COMPREHENSIVE TSUNAMI SIMULATOR FOR CANNON BEACH, OREGON

FINAL REPORT

to

City of Cannon Beach

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A comprehensive tsunami evacuation simulator was developed for Cannon Beach, Oregon. The development involved collection of data from various sources including geographical data, infrastructure and building data, demographic data, and hydrodynamic data. The data were used as input to run a model that integrates warning transmission with evacuation processes and outputs human casualty counts. Several simulations were run for a tsunami event originating from the Cascadia subduction zone, which is the most probable near-source tsunami scenario affecting Cannon Beach. We quantitatively determined the effectiveness of a tsunami evacuation building (TEB) for vertical evacuation and the effectiveness of an earthquake hardened bridge across Ecola Creek at the site of the current roadway bridge. Our results show 11% reduction in human fatalities if a TEB is constructed at the present City Hall location on Gower Avenue. Proper construction of a bridge would reduce fatalities by 55%; however we found that the bridge must be constructed with sufficiently high elevation. We also demonstrate that a TEB at an alternate location near the intersection of Washington St and Spruce St would be more effective than at Gower Ave: such a TEB could reduce fatalities by 65%.

Although the number of scenarios and situations we examined is limited, the simulator allows us to analyze the effectiveness of various mitigation plans. Further refinement of data and more simulations should be conducted to guide local and State officials.

A. INTRODUCTION

The City of Cannon Beach is located in the northern Oregon coast (Fig. 1) approximately 40 km south from the Columbia River. The City is situated along the Pacific coast, about 6 km long in the north-south direction and 1 km wide in the east-west direction. This community is mostly residential with a large seasonal and vacation population in summer. The area is vulnerable to local tsunamis triggered by a Cascadia subduction zone earthquake as well as distant tsunamis likely originating in the Aleutian Islands or Alaska.

When a significant seismic event occurs, there is usually some lead-time prior to arrival of a leading tsunami. This allows communities time to warn and evacuate the population. According to a tsunami study conducted by DOGAMI (the Department of Geology and Mineral Industries, Oregon, 2009), the initial tsunami could strike Cannon Beach in less than 15 minutes, followed by the peak arrival about 30 minutes after the earthquake (Fig. 2). For a mega Cascadia event like Mw 9, ground shaking could last more than 3 minutes. Effective time for evacuation is limited and evacuation to the natural high ground may not be an option for some people. Providing tsunami evacuation buildings at strategic locations can be a viable means to save lives.

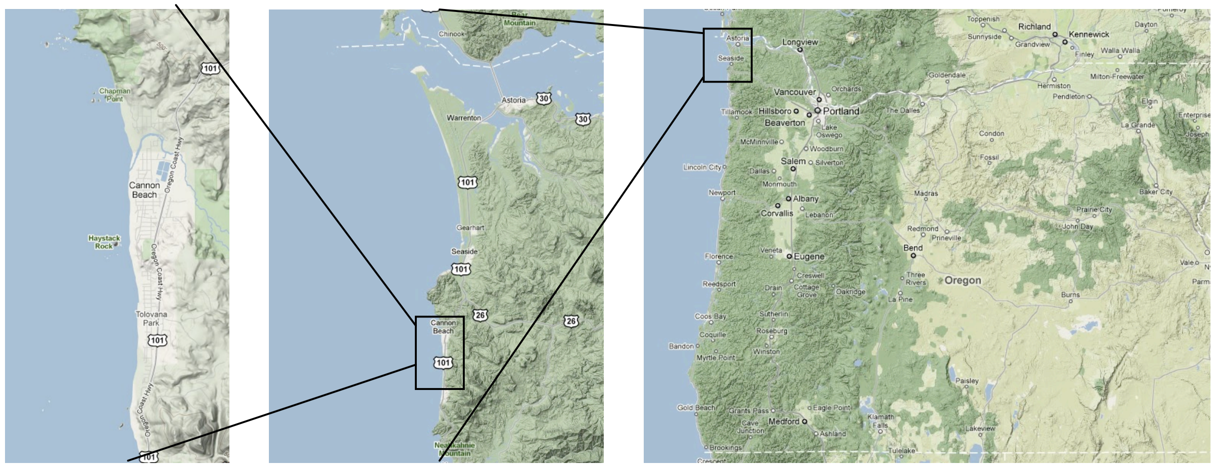


Figure 1. A location map for the city of Cannon Beach, Oregon.

