a better and more specific model that can help us better adapt our evacuation plans.

Figure 7: Aerial Map of Lincoln City taken from bluepacificvacationrentals.com

For my research, I used GeoClaw to inundate Lincoln City, Oregon a map of which can be seen in Figure 7. I chose Lincoln City because I wanted to focus on the human impact a tsunami could have on Cascadia. This idea of human impact led me to a couple of different criteria that I considered when choosing a city. I focused on coastal cities, with large populations and population densities so that I could maximize the potential for human impact. I also focused on cities that were flat and closer to sea level. Lincoln City has an elevation of 4 feet above sea level and runs parallel to the water. It is over 6 miles long and only about 1.5-2 miles wide. As of 2023, it had a population of 10,242 people with a population density of 1,692 people per square mile with many of the people living in houses directly across from the beach (World Population Review).

What Ruptures?

After picking what city I was going to inundate I had to pick the ruptures to simulate. I had hundreds of different simulations to choose from which I managed to narrow down to 15. When picking the 15 rupture scenarios I narrowed it down further by sorting the ruptures. I sorted it by where the rupture occurred, if it was a full rupture, or if the rupture was in the north or south. I also sorted it by the amount of slip and where the slip was concentrated. Finally, I sorted it by how strong the magnitude was. From there I looked at the ruptures and kept a couple that were centered around Lincoln City and a couple that were further away. I kept both bigger and smaller ruptures because I wanted to model the range of what could happen to Lincoln City. I picked ruptures that were likely to do very little damage as well as a lot of damage. I also made sure to pick ruptures that were not too similar to each other because then the tsunami would be similar and would not give any extra information.

Chapter 3: GeoClaw

GeoClaw is an open-source tsunami modeling program that uses Python. It takes a specific region designated by the user, a bathymetry file, a rupture scenario, a Manning Coefficient, an Adaptive Mesh Refinement (AMR) level, and a specified length of time for the simulation to run.

Adaptive Mesh Refinement

The AMR level refers to the adaptive resolution of the specific scenario. When running a simulation, it is beneficial to be as detailed as possible for the specific areas of interest. For this project, I care about when the tsunami makes landfall. I care less about the tsunami when it is still out at sea. So, I want a higher resolution when the tsunami is inland and a rougher resolution further out to save on computing power. Arcminutes and arcseconds are used to define the resolution in GeoClaw.

An arcminute is a unit of measurement equal to 1/60th of a degree. One arcminute corresponds to the distance needed to go from 1/60th degree to the next (just under 2 km) whereas arcsecond is the distance between 1/3600th of a degree (almost exactly 30m) and the next, and therefore has a higher resolution. I went from the resolution of 3 arcminutes to 3 arcseconds through a series of 4 jumps. The simulation starts out at 3 arcminutes while over the ocean and the jumps down to 2.5 arcminutes, then 45 arcseconds followed by 15 arcseconds before ending on 3 arcseconds when the tsunami is near the coast. If I were to do one big jump it could cause numerical instability in the calculations. By using smaller jumps, the transition between resolutions is smoother. GeoClaw then divides the area of interest into rectangular grid cells that vary in size depending on refinement level. The smaller the cell size the finer the resolution.

There are a couple of different ways to designate a specific geographical region. I designated my specific region by giving GeoClaw the latitude and longitude of the lower left and top right corners, and the amount of grid cells within the area defined. The grid cells within the box correspond to the finest AMR level specified (in this 3 arc seconds, which is approximately 90 meters). To find out how many grid cells lay within the region specified, the approximate length in kilometers between the points specified is divided by 90 meters. In my case, it is approximately 4 kms along the x-axis and 10.8 kms along the y-axis, so the grid is 45 by 121 cells. GeoClaw then uses that data to draw a box using that many grid cells. For this research, I used just the two points to make a rectangle, but the grid does not need to be rectangular; its shape can be changed depending on the points given to GeoClaw.

Manning Coefficient

GeoClaw also uses what is called the Manning coefficient (Czachorski). The Manning coefficient is a unitless value that represents the roughness or friction value of a material (Czachorski np). GeoClaw uses it to determine how much energy is lost through friction between the tsunami and the seabed. If detailed information about the bathymetry of the specified region is known, then multiple parameters can be used for different areas (Czachorski np). Most of the time, however, only one parameter is used, with the standard value being 0.025 (Czachorski np). Other values have been suggested, for example, 0.035 for the reefs surrounding the Hawaiian Islands but the results are near identical (Czachorski, np). Since the results are near identical, I am using a Manning coefficient of 0.025.

