A PHYSICAL MODEL STUDY OF TSUNAMI INUNDATION WITH COASTAL INFRASTRUCTURE

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Abstract

The Cascadia Subduction Zone, located just off the coast of the Pacific Northwest, has a high potential to trigger an earthquake-generated tsunami comparable to the event observed in the Indian Ocean in 2004. The wave would arrive onshore very quickly without much warning, and current evacuation plans are not adequate. Numerical models have been used to predict the inundation of the coast up to ten meters in some areas; however, few physical models have been studied. Seaside, a city located on the coast in northern Oregon, was chosen for the study. The macro-roughness of the city was depicted by accurately idealized houses, restaurants, shops, and hotels unique to the town. The reconstructed town was rebuilt on a 1:50 scale and tested against four wave heights; 10, 20, 30, and 50 centimeters which correspond to a 5, 10, 15, and 25 meter wave in prototype. The goal of the project is to determine pressure on two buildings in the center of the city with these different wave heights.

Problem Studied:

Located just 50 miles off the coast of the Pacific Northwest, the Cascadia Subduction Zone has a very high potential to trigger an earthquake-generated tsunami (USGS, 2007). There is a 1 in 14 chance that this fault will fail within the next 50 years. This wave would arrive onshore within 20 minutes of its generation (Yeh, 2007).
Seaside, Oregon is among the many cities along the coast that would see much inundation upon the arrival of the tsunami. In 2006, the population of Seaside was 6,187 and in the summer, that number is significantly higher due to increased tourism (City of Seaside, 2007). Current evacuation plans send people inland to three predetermined sites. One in particular is the Seaside Heights Elementary School and would be the closest site for anyone fleeing from the tsunami wave from the beach. The school is 1.8 miles away from the beach and could be an unrealistic goal for many people including the elderly, children, and anyone with a disability. According to the city of Seaside evacuation plan, people on the beach would have only one direct route (City of Seaside, 2007). They would first have to cross the Necanicum River with only four available bridges and then shortly after, the Neawanna Creek with just one available bridge both of which are subject to failure during the seismic activity associated with the earthquake. Figure 2 below is an aerial map of Seaside. The red line is the predicted inundation line mapped according to the topography of the area. The blue squares are the three evacuation sites for the city, the middle being Seaside Heights Elementary School which is the evacuation route for anyone on the beach. The yellow arrows indicate the quickest evacuation path for people in each area.

Fig. 2.
A current map of the evacuation plan for Seaside, Oregon.

Objectives:

The goal of this research project is to eventually explore more efficient evacuation options for the residents of Seaside. Since inland evacuation may not be reasonable for all cases, it would be worthwhile to investigate other ways of safely surviving a tsunami. Vertical evacuation is one of these options being explored and it is the idea that people could evacuate upwards in a building if going inland is not an option (Yeh, 2007). Buildings would be constructed to not only survive the seismic shock of the earthquake,
but also the tsunami wave. In order to explore this idea, we first must learn the behavior of the wave as it inundates the coast, including pressure, flow speed, flow depth, and inundation patterns. A physical model with realistic coastal infrastructure was constructed and although an entire model of the downtown area was built, this project focused primarily on a major ocean front hotel and a smaller building a block inland, Building Two. This research project aimed to determine pressure on these buildings due to the force of the tsunami wave. In order to determine this pressure, three pressure sensors were installed on the buildings, two on the ocean front hotel and one on Building 2. This information is useful as a preliminary study.