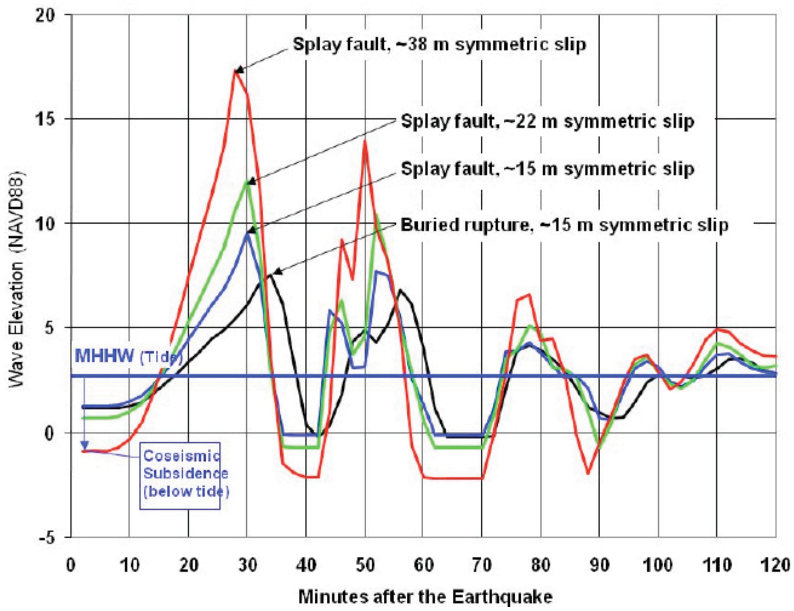


Figure 2. Time history of wave elevation for several scenarios of the Cascadia subduction tsunamis (Priest et al. 2009).

An integrated scenario simulator has been developed to evaluate the effectiveness of a planned TEB at the existing Cannon Beach City Hall site and the effectiveness of a planned pedestrian evacuation bridge across Ecola Creek at the north end of the City. In Section B the tsunami scenario simulator is discussed; then its application to Cannon Beach is described in Section C. The project involves collection of necessary data and integration of various models for warning transmission, evacuation, and casualty. A hypothetical tsunami originating from the Cascadia subduction zone was chosen and in Section D we discuss the results, including the effectiveness of the proposed TEB and the evacuation bridge, as well as an alternative TEB location.

B. Simulation of Tsunami Scenarios

A scenario simulator can be used to support quantifiable tsunami hazard and vulnerability analyses for coastal communities. The simulator integrates four modules: 1) hydrodynamic simulation of tsunami propagation and inundation, 2) warning transmission, 3) evacuation, and 4) a casualty model. Figure 3 depicts how those four modules interact.

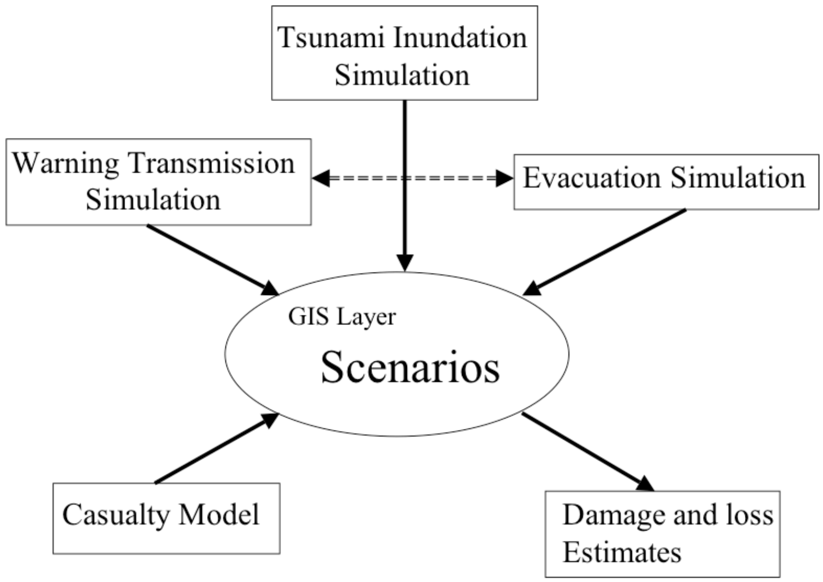


Figure 3. Schematic representation of the integrated tsunami scenario simulator.

Hydrodynamic models for tsunami generation, propagation, and runup have been used in practice (e.g., Titov & Synolakis, 1998; Lin, et al., 1999; Imamura, 1996). While the numerical algorithm itself is considered adequately accurate (e.g. Yeh, et al. 1996), it remains difficult to determine practical tsunami-source conditions. Fortunately, Oregon has completed a thorough investigation to estimate the most credible tsunami source for the Cascadia events (Priest, 2009). Furthermore, Zhang and Baptista (2008) conducted detailed numerical simulations specifically for the inundation in Cannon Beach. For the present study, the tsunami inundation data were acquired from Dr. Joseph Zhang of Oregon Graduate Institute. There are several scenarios available; we chose one tsunami condition for this study, the “95% confidence level” event, which means that there is a 95 percent confidence that a Cascadia tsunami will not exceed the projected inundation line.

The simulator computes evacuation routes for each individual to a refuge location based on the shortest navigable road path without accounting for the expected inundation area, signage, terrain elevation, or other queues that a person might pay attention to. At the same time, the simulator assumes all evacuees know the location of the nearest refuge location and how to reach it. We therefore specify refuge locations appropriate to guide people out of the inundation area to safety, and in the direction of officially designated assembly areas. The current simulator does not alter the rate of travel or routing in response to congestion nor does it account for time required to achieve “safety” once the location of a refuge is reached, such as time required to ascend the stairs of a TEB.

The casualty model used in this study is based on whether a person can remain standing within the tsunami flow. Once a body is pushed away or brought down by the flow, this constitutes a fatality. Tsunami runup can take a variety of forms. In some cases, the flow is swift and the flow depth is shallow; the flow force creates drag on a person's feet causing them to slide from their standing position. In other cases, the runup can be characterized as a gradual rise and fall of flooding water; even small flow force can bring the body down by rotation because the net body weight decreases due to buoyancy effects. These two failure modes were computed and the results for an average adult male are used in the present simulations. More detailed description of the casualty model can be found in Yeh (2010).

The integrated simulator uses a GIS framework to produce animations of the tsunami runup (typically occurring in multiple waves), warning transmission patterns, and individuals' protective responses.

C. A Simulator for Cannon Beach

A simulation domain covering 3 km in the east-west direction and 6.8 km in the north-south direction was used. Figure 4 shows the tsunami inundation map for Cannon Beach, indicating the locations of assembly areas and tsunami-safe high ground. The blue dots represent refuge sites used in the simulation. Those evacuation points do not coincide with assembly areas in the official evacuation map. Instead they were selectively placed to guide the evacuees to high ground. Because of the strong ground motion caused by the earthquake, we do not expect that the Ecola Creek Bridge (show in Fig. 4) will be intact and passable.

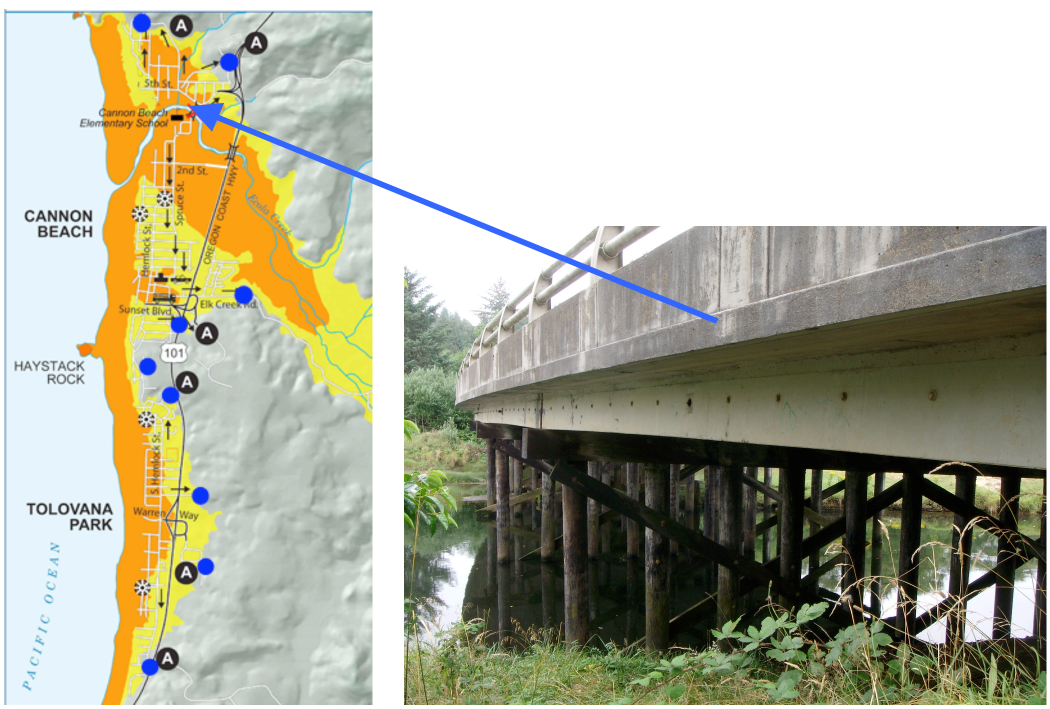


Figure 4. Simulation domain indicating the inundation zones of a distant tsunami (orange) and the Cascadia subduction tsunami (yellow), and the official assembly areas (circled A). The blue dots are evacuation targets used for the simulation. The photo shows the existing Ecola Creek Bridge that we assume will not survive the strong ground motion associated with a Cascadia earthquake.

GIS data for Cannon Beach was obtained from the City of Cannon Beach (Mark Scott). The data include a) road network, b) buildings (hotels, commercial, residential), c) bridges, d) elevations (LIDAR grids), e) ortho-photo map, and f) natural features including shoreline and rivers.

The model simulates the evacuation of individuals moving on foot toward the closest refuge sites or high ground (determined by shortest navigable road path) with a typical walking speed of 88 m/min. Figure 5 shows the locations of refuge sites used for the simulations.