Run Time of Simulation

GeoClaw lets the user pick how long the simulation should run, and how many times within that allotted period the output is collected. I ran the simulation for 4 hours and created a plot every 60 seconds. I chose to run the simulation for 4 hours because that way GeoClaw will plot both the initial tsunami but also the other waves as they come in afterward. When an earthquake creates a tsunami, it sends one giant wave, but then the wave recedes out to the ocean and comes back in again. It likely won't be as big as the initial wave, but it can still do significant damage. By plotting for four hours, I could record the data of the other smaller tsunami waves after the initial wave. I chose to make a plot every two minutes for the same reason. By having this many plots, I have more data to read. This in turn makes it so the simulation is more detailed. It does this by flipping from snapshot to snapshot in two minute intervals instead of longer time jumps, which makes the simulation appear smoother since it has more data to use.

Bathymetry and Rupture Scenario

GeoClaw also needs a bathymetry file and a rupture scenario to run. I used a Bathymetry file that models the layout of the ocean floor around Lincoln City. GeoClaw uses a bathymetry file because unlike the model in figure 5, the ocean floor is not flat. The real ocean floor is variable, so even if the bottom of the ocean in front of Lincoln City moved in a uniform way after the earthquake, the ocean floor would still stay variable. By mapping the ocean floor around the area of interest I got a more accurate result when I ran my rupture scenarios. Since I am focused on accuracy within my project the use of a bathymetry file is important.

GeoClaw also uses a rupture scenario. I used the 15 rupture scenarios already described which were generated with FakeQuakes. For each specific rupture scenario, FakeQuakes chose a target magnitude (for example 9.0 magnitude). Then FakeQuakes choses the length and width of the fault that will be ruptured randomly through the use of a probability density function. A probability density function is a way of picking a random variable while still accounting for the chance of that scenario being drawn. Then a random subfault is chosen to act as the center point of the rupture. The length and width chosen earlier are then used to calculate the size of the rupture. This is done by selecting all the subfaults within the area defined by the length and width found.

The next step is to figure out the slip. Slip refers to the movement of a fault. In the case of a subduction zone, it refers to the movement of the plates as they move toward one another. The amount of slip is calculated by drawing a random slip distribution through a probability density function. This slip distribution is then applied to the specified subfaults.

Simulation with GeoClaw

Once GeoClaw has a rupture scenario, a bathymetry file, an AMR level, and a specified region to model, it runs the simulation. It takes the rupture scenario and applies it to the region specified within the bathymetry file. The bathymetry is moved according to the rupture scenario and that in turn moves the water sitting atop the ocean floor. GeoClaw then "implements high-resolution finite volume methods to solve the nonlinear shallow water equations" (Arcos and LeVeque). In other words, GeoClaw calculates how much the water on top of the oceanic plate would move when the plate itself moves. It does this by dividing the specified region into rectangular grid cells according to the AMR levels. GeoClaw then calculates the velocities and depth of the water, considering the Manning coefficient. It does this in two different directions, the eastward direction, and the westward direction, and then it stores the averages of its mass and momentum in each cell (Arcos and LeVeque). These calculations are then performed for each cell at each specified time step (Arcos and LeVeque).

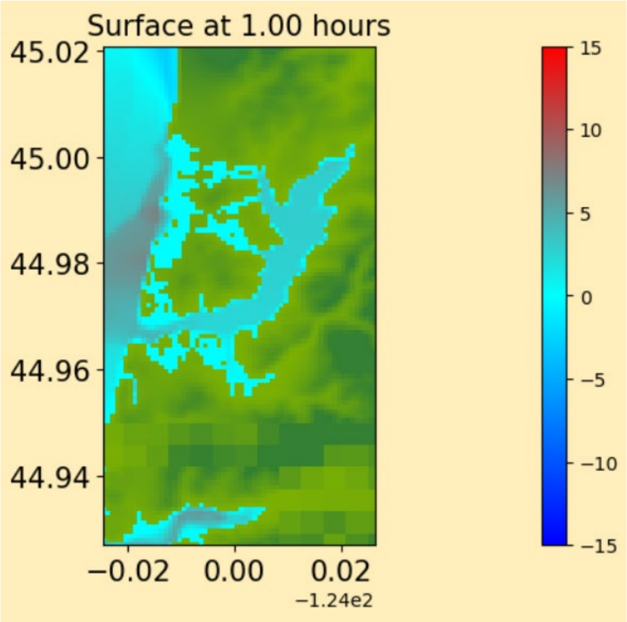

Figure 8: A GeoClaw representation of a tsunami hitting Lincoln City 1 hour after a Cascadia Earthquake (measured in meters).

The next step is to make the plots. GeoClaw makes as many plots as there are timesteps. GeoClaw makes them by taking the designated area and making a geographical map of it. For example, Figure 8 is zoomed in on Lincoln City, since that is my area of interest, and the green on the figure is the land. GeoClaw then takes all the points within a singular time step and plots them onto that geographical map. In Figure 8, the blue and red are the points plotted by GeoClaw. The colors are determined by the height of the water at the given time step, with the range being from -15 meters below sea level to 15 meters above sea level before landfall, and above the land elevation once the tsunami makes landfall.

GeoClaw then takes all the plots and converts it into an animation. The problem with the GeoClaw animation, though, is that while everything is plotted correctly, it only shows ground and water. The plots GeoClaw generates shows how far inland the water will go, but it does not show the areas of the city that will be impacted. How many houses does the tsunami cover? What districts of the city are destroyed? Are there any districts left untouched?

It is impossible to answer these questions using GeoClaw alone. To address this limitation, I took the data from GeoClaw and translated it into a kml file, which can then be ported into Google Earth.

Chapter 4: Google Earth

Since the Google Earth simulation uses the same data and time steps as the GeoClaw simulation the tsunami will look the same. But since it is run through Google Earth, instead of a plain block of green to represent the land, the simulation integrates houses and other features of a street map.

Because of this, Google Earth allows me to better highlight the potential impacts and damages of a Cascadia tsunami. Cascadia is a silent fault, so it can be easy to forget that it exists. By using Google Earth people will not only be able to know how far the tsunami will reach but also watch as it moves over their houses and favorite shops. The use of Google Earth makes the threat of a Cascadia earthquake feel more visceral and may encourage residents to plan for an eventual tsunami.

Google Earth makes the simulation by using a couple of different variables. It uses the time of the rupture, the size of the figure, and the color of the key.

Time of Rupture

The Google Earth simulation lets you set a specific date and time. This is useful if you are showcasing a tsunami that has already happened, but not as useful for simulations for what could happen. My Lincoln City simulations showcase what could happen and therefore don’t have a specific time. I originally had set the time of the rupture to NONE, for this reason, but then the simulation takes the time and date of when the simulation was made. Since I wanted the simulations to be comparable, I switched back to a specific time. For this project I picked the estimated date and time of the January 26th, 1700, earthquake, or the last time the Cascadia Fault Zone had an earthquake.

Factors that impact loading times

Output from tsunami simulations can lead to big data files, so different simulations load at different times depending on a couple of factors including the size of the figure and whether tiling is turned on. The bigger the size of the figure the longer it takes to load. The figure size is the size of the png file in inches. The figure needs to be big enough to cover the area of the simulation but if it is too big it can impact loading. The other factor that can impact loading time is tiling. Tiling controls when different resolutions load and therefore can make bigger files can load faster. By turning tiling on lower resolutions will load when zoomed out and higher resolutions will only load when zoomed in. That way the simulation only loads part of the file at a time. I have tiling turned off, because my inundation zone is so small, and it is unlikely to make much of a difference.

Transparent Vs. Dark

Geoclaw comes with three different color maps for the Google Earth simulation: transparent, light blue and dark blue. I use both the transparent and the dark blue color maps.

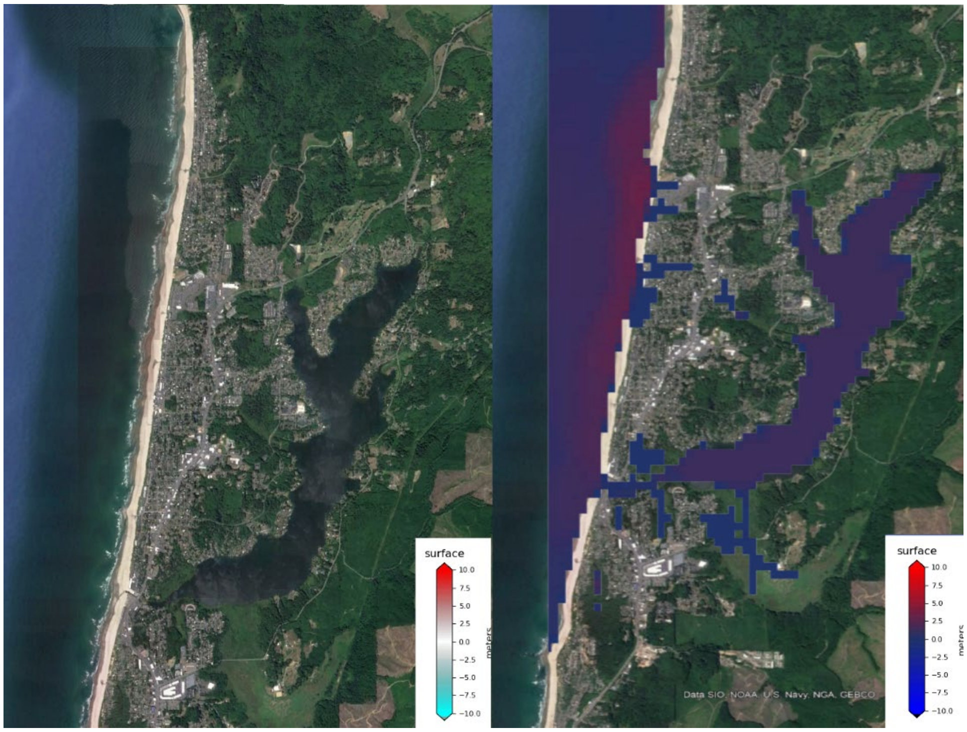

Figure 9: Two Google Earth Color maps of the same rupture. On the left is the transparent. On the right is the dark blue.

For this thesis, I used transparent because it is much easier to see what buildings and places of interest get innundated with the transparent color map. But since it is transparent the colors are much lighter with only the extremes having an easy to see color. In Figure 9, the transparent has a very light red tint to the simulation but it is hard to see. Because of this I also use the dark blue color map. The colors in the dark blue map are very saturated which makes it easier to see slighter differences. In Figure 9 the dark blue makes it much easier to see the variation that you cannot see in the transparent, but it completely blocks out buildings. Used together, the transparent and the dark blue maps compensate for each other's weaknesses.

By default, I tend to use the dark blue color map but the transparent is there for reference. Users can flip between the two color maps by checking and unchecking what is displayed on Google Earth.

Chapter 5: Results

I split up the fifteen ruptures that I ran into three different categories: minimal impact, moderate impact, and severe impact.

Minimal Impact

The minimal impact ruptures are the ruptures that never resulted in a tsunami. For the dark blue color maps these are the ones that don't transition out of dark blue. Of my 15 ruptures 3 of them are in this category (000168, 000265, 000487).

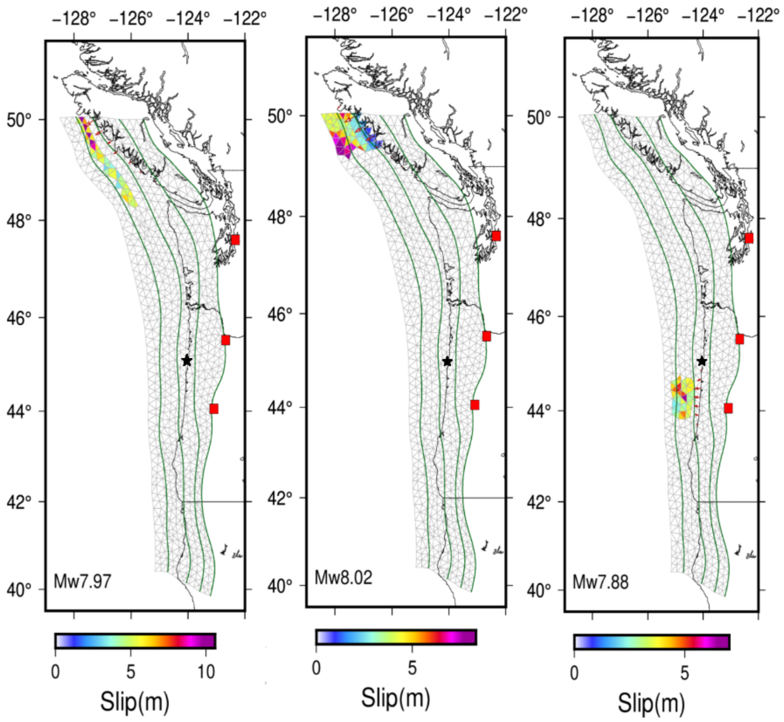

Figure 10: The Three Minimal Impact FakeQuake Ruptures. From the left to the right: 000168, 000265, 000487. (Lincoln City marked with a black star).

Both 000168 and 000265 are partial ruptures that only split around Canada and have lower amounts of slip and magnitude as can be seen in Figure 10. 000168 gets the farthest south at 48 degrees latitude, but Lincoln City, Oregon sits at about 45 degrees latitude. The distance coupled with the lower amounts of slip and magnitude means that any tsunami that would have been generated is unlikely to do much damage to Lincoln City.

However, as Figure 10 shows, 000487 ruptured close to Lincoln City. The rupture itself is relatively small and the amount of slip is even less than the slip generated in 000168 and 000265. Slip is important because it corresponds to how much the earth moves either up or down. Which in turn corresponds to the amount of water that is displaced to create the tsunami. 000486 is close to Lincoln City but since most of the slip is only between 2 and 3 meters a tsunami was not generated.

Moderate Impact

The moderate impact tsunamis are tsunamis that have a height of 0-5 meters or about 16 feet. Of the 15 rupture scenarios run 5 fall in this category (001198, 003455, 003925, 004516, 005004).

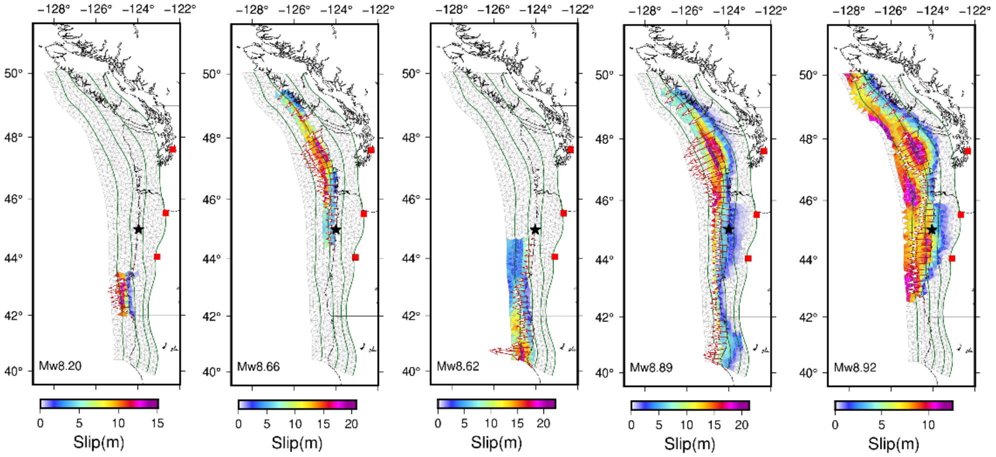

Figure 11: The Five Moderate Impact FakeQuake Ruptures. From the left to the right: 001198, 003455, 003925, 004516, 005004. (Lincoln City marked with black star).

Rupture 001198 isn’t too different from 000487. It is a partial rupture centered slightly South of Lincoln City, like 000487. But unlike 000487 it has a magnitude of 8.2 instead of 7.88

and a slip range of 0-15 meters instead of 0-6 meters. The higher the magnitude and slip the more water gets displaced to create a tsunami. The center of 001198 is at a latitude of about 43 degrees. Lincoln City is at about 45 degrees. One degree of latitude is roughly equivalent to 111 kilometers or 69 miles. The extra 111kms this tsunami would have had to travel to reach Lincoln City is likely what kept the tsunami below 2.5 meters or 8.2 feet.

Rupture 003455 like 000487 has a portion that lies near Lincoln City and the amount of slip in that area is smaller for 000487 (at about 5-8 meters for 003455 and 2-5 meters for 000487). Unlike 000487 though, the 003455 rupture extends over 50% of the Cascadia Subduction Zone and has portions that slipped a full 20 meters. These factors caused Lincoln City to be hit more than the 000487 rupture.

Rupture 003925 is not too different from rupture 003455. They both have a magnitude of 8.6 and a slip range of 0-20 meters. They are also less severe than they could be because they are only partial ruptures with the areas closest to Lincoln City having lower amounts of slip. For both ruptures, the fact that the largest amount of slip occurred further away from Lincoln City kept the tsunamis from being larger, and therefore kept these ruptures in the moderate impact category, not severe.

Rupture 004516 is the most potentially damaging rupture within the moderate impact group. The four other ruptures do not produce a tsunami with a height more than 2.5 meters, or 8.2 feet whereas the 004516 tsunami gets up to 5-6 meters high. It only has one wave that reaches that height, and the rest are around 2.5 meters. I considered putting 004516 in the severe impact category since it does get up to 5 meters but since it only has one wave that is that tall I kept it in the moderate impact category.

Rupture 005004 looks like a rupture that would cause a lot of damage at first glance. It is a magnitude 8.9 earthquake and most of the rupture is on the high end of this rupture's slip range. But at closer glance, it only has about 12 meters of slip at the max. Meaning most of the earthquake's slip is between 7-10 meters. This caused the tsunami to be weaker than thought at first glance.

Severe Impact

The severe impact scenarios are any in which the tsunami generated more than one wave that reached over 5 meters or 16 feet. Of the 15 rupture scenarios run 7 of them fall into this category (002433, 002926, 004338, 004717,005541, 006475, 006484).

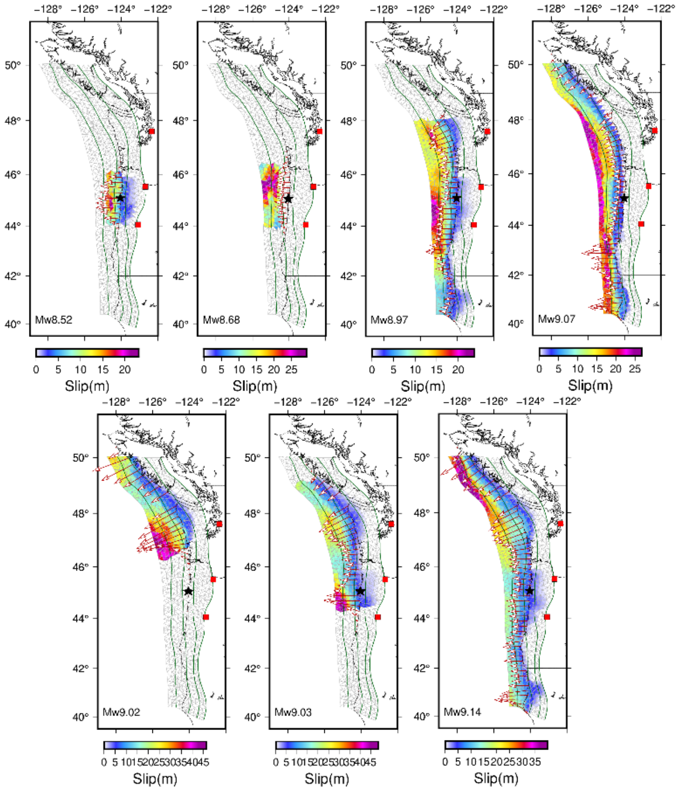

Figure 12: The Seven Severe Impact FakeQuake Ruptures. From the left to the right: 002433, 002926, 004338, 004717, 005541, 006475, 006484. (Lincoln City marked with black star).

Ruptures 002433 and 002926 are similar. They are both centered around Lincoln City, have similar magnitudes (8.52 and 8.68), and have similar slip ranges (0-20 and 0-25). They also both have exactly one wave that reaches 10 meters in height. Their similarities created similar tsunamis that have about the same potential for damage.

Ruptures 004717 and 006484 are also similar to each other. They are both full ruptures, with a magnitude 9 earthquake. The big difference is the slip range and distribution. Rupture 004717 has a slip range of 0-25 meters with 25 meters of slip occurring across the bottom 80% of the fault (starting around Seattle and continuing downwards). Whereas 006484 has a higher range of slip with 0-35 meters but the highest amount of slip occurs up in Canada at the North end of the fault. While around Lincoln City the slip is only about 15 meters. These differences in distribution is what made the tsunamis created by each rupture similar in damage potential. Each tsunami had one wave that reached 10 meters and multiple smaller waves of varying size in the following hours.

Rupture 004338 is similar to 004717, but its differences kept it from being as potentially damaging. Unlike 004717, 004338 is not a full rupture and instead only ruptured along the bottom 80% (up to around Seattle). 004338 also has a similar slip range to 004717 (0-20 vs 0-25), but its distribution is completely different. Rupture 004717, as previously discussed, has a slip of 20-25 meters across most of the rupture, whereas 004338's highest slip only occurs in a small section directly below where Lincoln City lies, as can be seen in Figure 12. This small section is what made the tsunami so devastating, and while not as potentially damaging as the rest of the ruptures in the severe impact section. They both have similar wave patterns, each with one 10 meter wave and many smaller ones afterwards. The difference is how far inland the tsunamis inundate. 004717 goes about 130 meters or about 42 feet further inland.

Ruptures 005541 and 006475 are also similar. They are both partial ruptures, that ruptured along the north end of the fault. They both have a slip range of 0-45 meters and a slip distribution where the worst was at the south end of the rupture. The difference is exactly where the rupture ended. 005541 ended around 46 degrees latitude whereas 006475 ended around 44 degrees latitude. Rupture 00541 and 006475 are similar but the potential damages could not be more different. 00541 is the tsunami within the severe impact category with the least amount of potential damages as the water only gets about 150 meters inland or 490 feet. On the other hand, 006475 gets over 1500 meters inland or almost 5000 feet.

What This Means

Overall, the potential damages for any rupture seemed to depend on three factors: the range of slip, the slip location and distribution, and the size of the rupture. The size of the rupture and range of slip controls how much of the earth will move in any one earthquake which in turn controls how much water will be used to create the tsunami. Whereas the slip distribution controls where the tsunami will be created which in turn controls the likelihood of a devastating tsunami reaching Lincoln City. This can be seen the best in 006475 which has the highest potential for damage out of all the ruptures run as can be seen in Figure 13. It has the highest amount of slip, with a big overall rupture, and the worst slip is directly south of Lincoln City.

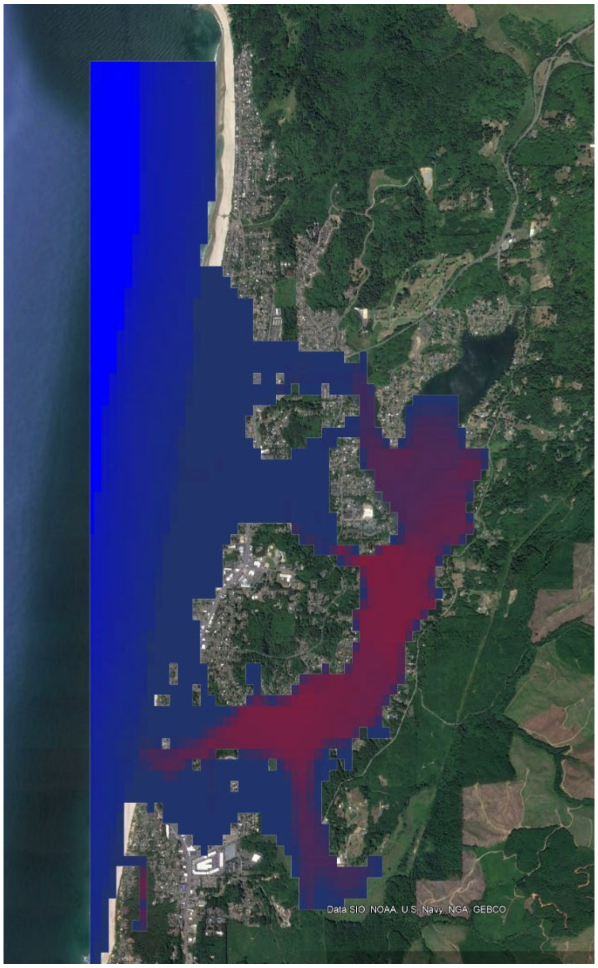

Figure 1: A Screenshot of rupture 006475 as the tsunami inundates Lincoln City

I chose 15 ruptures to simulate but the end goal of this project is to help the public better understand the potential impact of a Cascadia tsunami. Not all the 15 ruptures produced a tsunami and many of those that did were too similar for both to be useful. None of the minimal impact ruptures created a tsunami and as such shouldn't be used. From the moderate impact category, I would display 005004, 004516. They show the range in damage possible within this category. From the severe impact category, I would display 005541, 006475, and one of 002433 and 002926. Ruptures 005541 and 006475 show the range in this category like 005004 and 4516 whereas 002433 and 002926 show that the rupture does not need to be huge to cause damage.

Chapter 6: What's Next

This project only focuses on Lincoln City, but it could easily be expanded to cover many other cities up and down the Cascadia Fault Zone. It could even be expanded to cover many other faults around the globe and cities at risk of tsunamis from those faults.

Fixing Tsunami Height Calculation

When Geoclaw calculates the height of the tsunami at any particular point in time it uses the height of the ground before the earthquake. This is important because when an earthquake happens the exact topography and height of the ground changes. The earthquake might make the ground rise by 5 feet in one part of the coast but fall by 3 feet somewhere else. But because Geoclaw does not take this change into account when it models the height of the tsunami the model that is given is not necessarily giving the "correct" height predicted. In the future I would fix this so that the calculation is "correct" and the simulation could be as exact as possible.

User Friendliness

Right now, these simulations are not user friendly. They have some unused folders within them, and the simulations use meters as a form of measurement instead of feet.

In the future I would love to get rid of all but the 1 folder I use (sea surface) so that users won't accidentally turn on the folders that are either empty or have irrelevant information. The extra folders make the simulations less user friendly, especially the inclusion of two specific folders. The regions folder and levels folder make the simulation more chaotic and even unusable. The regions folder shows the computational domain, or what area I was specifically inundating. When the regions folder is turned on it covers all of Lincoln City in a light blue box which hides the actual simulation. The levels folder shows what areas are at what resolution. It does this by creating a bunch of black lines that move as the simulation does. Both folders could easily confuse users and are better off removed instead of just turned off.

My simulations also use meters as the form of measurement. This makes sense for the scientific community but since this project is meant for the public living in and visiting Lincoln City the use of feet makes more sense.

Further Research

There are avenues of research that I did not get to explore with this project. This project only covered 15 different ruptures, but it could be expanded with hundreds more ruptures. Then Probabilistic Tsunami Hazard Analysis (PTHA) could be performed. PTHA gives the probability of waves exceeding a specific height and intensity within a given period. By running hundreds of simulations on different ruptures the PTHA of Lincoln City could be found.

Another aspect that could be explored is the estimation of time between a Cascadia earthquake and the arrival of a tsunami. The amount of time people will have between the earthquake and the arrival of the tsunami is important. The more time people have before the tsunami arrives the more time they will have to get to higher ground. By running more simulations, the average time between earthquake and tsunami arrival could be found as well.

Community Outreach

Most of the public do not know that the Cascadia Subduction Zone exists, and of those that do know it exists most do not know the danger an earthquake and subsequent tsunami poses.

The simulations of Lincoln City give a concrete example of the potential of a Cascadia tsunami. Currently, the public has no way to view these simulations or get instructions on how to use them.

One way to give the public access is by making a website or providing some platform to make the simulations accessible. This website could also provide step by step instructions on how to get these simulations onto Google Earth and view them.

The 15 different scenarios show the full scope of what exactly could happen when the Cascadia Subduction Zone does rupture. The use of Google Earth makes the exact consequences of a tsunami along the West Coast easier to grasp. The water going over buildings and people's homes instead of just going over a plain green map makes it more impactful. The use of Google Earth also means that anyone with a computer can run these simulations since it does not need any special tools. The public can download these simulations and run them in their own homes.

The more people who understand the impact a Cascadia rupture could impose the safer everyone will be. A Cascadia Subduction Zone earthquake is coming, maybe not in 5 years, maybe not in 10, but it is coming, and we are not prepared. We have hospitals, schools, and retirement homes in inundation zones along the West Coast of Oregon (Schulz).

The coast of Oregon is flat enough that in the event of a tsunami many people will have nowhere to run to before the tsunami reaches them. These simulations could be used by organizations like the Federal Emergency Management Agency (FEMA). These simulations show where the tsunami damage is the heaviest, which could be used to help decide where structures like vertical tsunami evacuation towers are needed. Then with the help of organizations like FEMA these structures could be built.

Evacuation towers are built to withstand the rushing waters and debris from the incoming tsunami, but there are only three in North America (Washington State Geology News). These simulations show where the waters regularly inundate and could help decide where these towers should be built.

Even if evacuation towers were built, people would have to know where they and other evacuation options like them were. There are signs placed along the West Coast showing where the tsunami evacuation zones are, but many people do not pay attention to these signs. These simulations are more visceral than a statistic or a graph. With these simulations, people might pay more attention to possible evacuation routes when they visit the coast. By spreading awareness with this project, we could increase support for more safety provisions.

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