**Research Approach:**

Many numerical models have been used to predict tsunami inundation patterns for coastal cities however; few physical models have been explored. There are several benefits to physical modeling, including simplification, control and repeatability, and accurate data collection that would otherwise be non existent in field research (Munson, Young, Okiishi, 2006). Our physical model was built to represent the downtown oceanfront of Seaside on a 1:50 scale beginning at the beach. Geographic surveys were completed to measure the bathymetry, the local topography of the area, and a satellite image was taken to locate the position of the buildings, streets, and the Necanicum River in the town. Using the same satellite image, the streets and river were plotted. They were scaled, traced, and painted. Plotting a coordinate system on the wave basin floor also allowed for us to easily plot the macro-roughness of the city which consisted of homes, commercial buildings, and large scale structures in the town. Macro-roughness is defined as anything that can be put in a physical model that would be used in numerical model. The larger and more permanent structures of an area are included in the macro-roughness and would not include objects such as shrubs, curbs, or temporary objects. 125 of these structures were used to represent idealized homes in the area. The bases were 6” by 9” and made of solid plywood. The roofs were solid, wooden triangles screwed into the base. They were painted yellow and placed according to the map bolted into the concrete floor of the wave basin. Red, 55-pound concrete pavers corresponded to the 65 idealized commercial buildings in the model. Their dimensions were 16” by 16”. These represented restaurants and shops, and were also bolted down into the concrete. Lastly, the hotels and other large scale structures were placed in the model and securely bolted into the concrete. There were a total of 13 large scale buildings and they ranged in size according to the actual buildings they represented in the city. The seawall, which sits at 20 feet above sea level, was represented by idealized concrete poured to scale.

The city was constructed on a fixed bed. The buildings were built to last many waves so the experiment could be repeated multiple times. A 1:50 scale was chosen to model Seaside to accurately depict both the time and length scale of the prototype (Munson, Young, Okiishi, 2006).
Due to the U-shape of the hotel that faces towards the ocean, it was hypothesized that this particular building would experience extreme forces due to the incoming tsunami wave, referred to as the “U” of the hotel. Two holes were drilled in this building, one in the lower center and one in the lower right hand corner of the “U”. The third hole was drilled on Building 2 at the bottom center of the building. Building 2 is a block inland from the oceanfront. Holes were drilled with approximate size to the sensor and then mounted on the inside of the buildings with the only the sensor face exposed to the outside through the hole. Chords connected the pressure sensors to a computer outside of the wave basin where data was collected. Using the computer program, Labview, pressure measurements were successfully recorded.

![Image of hotel with pressure sensors added](image)

**Fig. 3**
Picture of hotel with pressure sensors added

### Results

Three separate trials were completed for each different wave height. Because the project focused primarily on maximum pressure, maximum pressure data in pounds per square inch (psi) was taken from each of the three documented wave heights and averaged. This was completed for each wave at each of the three locations where pressure sensors were placed. Those values were then placed on a graph relating the pressure readings with the corresponding wave heights shown in Table 1. The hotel center reading is represented by a dark blue triangle. The lower right-hand pressure sensor is represented by a pink square, and each reading taken by Building 2 is shown as a yellow triangle.
It was hypothesized that with increasing wave height, increased pressure would be recorded in a linear graph. This was not the case. During the 10 centimeter wave, the pressure sensors documented a huge amount of pressure, much more than expected. The pressure for the 20 centimeter wave decreased significantly. From there, the pressure from the 20 to the 50 centimeter wave rose exponentially. Looking at the graph, the 10 centimeter wave was the only wave that had a maximum pressure different than what was anticipated. There are many reasons for this anomaly. The location of the wave when it breaks is a factor of its speed and pressure as it inundates the coast. Although it was not observed in the lab, it is very possible that the small wave broke much later, or closer to the city while the larger waves broke farther back from the shore. This would account for the unexpected difference in pressure values. To verify this, one person would simply need to visually record at which point each of the tsunami waves broke during their propagation.

It was also hypothesized that less pressure on Building 2 would be recorded during each wave event. In each trial, this was the case. In fact, for the 10 and 20 centimeter wave, no pressure was even documented.
Table 2 below shows a chart listing each wave height and the observed maximum pressure from the sensors that were recorded. To scale up the pressure to prototype, the observed pressure per square inch (psi) was multiplied by 50. Column 3 shows the average maximum pressure in prototype for each wave. It is interesting to note that pressure on the building during a 25 meter tsunami is 130 psi, almost four times larger than the predicted event.