Refuge Site 1	8th St. between Ash and Oak St., West of Ecola Park Rd.
Refuge Site 2	Intersection of Old Cannon Beach Rd. and 6th St.
Refuge Site 3	Milepost 30 – Vehicle turnout adjacent to HWY 101
Refuge Site 4	Sunset Hill – East Sunset Blvd. in the vicinity of Seascape and Elk Mtn. Rd.
Refuge Site 5	Haystack Heights – East Chinook Ave., South of Elk Run Ave.
Refuge Site 6	Hemlock at HWY 101 near Tolovana Mainline Rd.
Refuge Site 7	E Chena St – South end of Haystack Hill Park
Refuge Site 8	Haystack Ln. – Northwest edge of Haystack Hill Park
Refuge Site 9	Intersection of Fir St. and HWY 101, North entrance to the City.

Figure 5. The locations of refuge sites used in the simulations.

Population distribution for the residents and visitors is difficult to determine because there are a large number of seasonal residents and short-term visitors. Considering a summer situation, City officials suggested daytime estimates between 6,000 and 10,000 people in the city. Guided by this estimate, we assume that the number of people present during the simulated earthquake is 7885 people. This number is derived by placing 3 people in each zoned tax lot (there are 2455 tax lots within the simulation area) plus 106 people at the Elementary School on Beaver St., 121 people at the Christian Conference Center on Spruce St., and 293 additional people on the beach and in city parks.

The warning transmission model simulates both official and informal processes. For the Cascadia event, strong ground shaking is the primary and distinct cue for evacuation.

Considering the 2004 Great Indian Ocean Tsunami and, more important, the very recent March 11, 2011 Tohoku-Japan Tsunami, people's tsunami awareness is extremely high at the present time. Thus, we assume an 80% probability that people would commence evacuation as soon as possible after the earthquake. The earliest time for evacuation is 5 minutes after earthquake onset, accounting for prolonged ground motion (3 minutes) and a short preparation time (2 minutes). Each minute thereafter we impose a 15% probability that each of the remaining people initiate evacuation.

An additional parameter used in this study is the effect of loud speakers. The city has 5 elevated warning loud speakers, distributed north to south near the edge of the beach line, which may be triggered in the event of a tsunami warning. These speakers take approximately 5 minutes to activate, assuming power is available and access to the control system is possible. We set the speakers to sound 10 minutes after onset of the earthquake with an audible distance of 300m in radius from each loudspeaker, and assume that 75% of the people within the audible range recognize the warning and initiate evacuation. No other mass media announcement (TV and radio) was considered.

D. RESULTS

We performed six sets of simulations, although only four were originally proposed. The originally proposed simulations are:

a. Baseline case: the current city assuming failure of the Ecola Creek Bridge.

b. Same as (a) with a TEB at Gower Ave (the current site of City Hall).

c. Same as (a) with a reinforced bridge over Ecola Creek. The bridge elevation is set at 3 meters above the high tide line; the same as the north bank terminus of the bridge at the intersection of 5th and Fir St.

d. Combination of (b) and (c).

The following additional simulations were motivated by results from simulations a) – d):

e. Same as (c) but the bridge is placed at a lower elevation, 0.5 meters above the mean high tide line; the same as the south bank terminus of the bridge at the intersection of Beaver St. and Elm Ave.

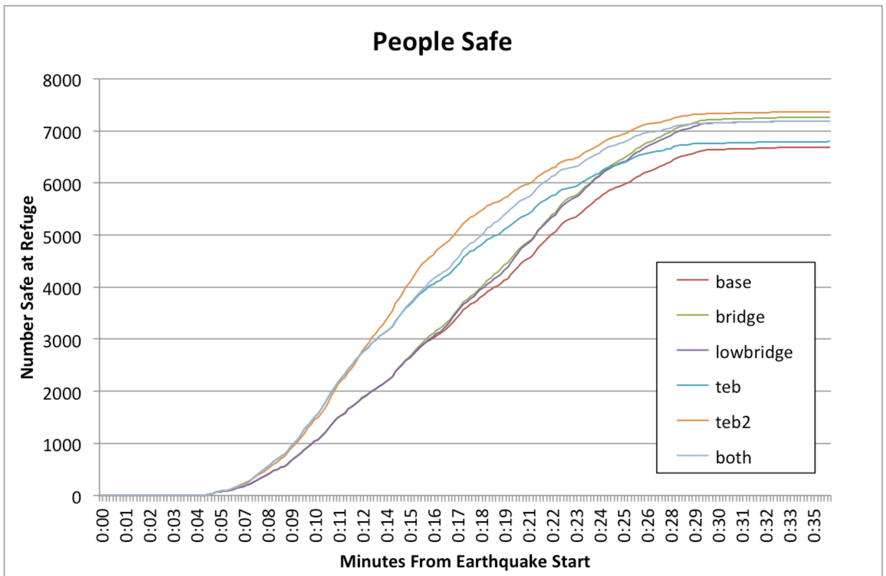
f. Same as (b) but place the TEB 0.6 km north of the current city hall site, near the intersection of Washington and Spruce Streets.

Figure 6 shows the time history of the number of people who reached refuge sites, and the time history of the number of people killed by tsunamis. The fatality time histories show initial fatalities of 33 at $t = 0$. This is a simulation defect caused by a mismatch in ground and seawater elevations at the beginning of the tsunami event. As shown in Fig. 2, the focused tsunami study made by DOGAMI (Priest et al, 2009) and Zhang and Baptista (2008) made several estimates for the land subsidence. Their predicted land subsidence and the seafloor deformation by the fault displacement were estimated with different methodologies, resulting in an unrealistic mismatch between the water level and the subsided land level at the beginning of the simulation. This error is considered to be small. In fact, given that the casualties occur near the water line we could consider these initial fatalities to be caused by the earthquake itself.

In the early stage of evacuation, say from $t = 10$ to 15 min, evacuees reach the TEB at about the same rate regardless its location, but more people reach safety faster than in scenarios without a TEB. Early on, the evacuation bridge (Cases c and e) makes no difference from the baseline case; the bridge becomes effective during the later evacuation process ($t > 15$ min).

Up to 17 ~ 18 min, the fatality rate is essentially independent of the TEB and evacuation bridge. People killed by the early surge are near the shore and other low-lying areas where it is not possible to reach higher ground ahead of the initial tsunami surge. A rapid penetration by the tsunami occurs around $t = 18$ min. Careful observation reveals that the TEB placed at Gower Ave performs better than the bridge until $t = 23.5$ min. After that, the bridge's impact on survival rates surpasses that of the Gower TEB.

a)



b)

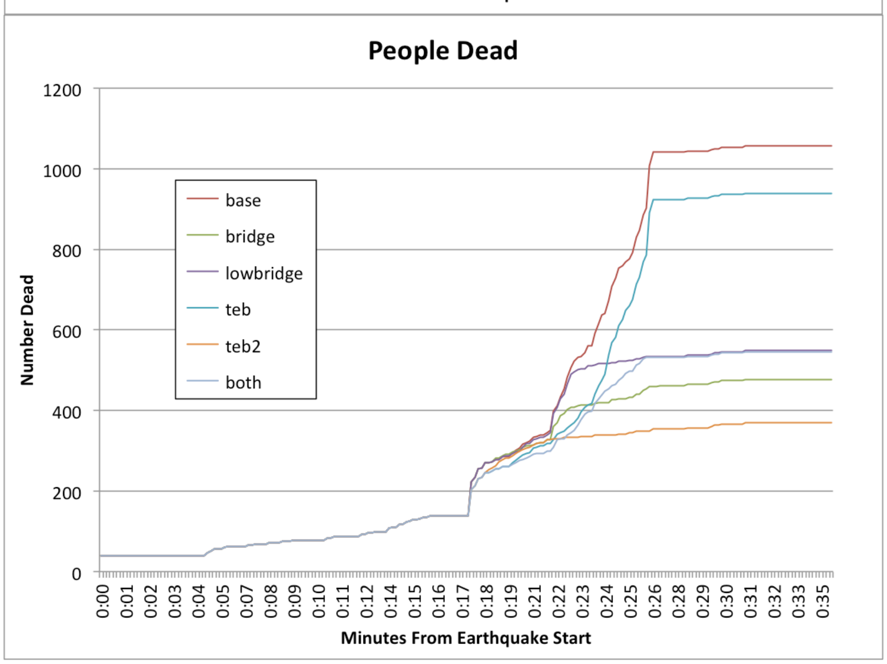


Figure 6. Time history of the number of (a) survivors and (b) casualties for different scenarios.

Figures 7A, B, and C show the evacuation patterns for the baseline case (Case a), the case with the Gower TEB (Case b), and the case with the evacuation bridge (Case e), respectively. Refuge sites 1, 5 and 6 are unaffected by the TEB or bridge because those refuge sites are far away from the TEB and bridge. Refuge site 9 is unused due to it's proximity to Refuge site 2 and the inability of evacuees to safely travel north on Highway 101. With the evacuation bridge Refuge site 2 received 579 additional evacuees in comparison with the baseline case (no bridge).

The TEB at City Hall is effective at accommodating people in the early stage of the evacuation (see Fig. 7B). In this scenario the number of people reaching Refuge site 4 drops dramatically. Evacuees headed inland to site 4 in the baseline case instead travel to the TEB when it is located nearby.

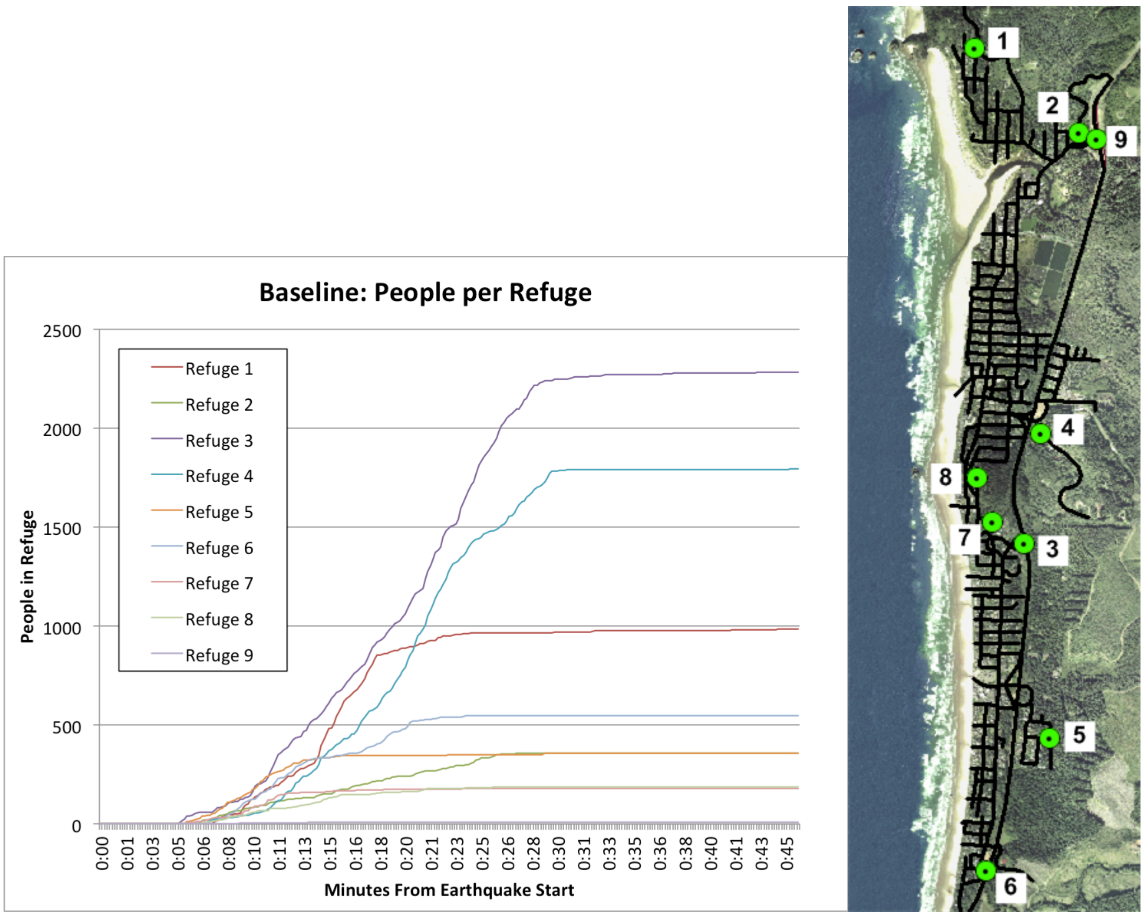


Figure 7A. Time history of the number of evacuees who reach the refuge sites in the baseline case.

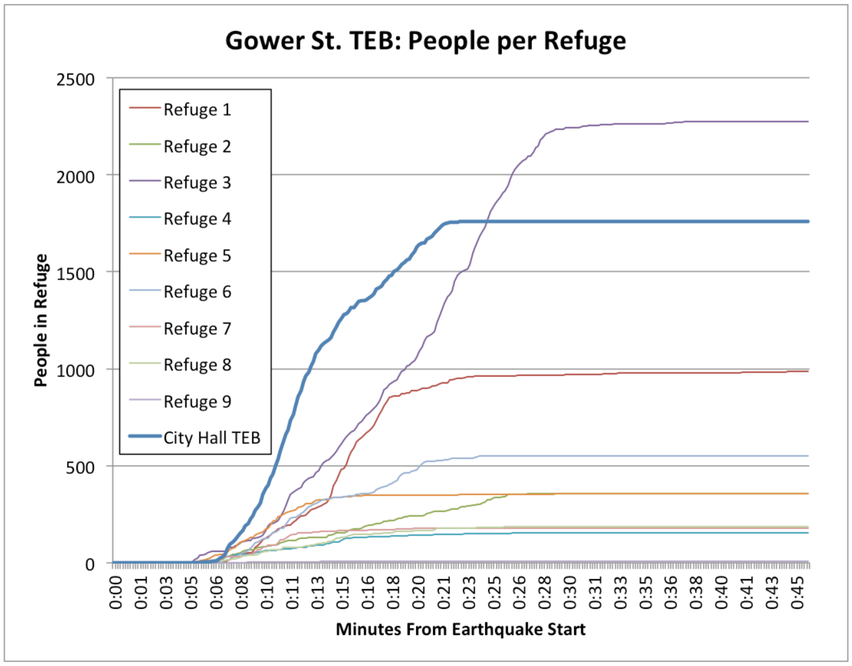


Figure 7B. Time history of the number of evacuees who reach the refuge sites in the Gower TEB case.

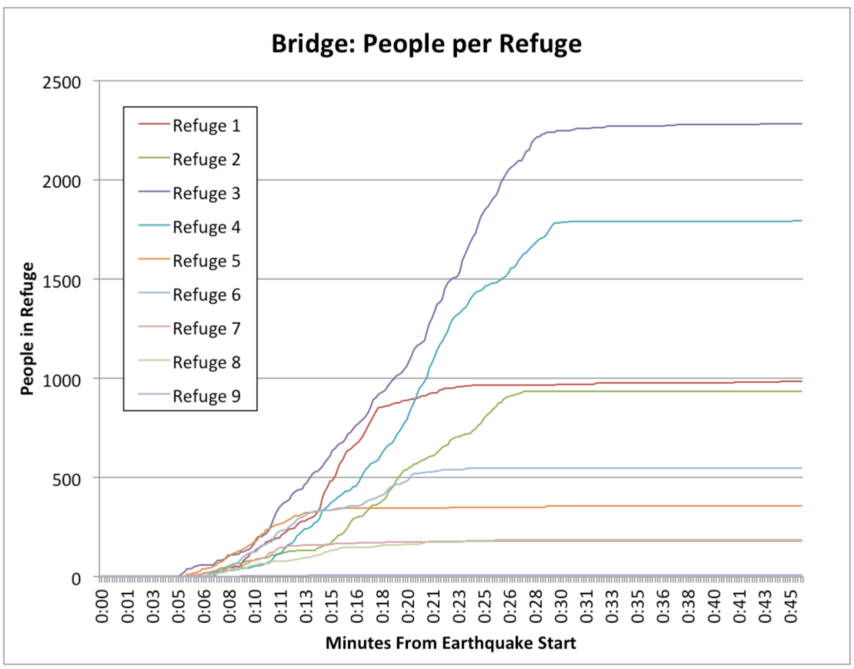


Figure 7C. Time history of the number of evacuees who reach the refuge sites with the evacuation bridge.

Table 1 shows the summary of the final counts of survivors and fatalities. The best performance among the simulations is Case (f): construct a TEB at the intersection of Washington and Spruce Streets. Note that the performance of the evacuation bridge depends on the height of the bridge. This is because the simulated tsunami arrives at Canon Beach very soon after the earthquake and the south bank of Ecola Creek is significantly lowered due to subsidence. If the bridge is not sufficiently raised, it is covered by the tsunami while evacuees are on it.

Table 1. Summary of simulations (casualties and survivors).

Refuge Sites	1	2	3	4	5	6	7	8	9	TEB	TOTAL
(a) Base Case											
Saved	1015	357	2282	1794	357	549	180	186	9	0	6729
Killed	45	42	150	768	0	30	0	0	21	0	1056 (*)
(b) TEB											
Saved	1015	357	2276	156	357	549	180	186	9	1761	6846
Killed	45	42	150	0	0	30	0	0	21	651	939 (– 11 %)
(c) Bridge											
Saved	1015	936	2282	1794	357	549	180	186	9	0	7308
Killed	45	123	150	108	0	30	0	0	21	0	477 (– 55 %)
(d) TEB + Bridge											
Saved	1015	750	2276	156	357	549	180	186	9	1761	7239
Killed	45	48	150	0	0	30	0	0	21	252	546 (– 48 %)
(e) Low Bridge											
Saved	1015	864	2282	1794	357	549	180	186	9	0	7236
Killed	45	105	150	198	0	30	0	0	21	0	549 (– 48 %)
(f) TEB (Alt.)											
Saved	1015	357	2282	663	357	549	180	186	9	1818	7416
Killed	45	42	150	3	0	30	0	0	21	78	369 (– 65 %)

The performance of Case (c), bridge alone, is better than Case (d), when the bridge and Gower St. TEB are combined. This is because the presence of the Gower TEB attracts people to move south who would otherwise cross the bridge, leaving them in the vulnerable lowlands for a longer time.

Note that the number of people reaching the Gower Ave TEB is only 5% smaller than that for the Washington St TEB (1761 vs. 1818) yet the survival rate improves almost 500% when the TEB is located at Washington St. The relatively even population distribution throughout the area accounts for the similarity in arrival rates, timing, and total evacuee counts between the two TEB sites.

There are two factors involved in the significant difference in casualty rates. One is that people south of Gower St who were diverted from Refuge site 4 by the Gower St TEB do not attempt to reach the Washington St TEB, which is farther away from them. The second factor is that those north of Washington St, who could not reach the Gower St TEB before the area floods, can reach the Washington St TEB quickly enough to achieve safety ahead of the tsunami inundation occurring between $t = 23$ and $t = 30$ minutes.

Detailed performance of the Gower TEB and the bridge are shown in Fig. 8. This information should be useful when designing the TEB and/or bridge for construction. According to our simulation, the peak number of evacuees entering the TEB is 48 people per 10 seconds, which indicates serious entrance congestion at the TEB. 241 people could be on the bridge at one time, at $t = 10$ min, which may inform bridge capacity and structural design. Fig. 8 shows the net change in people on the bridge in green, with a maximum of 27 people per 10 sec. A floating or suspended pedestrian foot bridge, one of the contemplated bridge designs, would likely not accommodate all of the evacuees and might create a dangerous bottleneck during evacuation.

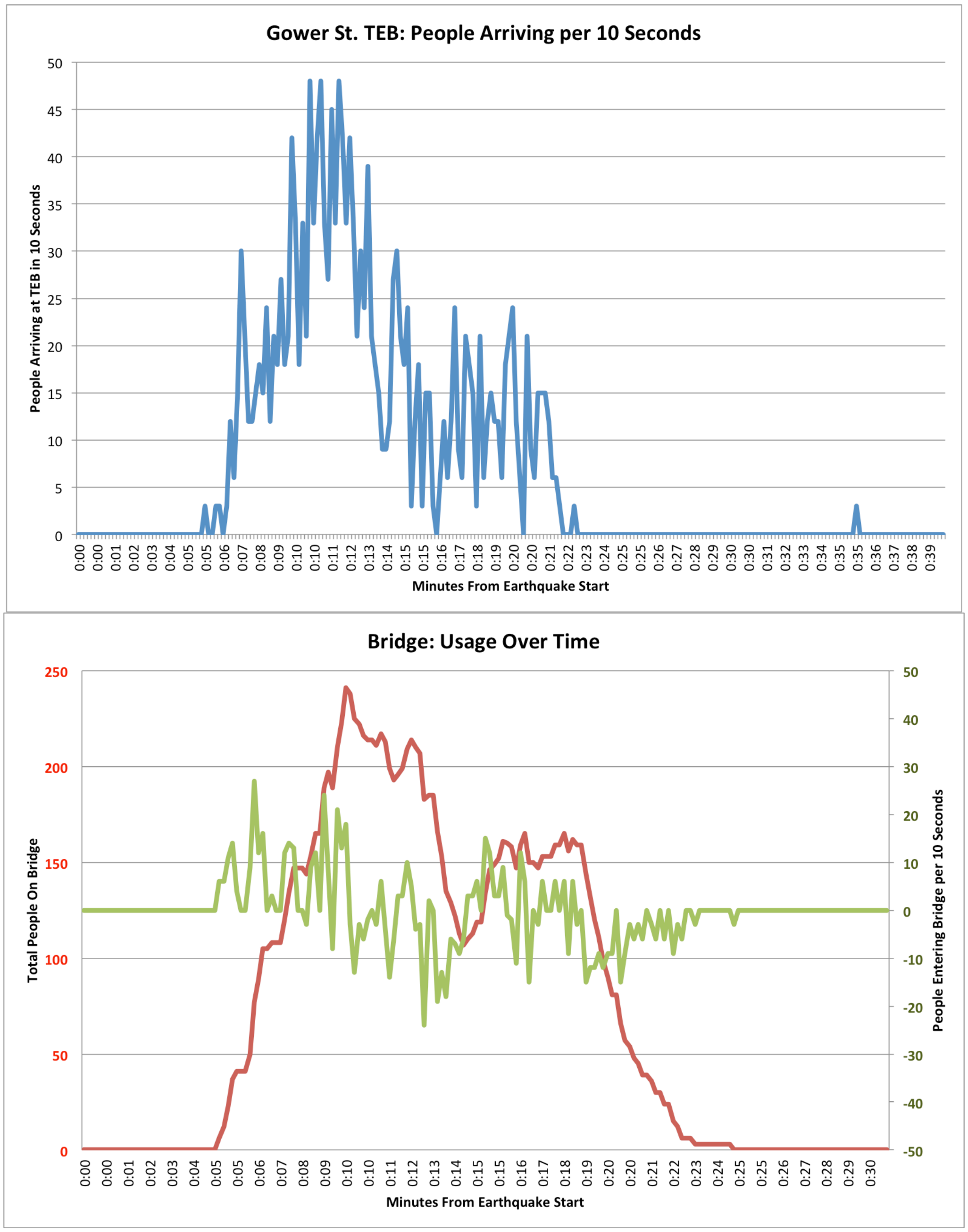


Figure 8. Detailed evacuee flows to the TEB (top) and the pedestrian bridge (bottom).

E. Summary and Remarks

We have developed a comprehensive tsunami simulator for Cannon Beach, Oregon. The development involved collection and integration of essential data from various sources. Several cases were performed to demonstrate the effectiveness of the tsunami evacuation building and the evacuation bridge.

Although tsunami-warning tactics, evacuation plans and mitigation measures are determined by considering many factors and the simulation cannot take into account the many complexities of a real emergency evacuation, the scenario simulator can be used as an effective tool for quantitative evaluation and decision making. The results of this project should inform improvements in the planning and operations of emergency evacuations in the case of tsunami incidents at Cannon Beach. For future study, the following are recommended:

Alternate population distributions for other seasonally-dependent scenarios should be used for the simulations including detailed demographic data so that gender and age differences can be included in the casualty model.

The present simulator uses control parameters to determine human behavior based on data obtained in Japan. Such parameters should be revised based on survey data obtained from the residents and visitors in Cannon Beach. Thorough collections of such data might be available for Cannon Beach (Wood, 2007, e.g.).

A distant tsunami (probably originating from the Aleutian Islands or Alaska) may not cause extraordinary runup like a Cascadia subduction event but could still be significant. Even a small inundation, as was seen with the March 11, 2011 Tohoku-Japan tsunami, can be a significant and dangerous event, especially if landfall happens to coincide with high tide. It is recommended to study such tsunami cases.

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