<table>
<thead>
<tr>
<th>Wave Height (cm)</th>
<th>Wave Height (m)</th>
<th>Observed (psi)</th>
<th>Prototype (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5</td>
<td>0.89</td>
<td>44.25</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0.68</td>
<td>33.85</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.93</td>
<td>46.65</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>2.60</td>
<td>130</td>
</tr>
</tbody>
</table>

Table 2
Observed pressure scaled up to prototype

It is interesting to note that the predicted tsunami event for the Pacific Northwest falls somewhere between the 10 and 20 centimeter wave.

Further Study

With the increasing threat of tsunami inundation, current evacuation plans for many coastal cities need to be updated. This was obvious to my research group, as we had the opportunity to visit Seaside during the last week of the program. Starting from just before the beach, we decided to trace the tsunami evacuation route as tourists, by simply following the evacuation signs. We followed the path which did not lead us directly to elevation. Remembering we only have 20 minutes, we briskly walked according to the evacuation signs to the Seaside Heights Elementary School. We noticed many setbacks that could, in a time of emergency and panic, only delay people from safety. First of all, the tsunami evacuation route signs are small and hard to see. Figure 4 below is a photograph taken in Seaside as our team was mapping out the route to the Elementary School. This picture was taken less than a block away from the sign and it is hardly visible.
Secondly, 20 minutes into the experiment, at the estimated time of arrival of the wave, we found ourselves at ground level with the elevation was just ahead. Again, we were not running but we were walking very quickly. At the base of the hill, the tsunami evacuation signs stopped, and we found ourselves walking tiredly up the hill clueless to where the school was. After a half hour, 10 minutes after the wave was expected to hit, we gave up and decided to check the map. We were frustrated, tired, and blocks away from the school.

The idea of vertical evacuation is one that should be pursued as an alternate option to inland evacuation. Vertical evacuation is the idea that people could seek shelter by going up and not necessarily out in buildings closer to the coast. These buildings would be built to not only withstand the seismic shock of the earthquake, but also the following tsunami waves. It was the experience at Seaside that made our group realize how much time really matters in this situation, and any spare time, even minutes is vital.
In order to explore the idea of vertical evacuation, more studies on the behavior of tsunamis need to be completed. Along with pressure estimations, other elements of wave patterns need to be measured. Using the same type of waves, flow depth, flow speed, and inundation patterns can be documented. Using an ADV (Acoustic Doppler Velocimeter), flow speed can be recorded. Knowing the speed of an incoming tsunami can more accurately predict the time people have to reach safety. An ADV was placed on an ocean front building in our model and is ready to take these measurements. To measure flow depth, a simple grid was placed on the outside wall of the same hotel the pressure sensors were mounted. A predetermined grid scale was made and placed on the side of the ocean front hotel. Pictures taken from the outside of the wave basin as the water flows by can accurately model flow depth. Lastly, using a high speed camera with known shutter speed, patterns of the water as it inundated the city can be captured. Observing inundation patterns can give researchers insight as to how the macro-roughness of a particular area will affect wave properties.

I would like to give deep thanks and appreciation to The National Science Foundation and The Network for Earthquake Engineering Simulation for the opportunity to participate in this program. I would also like to thank Oregon State University and the Hinsdale Wave Research Laboratory for allowing me to spend the summer working and learning in their facility. A special thank you goes out to my mentors Dr. Dan Cox and Dr. Harry Yeh for the endless amount of help and advice they gave me throughout my learning experience. I would also like to thank Chris Bradner for helping me during the
entire process of the project both in the lab and outside. Rounds of heartfelt thank-you’s to everyone at the wave lab facility for sharing their summer with me and making me feel truly at home. I heartedly extend a sincere thank you to Brittany Snyder in particular, with whom I gladly acknowledge as my partner and true friend in this project.

References:


