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# An agent-based vertical evacuation model for a near-field tsunami: Choice behavior, logical shelter locations, and life safety

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ABSTRACT

In the event of near-field tsunamis, vertical evacuation can be an alternative protective action to horizontal evacuation. The objective of this paper is to present an agent-based modeling (ABM) framework to evaluate vertical evacuation behavior and shelter locations for a near-field tsunami hazard from a Magnitude 9.0 Cascadia Subduction Zone (CSZ) earthquake. The expected mortality rate depending on the location of the vertical evacuation shelter (VES) has been chosen as the primary criterion to assess the effectiveness of the vertical evacuation. In addition, maximum tsunami wave height and the vertical evacuation behavior changes with changes in the placement of the VES have been assessed from a constraint point of view. The results revealed that (1) the choice of VES locations will directly impact the proportion of the people who evacuate vertically; (2) The percentage of people who evacuate vertically exponentially drops as the shelter gets farther from the population centroid; (3) the location of shelter significantly impacts the total mortality rates; (4) improvements in evacuees' mobility, such as faster walking speed or shorter milling time, will significantly reduce mortality rate and expand the area of choices for VES locations; and (5) when more people choose to evacuate vertically, the total mortality rate reduces notably. However, wrong placement of VES, and at the same time promoting vertical evacuation behavior can result in catastrophic mortality rates. In addition, a study on the impact of the distance of the VES to the ocean, to the population centroid, and to the horizontal shelters outside of the inundation zone, on the total mortality rate and the evacuation efficiency has been performed. This work reveals the non-linear correlation between the aforementioned characteristics of the VES on the expected mortality rate. The results of this research provide an evidence-driven vertical evacuation modeling framework to guide decision makers at city, state, and federal level to understand the dynamics of vertical evacuation behavior and choice of vertical evacuation shelter locations for a community.

## 1. Introduction

Many communities around the world are vulnerable to either slow or rapid onset disasters with varying temporal and spatial footprints. Such disasters include natural hazards like earthquakes, tsunamis, landslides, tornadoes, flash floods, sea level rise and storm surges, wildfires, hurricanes, as well as man-made hazards, like chemical accidents and nuclear disasters. The ability to rapidly withdraw from areas affected by an impending disaster to safety is critical to the survival of at-risk populations. The response is often dependent on the nature of the hazard and an individual's risk perception and personalization [7,30,34,42,64].

Near-field tsunamis, flash floods, and some wildfires are more challenging because they often provide only minutes of forewarning [52,70]. In the case of the Cascadia Subduction Zone (CSZ), the threat of near-field tsunamis has been recognized only relatively recently, so many community emergency response plans have been based on far-field tsunami scenarios [14,25,27]. The CSZ fault runs from Northern California to British Columbia and is less than 160 km offshore in most places. Moreover, CSZ tsunamis are a particularly vexing problem because the earthquakes that cause them can severely damage the roads and bridges people need to evacuate [44,52]. Such damage, combined with uncertainties about the time lost to milling behavior [33,34] while seeking to confirm the threat, reunify the family, and formulate an evacuation plan (e.g., an evacuation mode, route, and destination [71]), adds complexity to the problem of tsunami evacuation. The problem of tsunami evacuation model complexity is compounded by its urgency; the likelihood of an M9.0 CSZ earthquake occurring in the

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next 50 years is 7–12% [13], which poses one of the greatest natural threats to the United States [59,60]. This event will trigger intense ground motion for several minutes across the region, followed by a tsunami in excess of 10 m that will inundate coastal communities within 20–40 min [14]. This event poses one of the largest natural hazards threatening the life safety and resilience of not only Oregon's coastal communities but also visitors [66] to the coast. We cannot prevent the CSZ earthquake and tsunami, but we can learn to live with them and be better prepared to survive them when the inevitable earthquake strikes. Evacuation is one of the most effective protective action strategies to prepare for the CSZ event [33]. Evacuations for the near-field tsunami is likely to be self-initiated, relying on an individual's perception of risk and knowledge of the correct course of actions. Unlike other common natural disasters such as hurricanes, the rarity of tsunami events in the U.S. makes the tsunami scenario difficult to imagine, particularly in relation to a person's sense of place and evacuation plans, including preparation time and route choice.

The idea of Vertical Evacuation has emerged in the past decade in the pacific northwest region of US as more attentions were diverted towards the Cascadia Subduction Zone fault and the foreseeable earthquake. The short warning time of the near-filed tsunamis and limited access to high ground in these communities call for an urgent need in effective evacuation strategies and shelter location placement. Horizontal evacuation shelters (HES) are currently the main focus of the evacuation strategies, and are defined as permanent evacuation shelters located at naturally high ground and out of the inundation area [75]. On the contrary to the HES, vertical evacuation is an alternative protective action for bringing people to safety by having them "go up" in multi-story buildings in flooding or tsunami hazards. Vertical evacuation shelters (VES) provide a mean to create areas of refuge for communities in which evacuation out of the inundation zone is not feasible [76]. Typical VES includes existing or engineered high ground, parking garages, community facilities, commercial buildings, school facilities, and designated buildings. VES can be identified as any shelter that could withstand the tsunami inundation forces, performing as temporary shelter within the inundation area. In general, it is challenging for all of the residents to evacuate to lateral-evacuation shelters because of the short forewarning times for near-field tsunamis. Thus, "sheltering-in-place" or "sheltering-near-place" using VES should be considered as an alternative protective action to lateral-evacuation from a tsunami inundation zone. In addition, growing coastal communities on the west coast of US is projected to increase by 3880 households and 6940 residents in tsunami hazard zone [61], which seeks a long-term and lasting solution to this problem, such as designing and building vertical evacuation shelters where it is most beneficial. However, the effectiveness of vertical evacuation shelters to save lives depends critically on whether people know where they are, believe they will be effective in protecting themselves and their families, and therefore choose to evacuate to them. Despite all these uncertainties however, Haynes et al. [17] have shown emotional and practical reasons, based on past events, that warrants and promotes sheltering in place during floods. Thus, compared to the traditional vehicle-based horizontal evacuation, we know little about mobilizing for vertical evacuation, and this is the core motivation of this work to investigate the vertical sheltering behavior and its impacts on evacuation efficiency. As where to build the vertical evacuation is critical for the success of the evacuation, driven by the goal of minimizing the life loss during the evacuation, we conducted the simulation to locate the reasoned sites for the VES, that yield the lowest mortality rate, under different scenarios. Our work will inform the hazards mitigation planning and policy making to reduce the tsunami risk that the coastal community exposed to.

### 1.1. Objective and motivation

The goal of this research is to study the vertical evacuation behavior, specifically how people decide to evacuate vertically or not and which shelter they choose to evacuate to, as well as the impact of shelter locations on their behavior and on the effectiveness of the evacuation in the context of the near-field tsunami hazard. We use an agent-based evacuation model which considers the milling time and variation in travel speeds to estimate the loss of life due to the tsunami hazard. We compare different placements of shelters, and we outline a more comprehensive plan to locate logical spots for the VES, based on a systematic decision-making framework. Placement of a VES necessitates a comprehensive understanding of the people's behavior towards this type of evacuation, the structural need for this type of shelter, and the resultant expected mortality rate corresponding to the location of the shelter. It is of note that we define *logical* location or *logical* area the spot at which placing the VES yields the lowest mortality rate. We refer to the *logical* placement of the VES quite often throughout this manuscript which is drawn from the simulation results.

### 1.2. Outline of paper

The rest of the paper is organized as follows: Section 2 presents a brief review of the existing studies on tsunami evacuation modeling, and more specifically vertical evacuation. In Section 3, the methodology and the concept and design of our experiments are explained. In addition, the vertical evacuation behavior and the maximum tsunami wave height are discussed in this section as the factors that needs to be taken into consideration in the design of vertical evacuation strategy. Next, Section 4 describes the study site. Section 5 presents the results of our framework for VES reasoned location selection from different perspectives. Finally, section 6 summarizes the major research findings.

## 2. Literature review

### 2.1. Gaps in tsunami evacuation modeling

With the exception of [62], the only comprehensive reviews of protective action in disasters have mostly focused on hurricane evacuation [1,5,19]. There have been a few studies of responses to tsunamis such as the 2009 South Pacific tsunami [34], the 2011 Tohoku earthquake and tsunami [40,65] and 2004 Sumatra tsunami [69], and earthquakes that could cause tsunamis [24,35,72]. There has been little research on evacuation logistics such as choice of evacuation routes, destinations, and accommodations [31,88,87] or evacuation time components [20,26,12,29,32,55,56], and even most of those studies were about hurricane evacuations. Moreover, compared to traditional vehicular evacuation [51], we know little about people's pedestrian evacuation or vertical evacuation/shelter in-place [63]. Traditional methods such as least cost distance in a Geographic Information System [79,80,85,75] lack the capacity to describe the individuals' decision-making behavior, and do not fully incorporate the potential interaction effects between evacuees and the complex physics of actual tsunami inundation.

### 2.2. Vertical evacuation behavior

During a tsunami event, vehicular-based evacuations could potentially result in gridlocks and traffic congestion due to the unplanned infrastructure disruptions to highway roads and bridges [3,44] or traffic signal failures [10] after the preceding earthquake. In the tsunami evacuation study in the Pacific Northwest, Wood et al. [82] found that 23% of residents and 15% of employees in tsunami-hazard zones are in the areas where modeled pedestrian evacuation times are greater than wave-arrival times. This suggests the use of vertical evacuation shelters or other long-term mitigation strategies to minimize the number of causality [82,58]. In addition, vertical evacuation can be an alternative mean to reduce vehicle use in evacuation for the cases where majority of the population are located in the inundation zone [74].

Tsunami vertical-evacuation shelters are proved to be an effective risk-reduction option for coastal communities where local tsunami threats are rising but there is no accessible high ground for evacuations [38,75], or where for a portion of a population the higher ground is not reachable in time before the tsunami arrival [4,10]. McCaughey et al. [41] extended the protection motivation theory to examine people's trust or distrust of tsunami vertical evacuation shelters/buildings using a survey data from the 2004 Indonesia Ocean event. Artificial berms, towers, buildings, and platforms have been built to provide vertical-evacuation refuges in several Japanese coastal communities [28,9,11] and are being planned in United States [6,8]. During the 2011 Tohoku *M*9.0 earthquake and tsunami, VES buildings provided safe refuge to thousands of people in coastal communities in Japan [10]. Raskin and Wang [54] suggested creating a berm to serve as the tsunami vertical refuge to improve tsunami evacuation within the zone. This shelter can serve as a public park and be a tsunami refuge in time of need. However, there arises the issue of limited land availability. Private buildings can also be used as tsunami shelters [54]. The tsunami evacuation modeling has also demonstrated the necessity of vertical evacuations in low-lying areas [40]. Such identification of risk cannot be achieved using static approaches such as GIS least-cost distance analysis, shelter location-allocation solutions, or direct comparison of the available space to the number of residents without considering the spatio-temporal factors [40]. Fraser et al. [10] conducted a field survey during October 2011 to investigate tsunami vertical evacuation in six towns and cities in Iwate and Miyagi. According to Fraser et al. [10], although there has been a number of VES buildings distributed around the studied cities, there was little planning for vertical evacuation in the locations where minimal tsunami inundation was expected based on previous events and numerical modelings. However, informal vertical evacuation to non-designated buildings was significant in mitigating the loss of life. VES buildings save thousands of lives [10], and these observations suggest that vertical evacuation can be successful where the best possible distribution of VES buildings is not implemented.

### 2.3. Tsunami vertical evacuation shelter location

VES location is a difficult policy question and is largely undocumented in the United States [2]. One of the major issues is the lack of vertical evacuation modeling framework to effectively identify areas where shelters may be needed [2]. The fact that multiple sites within a community and across a region may be warranted made vertical evacuation shelter location selection even more complicated [75]. Park et al. [49] proposed to use genetic algorithms for VES location selection in coastal Oregon (USA). However, several critical factors are not sufficiently considered such as accessibility, location constraints, and open travel across a landscape to high ground. Mas et al. [38] suggested that if spatial distribution of the available VES capacity is not well displayed, over-demand and under-demand would occur. Mas et al. [38] conducted a numerical simulation integrated with a multi-agent model of human evacuation to approximate a possible earthquake in Peru. Employing the stochastic simulation of the initial spatial distribution of residents and evacuation milling time, Mas et al. [38] evaluated the capacity-demand relation at each official tsunami evacuation building in La Punta district of Callao in Peru. The Capacity-Demand Index (CDI) is introduced to map and identify the areas for mitigation. According to government guideline [23], vertical shelters are encouraged to be built in locations that can provide adequate refuge capacity and in areas where it is not possible to evacuate to high ground. Optimal distribution of buildings can be derived from local population estimates, evacuation routes and walking speeds [16,21,85]. However, the number and distribution of shelters may be constrained by the availability of suitable buildings or land.

Further, there are very few models that suggest a framework to logically select VES location due to the large area in tsunami hazard zones and varying priorities, values, and economic capital to decide which at-risk populations to protect first [75]. Although Geospatial, multi-criteria decision analysis (MCDA) can be a useful tool [22,36,37], and has been implemented in regard to selecting the location of earthquake evacuation shelter [89] and general disaster service area [18], no study is found to explore the decision making for tsunami VES planning under varying evacuation scenario characteristics. Wood et al. [75] introduced MCDA concepts and potential use of geospatial modeling for selecting logical VES locations. A multi-attribute, group-decision process under conditions of relative certainty is proposed in their study. There are four steps included in the MCDA process: (1) defining the problem through geospatial evacuation modeling, (2) identifying the stakeholders, alternatives, and criteria through community workshops, (3) statistically evaluating the alternatives and the weights of criteria, and (4) decision and sensitivity analysis. A case study in Washington is further conducted to demonstrate the approach [75].

With the goal of reducing evacuation time, and consequently, minimizing the probability of the causality, Park et al. [49] developed a method that applies genetic optimization to determine tsunami shelter locations. The results suggest that the logical location of VES relies on the number of the shelters considered. Priest et al. [52] evaluated the pedestrian evacuation of Seaside, Oregon for a local tsunami generated by a CSZ earthquake. The evacuation path is calculated by the least-cost distance (LCD) to safety using geospatial, anisotropic path distance algorithms. Tsunami vertical evacuation refuges or additional pedestrian bridges are found to be the effective ways to reduce the loss of life. Rojahn et al. [57] suggested that travel time to safety is the major factor in selection of the location of the vertical evacuation shelters. The study further proposed that vertical evacuation shelters should be located away from potential hazards that could result in additional damage to the shelter and reduced safety for the occupants.

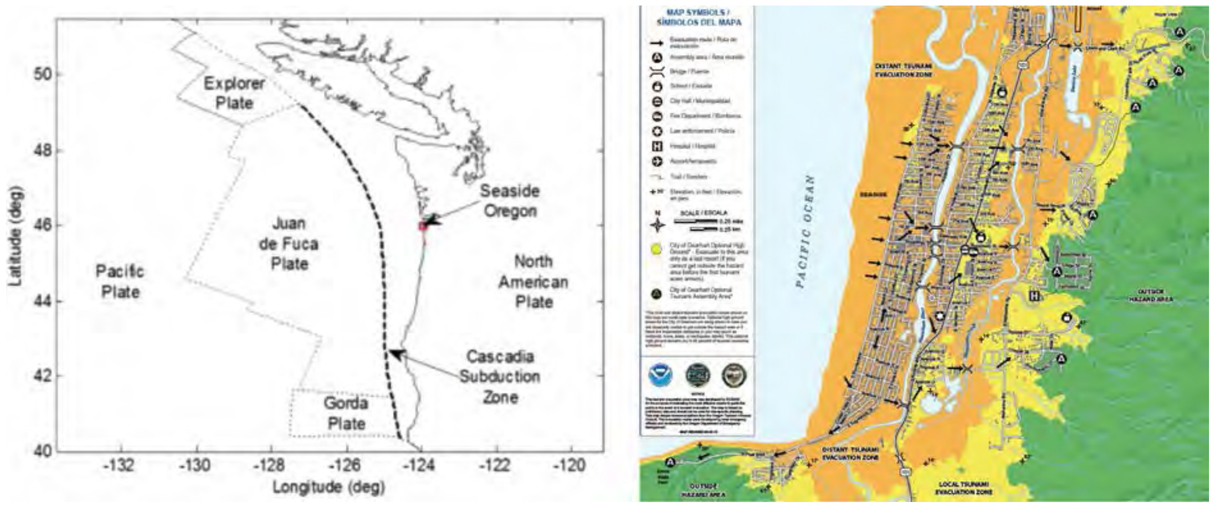
## 3. Methodology: agent-based tsunami evacuation model (ABTEM)

### 3.1. Study site

The city of Seaside, Oregon was chosen as a case study site because of its higher susceptibility to tsunami hazard from a M9.0 CSZ earthquake as the community has a large number of senior elderly and visitor population [81,79,78,77,15,80,86,84,75,83,71,43,52,44]. This is due, in part, to the geographic location, close proximity to the Cascadia Subduction Zone (Fig. 1(a)), and its rather flat landscape and topography [79]. The Necanicum River that flows from south to north, bisecting the city, is spanned by six bridges which creates additional complexity for the horizontal evacuation considering the potential bridge failures in the preceding earthquake [44,43]. The current tsunami evacuation plan for the area requires horizontal evacuation on foot (Fig. 1(b)), and the option of vertical evacuation has only been discussed in recent years as a possible alternative. 83% of its population, 89% of its employees and almost 100% of its critical facilities are located inside the tsunami inundation zone [46]. In the meantime, all primary horizontal evacuation shelters of the city are located more than 1.5 mile away from the shoreline. Considering the milling time, potential damages to the transportation system (bridges, highway segments), and variation in travel speeds (i.e., walking, driving, or public transit), the current horizontal evacuation strategy of Seaside, OR may not be sufficient to address the evacuation needs associated with near-field tsunami hazard.

### 3.2. Tsunami inundation

One critical issue that needs to be taken into consideration in tsunami evacuation is the expected inundation water depth that a shelter is exposed to. Fig. 2 shows the maximum wave height that each location in the city faces throughout a one-hour-long inundation period. As the return interval increases (from left to right), the intensity of the earthquake initiating the tsunami, and the resulting inundation water




(a) Relative Location of Seaside, OR with respect to the Cascadia Subduction Zone (Wang et al., 2016)

(b) Seaside's Evacuation Map by DOGAMI (of Geology and Industries, 2013)

**Fig. 1.** Seaside, OR [45,71].

depths both increase [48,47].

It can be seen that the maximum wave height increases from 8.4 to 15.4 m with increase in return interval from 500 to 2500 years. In addition, in case of a 500-year event, the city will be partially inundated. The inundation zone enlarges as the intensity of the tsunami increases. Moreover, in a high intensity event, the entire city is inundated fairly uniformly, as opposed to low-intensity tsunami inundation that the east side of the inundation zone experiences significantly lower water depths. In any case, generally, the closer a shelter gets to the east side of the city, the lower the risk of structural damage or failure is.

### 3.3. Development of ABTEM for vertical evacuation

The methodology for this VES location modeling is through an agent-based tsunami evacuation model (ABTEM). Agent-based models, especially in modeling of the human behavior, have proven to be highly effective in the past decades. The evacuation modeling and simulation environment was coded in NetLogo, one of the primary agent-based modeling platforms which is widely used in a variety of subjects [73]. Prior investigation and use of the agent-based evacuation model in the context of transportation network vulnerability analysis [43,44] and multimodal behavior of evacuation [71] has shown its potential in evacuation efficiency analysis. The model in this study has been customized to analyze the impact of VES on evacuation mortality rate. Fig. 3 shows a screen capture of the model interface.

On the left panel, the user is able to adjust the model inputs. The inputs of the model include, to name a few, walking speed distribution of the evacuees, split of different evacuation options (i.e., horizontal or vertical evacuation), the inundation level, vulnerability of the community to the inundation, and milling time or preparation time distribution. The middle panel visualizes the time-dependent dynamics of the evacuees along with the inundation motion. As shown in the Fig. 3 blue and orange dots represent the pedestrians with different evacuation decisions. Orange dots show the evacuees who do not consider vertical evacuation as an option and walk to a shelter outside the inundation zone, and the blue dots represent the evacuees who are open to both types of shelter. Yellow circles show the current tsunami evacuation shelters of Seaside, OR, as proposed by the Oregon Department of Geology and Mineral Industries [53]. In addition to the horizontal evacuation shelter, the vertical evacuation shelter(s) can be placed through the graphical user interface (GUI), and thus, different placements of the vertical evacuation shelters can be analyzed. In Fig. 3 the purple circle in the middle of the network shows the location of the simulated vertical shelter. The blue and black shade shows the inundation and the water depth at each point in space and time. The darker the shade, the higher the wave height, and accordingly, based on the wave height and the danger of the agents exposed to the tsunami force (once the wave reaches the evacuation crowd), evacuees will be considered as casualty and marked with red color. The outputs of the model include the number of evacuated, number of casualties, and number of people evacuated to the vertical evacuation (i.e., needed capacity), monitored on the right panel.


(a) 500 Years (b) 1000 Years (c) 2500 Years

**Fig. 2.** Tsunami maximum wave height (m) for events with different return intervals. The darker the shade of blue is, the higher the maximum wave height is for a specific location in the study site. In addition, the final inundation zone can be draw from these plots.

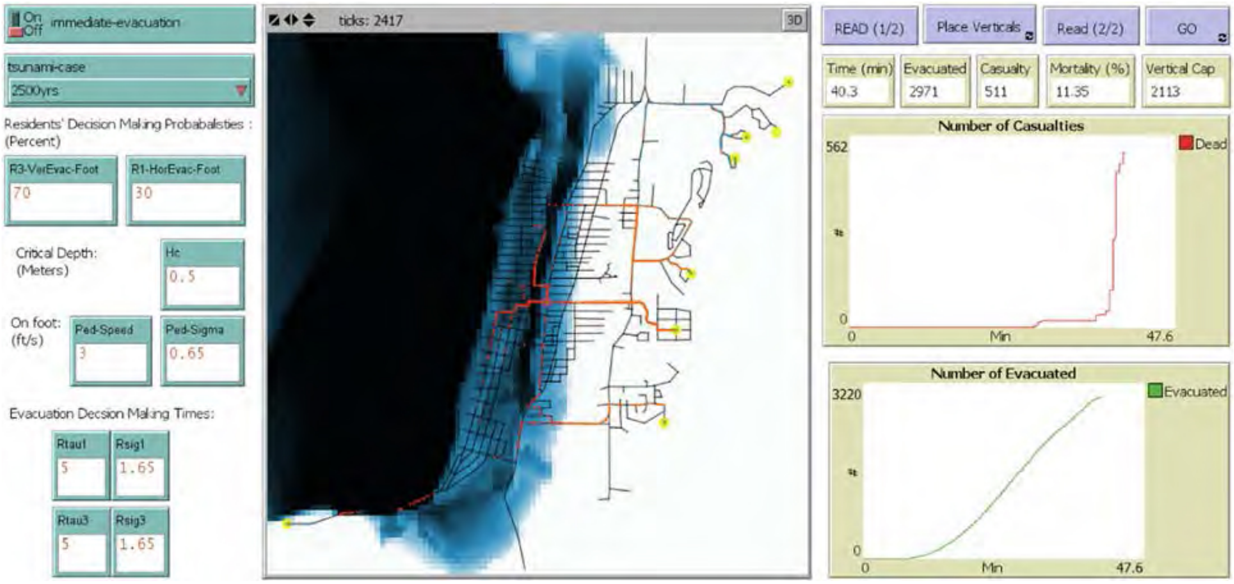



**Fig. 3.** Agent-based Tsunami Evacuation Model in Netlogo. The left panel shows the inputs of the model. The results of the simulation are presented in the right panel. The middle panel shows the simulation dynamics where moving agents are presented in orange, the red dots are the casualties.

The agent-based model consists of different components, namely Transportation Network, Population Distribution, Shelter Locations, Tsunami Inundation, and Casualty Model. For the details of each component, please refer to Mostafizi [43], Mostafizi et al. [44]. In this study, we have used 8 current shelters outside the inundation zone which were proposed by [53]. In addition, the simulated VES can be placed through the GUI of the model. For the purpose of this study, the major decisions that agents are facing are the evacuation shelter type and the departure time or milling time. Evacuees can either evacuate to a horizontal shelter outside the hazard zone, or they can evacuate vertically inside the inundation zone. This choice is enforced by the percentage of the evacuees who are *open to* vertical evacuation. Obviously, for an evacuee who considers vertical evacuation, if there is a closer shelter outside the hazard zone, they are not going to move towards the hazard to evacuate vertically. Therefore, there will be a difference between the percentage of the people who consider vertical evacuation as a possible method, and the percentage of the evacuees who actually evacuate vertically. Our assessments have showed that no more than 80% of the population evacuate vertically, even if the entire community consider vertical evacuation as an option. The objective of this study is to assess the impact of the proportion of the evacuees who consider vertical evacuation on the logical placement and the capacity needed for a shelter. Thus simulations have been conducted with this percentage being either 25% or 100%.

Moreover, the milling time is modeled using Rayleigh Distribution [39], with varying Minimum Milling Time ($\tau$) and scale parameter ($\sigma$) of 1.65. With this setting, it is ensured that 99% of the evacuees start their evacuation within 5 min after the minimum milling time. In this study, we assess the impact of milling time on the logical location of the VES, by comparing the cases with 0 and 10 min minimum milling times. This study also aims to assess the effect of the average walking speed of the community on the logical placement of the vertical shelter. The standard deviation of the walking speed's normal distribution is set to 0.65 ft/s (0.20 m/s), and the mean is varied from 3 to 5 ft/s (0.91–1.52 m/s) [50]. Each agent's speed is constant throughout a simulation run and we have neglected the effect of tiredness and topography of the environment.

### 3.4. Overview of simulation

The overview of the simulation is presented in Fig. 4 as time-series snapshots of the model. At $t = 0$, right after the earthquake, the evacuation is called. Brown dots represent the initial placement of evacuees and distribution of the population. After $t = 0$, depending on each individual milling time, people start to evacuate on the shortest path to the shelter of interest, and at $t = 15$ min we observe that most of the evacuees are en-route, except the ones that are yet to move. Depending on the decision regarding the evacuation shelter destination, agents either turn orange, meaning that they do not consider vertical evacuation, or they turn blue, indicating that they do consider vertical evacuation if the VES is closer than the shelters outside the inundation zone. It has been assumed that the agents are autonomous, and their choices are not affected by each other, and therefore, their behaviors will not vary with time. At $t = 35$ min first wave hits the city, and interestingly after 5 min ($t = 40$ min), half of the city is inundated, and in about 10 min ($t = 45$ min), the entire city is inundated. Depending on the critical depth defined earlier, a portion of the evacuees are considered as casualties, marked with red color, and stopped moving. On the other hand, people who have reached the shelters are safe, marked with green color, and considered as evacuated. At $t = 55$ min, the second wave inundates the city. The simulation lasts for an hour and at the end of the simulation, the number of casualties and number of evacuees for each decision category as well as the number of people who are evacuated in the vertical shelter are recorded for further assessment of the evacuation efficiency, measured by the mortality rate of the scenario.

### 3.5. Vertical evacuation shelters as alternative protection actions

Fig. 5(a) reflects the proportion of the people who actually evacuate vertically to the people who consider vertical evacuation as an alternative. It shows that this percentage varies with the change in the location of vertical shelter. Intuitively, a person may not evacuate vertically if there exists a shelter that is closer and outside the inundation zone. Based on the placement of a shelter, the percentage of people who evacuate to it can be as low as 24% or as high as 79%. These results reflect the location of the VES in a way that it makes logical sense for a certain portion of the people to evacuate to it, considering the location of current shelters and the initial population distribution.

Comparing the population distribution in Fig. 6(b) and 5(a), it suggests that the utilization of VES is at its maximum when the shelter is mapped to the centroid of population distribution, and not

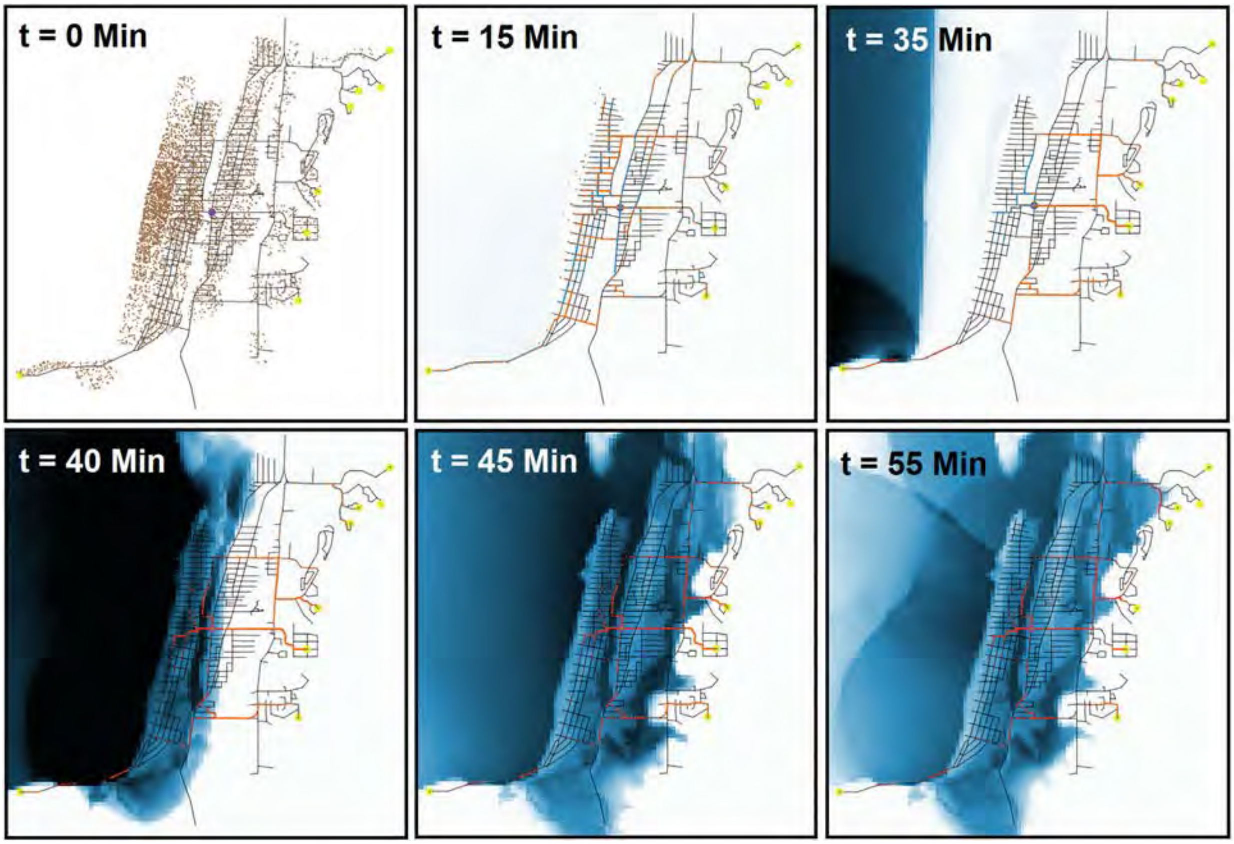



**Fig. 4.** Simulation overview. Brown dots represent the initial population distribution at $t = 0$. The agents start moving after their milling time, heading to an evacuation shelter. At $t = 35$ the first wave inundates the city, causing casualties. The second wave hits the city at $t = 55$.

necessarily the densely populated areas. Fig. 5(b) shows the non-linear relationship between the percentage of vertically evacuated people and the distance of the shelter from the population centroid. The farther the location gets from the population centroid, the lower the percentage of the people who evacuate to the vertical shelter. This non-linear behavior shows a lower margin of error for the placement of the VES, as long as it is fairly close to the center of the population. For distances beyond 0.5 mile, the percentage of population who evacuate vertically drops significantly. It is also worthy mentioning that, Generally, vertical evacuation is associated with the inherent risk of structural failure [47], and maximizing or minimizing the use of VES depends on the local evacuation plans. Moreover, this type of measurement can inform the VES capacity design.

In addition, vertical evacuation behavior as presented in this section, although an important evacuation characteristics that needs to be studied, is not justified to be used as the primary criterion for VES location selection. The resultant mortality rate, explained later in Section 5 and Figs. 7 and 8 must be the only selection criterion.

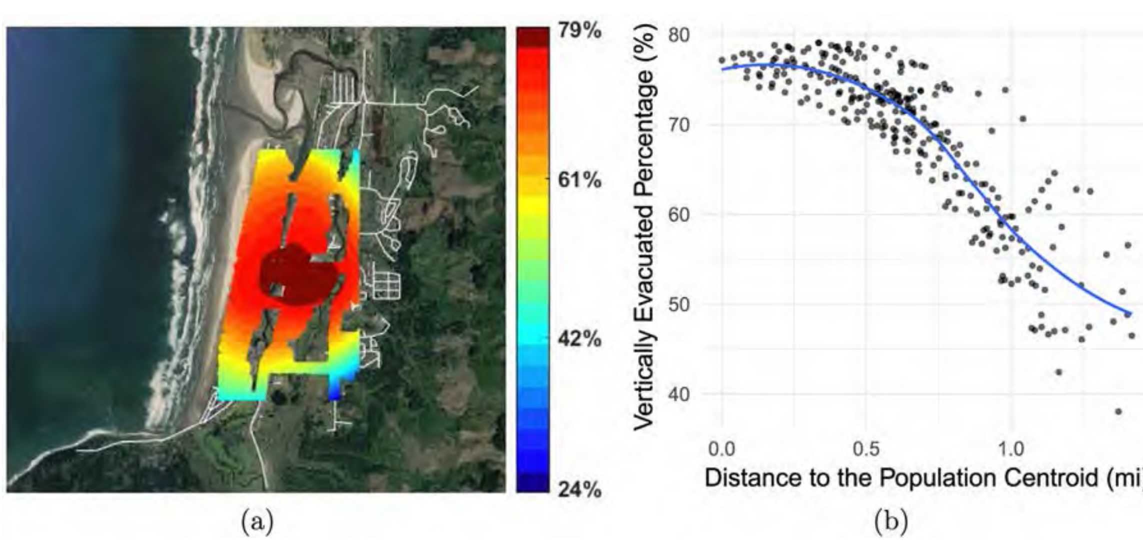
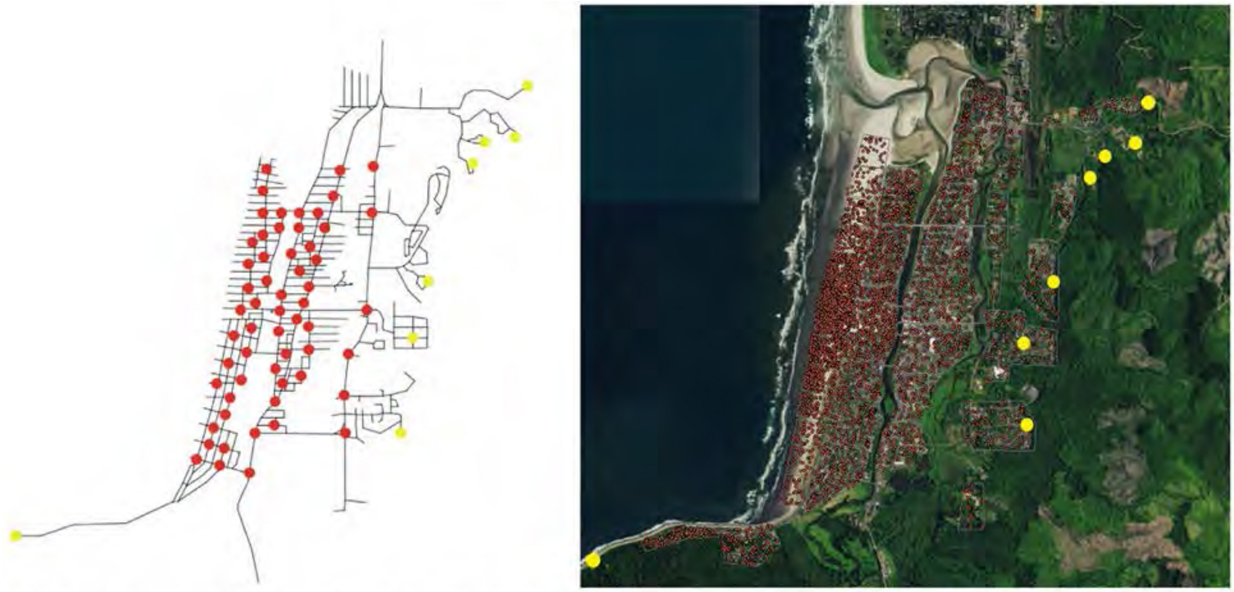



**Fig. 5.** Proportion of vertically evacuated (With respect to people who considered vertical evacuation).



(a) The Proposed Candidate VES Locations (b) Population Distribution (Mostafizi et al., 2017)

**Fig. 6.** Seaside population distribution and vertical shelter candidates.

## 4. Experiment design

To identify the logical location for the VES, the authors discretized the entire city into cells and selected 60 potential positions which are the centroids of the cells and marked as red dots in Fig. 6(a). The logical placement of VES is likely to be a function of numerous factors in combination. For instance, population distribution, walking speed, and milling time all could greatly impact the logical location of vertical evacuation shelters, that leads to the lowest mortality rate. However, in this study, the idea is to find the logical placement of a single evacuation shelter specifically under different evacuation settings such as minimum milling time, average walking speed, and opinion of the public towards the vertical evacuation shelters which is measured by the proportion of the people who consider vertical evacuation. To accomplish this objective, the simulations were conducted by iterating through the 60 possible VES locations, as well as varying the average walking speed from 3, 4, and 5 ft/s (0.91, 1.22, 1.52 m/s), changing the minimum milling time from 0, 5, to 10 min, and varying the percentage of people who consider vertical evacuation from 25% to 100%. These 60 data points are used to estimate the mortality rate for any other arbitrary points, using Biharmonic spline interpolation.

For automation purposes, authors have used R combined with RNetlogo package that bridges the gap between NetLogo and R. RNetLogo is an open-source package that enables the modeler to run, control, execute commands, push and get data from or to Netlogo in R environment, and store and analyze the simulated data using powerful statistical tools in R [68,67]. After each simulation the following data were calculated:

- Percentage of the agents who actually evacuated vertically
- Number of people evacuated safely in the vertical shelter
- Total mortality rate

It is worth noting that there is a primary difference between the number of evacuees who considered vertical evacuation and the number of people who actually evacuated vertically. As mentioned earlier, for the people who consider vertical evacuation as an alternative protective action, in case there is another shelter closer and outside the inundation zone, the agent does not move towards the hazard and to the vertical shelter. Therefore, the number of people who evacuate vertically is definitely less than the people who consider vertical evacuation.

The results of this study will inform decision-makers, city planners, and officials on the logical location to place a vertical evacuation shelter and its needed capacity. In addition, this study quantifies the impacts of community physical (walking speed) and psychological (milling time and perception of vertical evacuation) characteristics on the placement and efficiency of the vertical evacuation shelter.

## 5. Modeling results

In order to outline a comprehensive plan to select a logical location for the VES, the resultant mortality rate associated with the location of VES were analyzed. It has to be noted that maximum wave height which is an indicator of the tsunami force on the vertical structure, and the vertical evacuation behavior which shows the level of response of the evacuees to the VES should be viewed more as a constraint, rather than selection criterion.

### *5.1. Mortality rate*

In this work, we study the mortality rate of the evacuation scenario with changes in the location of VES. Total mortality rate is normally used to reason for the location of the shelter. However, additionally, this study intends to analyze the effect of minimum milling time ($T_{\text{Milling}}^{\text{Min}}$), average walking speed ($\bar{V}_{\text{Walk}}$), and the percentage of people who consider vertical evacuation ($\text{Evac}_{\text{Ver}}$) as an alternative protective action, on the logical placement of the VES that leads to the lowest total mortality rate for a particular scenario.

The results are presented in Fig. 7 and 8 show total mortality rate ($\text{MR}_{\text{Total}}$) of the scenario, for various milling times and walking speeds. The color at each point is associated with the resultant mortality rate of the evacuation scenario if the VES is located at that specific point. Fig. 7 reflects the mortality rates for the case that 100% of the community consider vertical evacuation option, while Fig. 8 represents the case where only 25% of the evacuees consider vertical evacuation, if they have any shelter closer to them, compared to typical shelters outside the inundation zone. For comparison purposes, both of these scenarios have been implemented with average walking speed ($\bar{V}_{\text{Walk}}$) of 3 and $5 ft/s$ (0.91 and 1.52 m/s), as well as minimum milling time ($T_{\text{Milling}}^{\text{Min}}$) of 0 and 10 min.

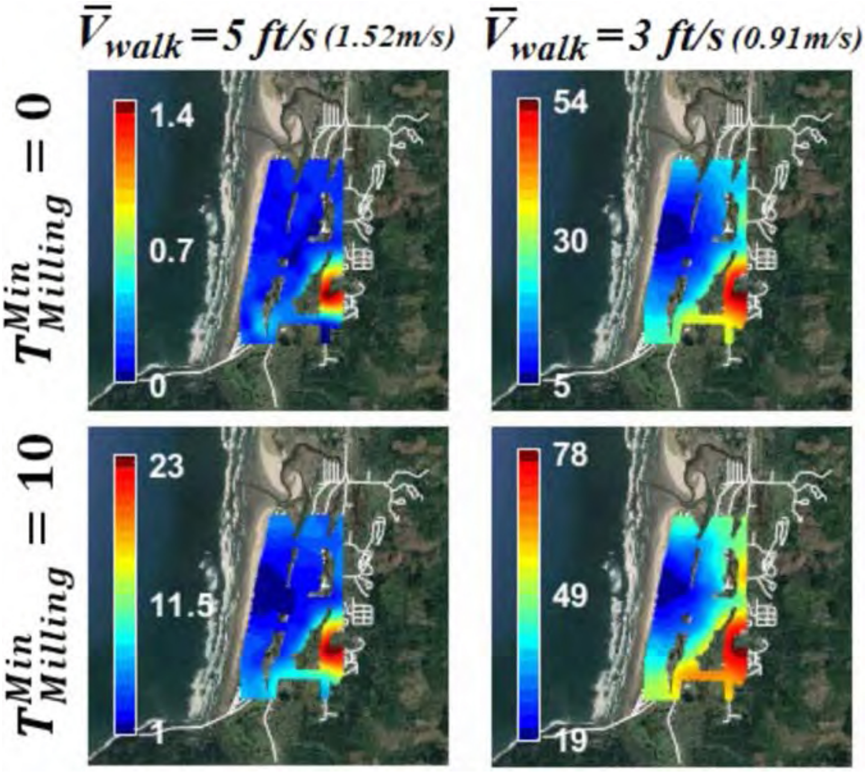



**Fig. 7.** Total mortality rate for different $\bar{V}_{\rm walk}$ and $T^{\rm Min}_{\rm Milling}$. $\text{Evac}_{\text{Ver}}$ = 100%.

*5.1.1. Total mortality rate analysis*

From Fig. 7 and the total mortality rate ($MR_{Total}$) for $\bar{V}_{\rm walk} = 3ft/s$ (0.91 m/s), the dark blue color represents the area at which placement of the vertical shelter leads to the lowest mortality rate. Please note that this area is generally adjacent to the shoreline and locates in the middle of it as the population is distributed normally along the beach and around the center. It can be seen that the mortality rate increases non-linearly as the vertical shelter moves away from the logical location that yields the lowest mortality rate. Results show that, even under the assumption of immediate evacuation ($T^{\rm Min}_{\rm Milling} = 0$) the mortality rate

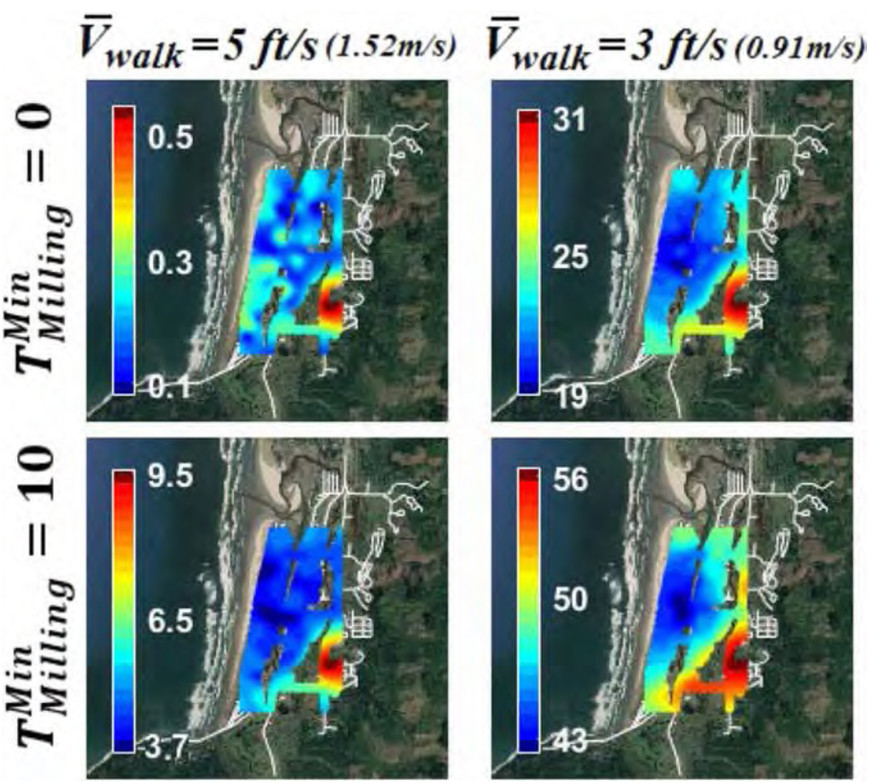



**Fig. 8.** Total mortality rate for different $\bar{V}_{walk}$ and $T^{Min}_{Milling}$. $Evac_{Ver}$ = 25%.

increases from 5% to 54% when the shelter is placed around south-east of the city, which shows the importance of VES location in terms of total mortality rate. In addition, in the case where $Evac_{Ver}$ = 100%, all the people in this scenario consider vertical evacuation. This can inform decision makers regarding the communication of the best policies and actions to the communities at risk.

*5.1.2. Milling time and walking speed*

Comparing $T_{Milling}^{Min}$ of 0 and 10 min in Fig. 7 clarifies the impact of minimum milling time on location of the shelter. With increase in minimum milling time, evacuation gets more critical, and therefore, the logical area for the VES gets narrower towards its centroid. For instance, logical area shifts towards the shoreline. In addition, the range of mortality rate as well as its minimum increase dramatically. On the other hand, the exact opposite phenomenon happens as $\bar{V}_{Walk}$ increases as the criticality of the event decreases. With the increase in average walking speed which in turn increases the evacuees' mobility, the mortality rate drops significantly, and the logical area covers a larger portion of the city, compared to their equivalent scenario with lower average walking speed.

*5.1.3. Evacuation decision*

Fig. 8 shows the total mortality rate with respect to changes in the location of the shelter, and as a function of minimum milling time and walking speed, with only 25% of the people considering vertical evacuation. Comparing Figs. 7 and 8, it can be seen that in general, with the same setting but less people considering vertical evacuation, the lowest total mortality rate (i.e., the case that the shelter is placed in the logical area) increases significantly. In other words, the more the community considers vertical evacuation as an alternative, the lower the evacuation mortality rate will be. The same correlations with milling time and walking speed, as interpreted for the case where $Evac_{Ver}$ = 100%, apply to this case as well. The logical area shrinks as the evacuation becomes more critical (e.g., increase in $T_{Milling}^{Min}$ or decrease in $\bar{V}_{Walk}$). At the same time, and surprisingly, it can be seen that the upper bound of mortality when $Evac_{Ver}$ = 100% is higher than that of when $Evac_{Ver}$ = 25%. This means that if vertical shelter is placed in an irrational spot, and the evacuees are guided to consider vertical evacuation, this will result in extremely high mortality rates and catastrophic evacuation scenarios. Therefore, the logical placement of the shelter is extremely critical. The results provided in this work will benefit decision makers and officials to logically locate the VES, and devise policies accordingly, with consideration of available resources and the community socio-physical attributes and openness towards vertical tsunami evacuation.

*5.1.4. Shelter's distance to ocean, population centroid, and outside of the inundation zone*

To deepen the analysis on the logical placement of a VES, the impact of the distance of the shelter to the population centroid, to the ocean, and to the shelters outside of the inundation zone on the total mortality rate, and thus, the effectiveness of a VES has been studied. Fig. 9 shows these nonlinear relationships for an evacuation scenario, with 10, 5, and 0 min of minimum milling time with an average walking speed of 3, 4, and 5 $ft/s$ (0.91, 1.22, and 1.52 m/s), where the entire population consider vertical evacuation as an alternative protective action.

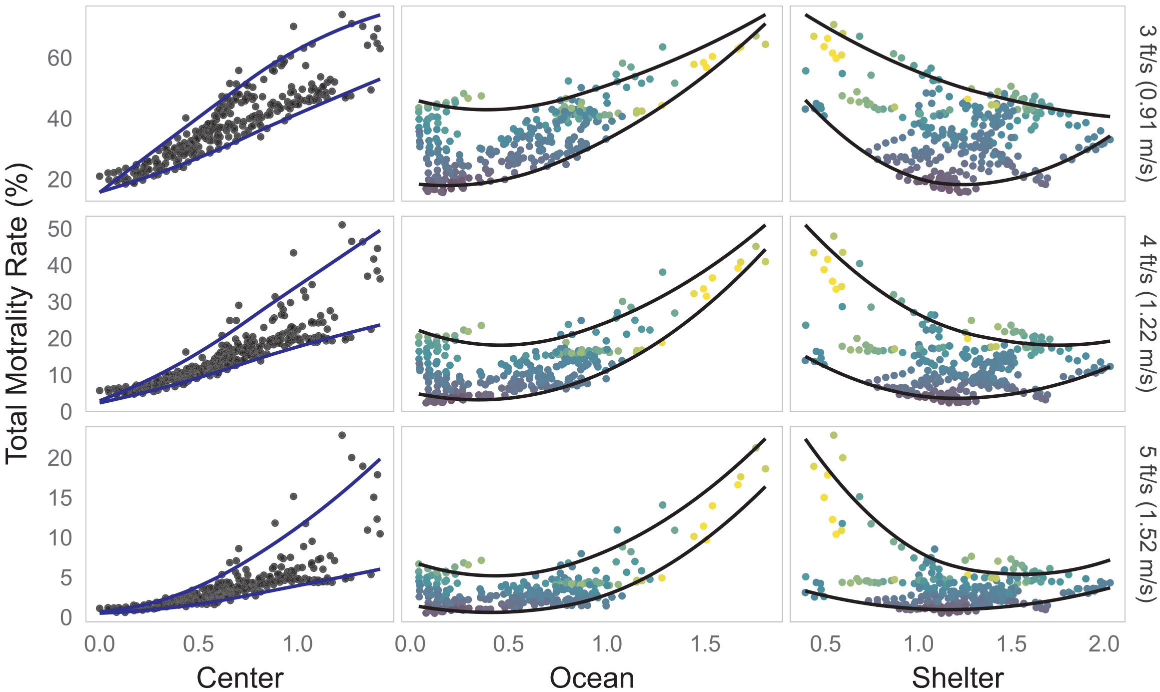
The left panel in each plot in Fig. 9 represents the nonlinear relationship between the mortality rate and the distance to the population centroid. As the shelter location gets further away from the center of the initial evacuee population, the mortality rate increases. Blue curves in Fig. 9 reflect the 98% and 2% percentiles of the mortality rate. The correlation between these two variables is stronger and steeper if the average walking speed is low. Similar patterns are also observed for higher milling time scenarios in Fig. 9(b) and (a). In addition, the range of expected mortality rates increases as VES gets farther from the population centroid. This suggests that placing a VES far from the center necessitates further analysis as the confidence in mortality rate is low and the variance is high. Moreover, it can be seen that the positive pattern diverges for the shelters that are more than 0.5 mile further away from the population centroid, indicating that distance from this logical location can result in negative impacts with different magnitudes, depending on the direction (e.g. towards the shore or the outside of the hazard zone) of the distance from the logical location. This divergence is less obvious when the evacuation pressure is low (e.g., low milling time or fast walking speed).

There are also correlations between mortality rate and the distance of the VES to the ocean and to the shelters outside of the inundation zone. The middle panel in Fig. 9 shows that the closer the shelter to the ocean, the lower the total mortality rate. However, VES being close to the ocean does not guarantee a successful evacuation as the variation of mortality rate is large when VES is closer to the ocean. This variation is higher when the average walking speed is 3 $ft/s$ (0.91 m/s) or minimum milling time is 10 min. Moreover, the minimum mortality rate is highly associated with shelters that are close to the ocean as well as the population centroid (the darker colors). For evacuation scenarios with high average walking speeds (or similarly low milling times), the effect of distance to the ocean is minimal for distances lower than 1 mile, interpreted from the beginning and relatively flat part of the graph for walking speed of 5 $ft/s$ (1.52 m/s) or minimum milling time of 0. After this threshold, the impact of distance to the ocean on the mortality rate is significant. This neutral correlation is significantly less for a low average walking speed of 3 $ft/s$ (0.91 m/s) or a high minimum milling time of 10 min. However, it gives a higher margin for error as long as the VES is located close to the population center.

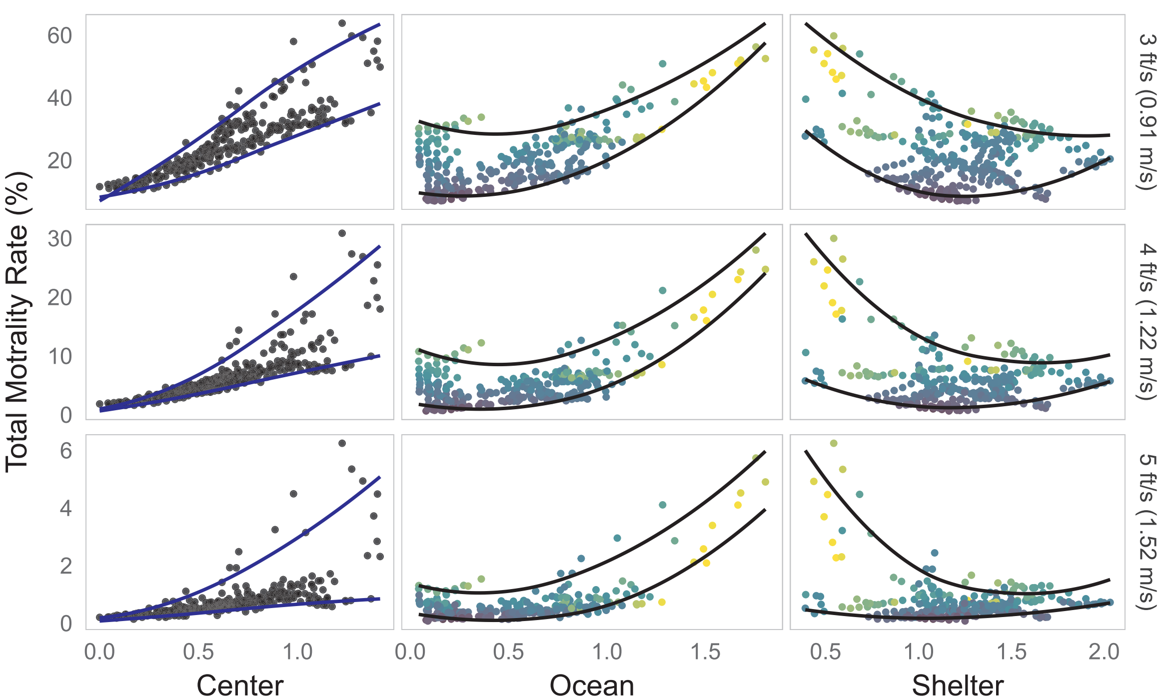
The opposite and generally negative trend is visible when analyzing the mortality rate of the evacuation with respect to the distance of the VES to the horizontal shelters outside of the inundation zone. However, the results show that the logical location is placed roughly a mile from outside the inundation zone, and again as expected, close to the center of the population. Beyond this threshold, the mortality rate starts to increase.

## 6. Conclusion

In this paper, we addressed a vertical tsunami evacuation shelter (VES) location selection problem through an agent-based tsunami evacuation model (ABTEM). The city of Seaside, Oregon is selected as the study site since the community is highly prone to tsunami hazard from a M9.0 CSZ earthquake due to the large number of senior elderly and visitor population. This risk to tsunami is also compounded by the flat topography from the ocean to the city designated tsunami shelters. The resultant mortality rate in case of various vertical evacuation shelter locations was selected as the primary VES location selection criterion. Three different factors are considered and evaluated in this case including minimum milling time, average walking speed, and the percentage of people who consider vertical evacuation. It is observed that in most cases, there is a logical area that leads to the lowest mortality rate. Moreover, the mortality rate increases non-linearly as the vertical shelter moves away from the logical location. Further, by increasing the average walking speed or decreasing the minimum milling time, we found that the increase of evacuees' mobility will reduce the mortality rate significantly, and accordingly, the logical shelter location area covers a larger portion of the city. In addition, when the proportion of people who consider vertical evacuation decreases with other settings remaining unchanged, the lowest mortality rate increases significantly. In other words, the more people consider vertical evacuation as an option, the lower the evacuation mortality rate will be. This study also uncovers the impacts of the distance of the vertical shelter to the key topographic features (e.g., ocean, population centroid, and the horizontal shelters outside of the inundation zone) on the evacuation efficiency and the total mortality rate. The outcomes of this research clarify a systematic decision-making problem that encircles the




(a) $T^{Min}_{Milling} = 10$ mins

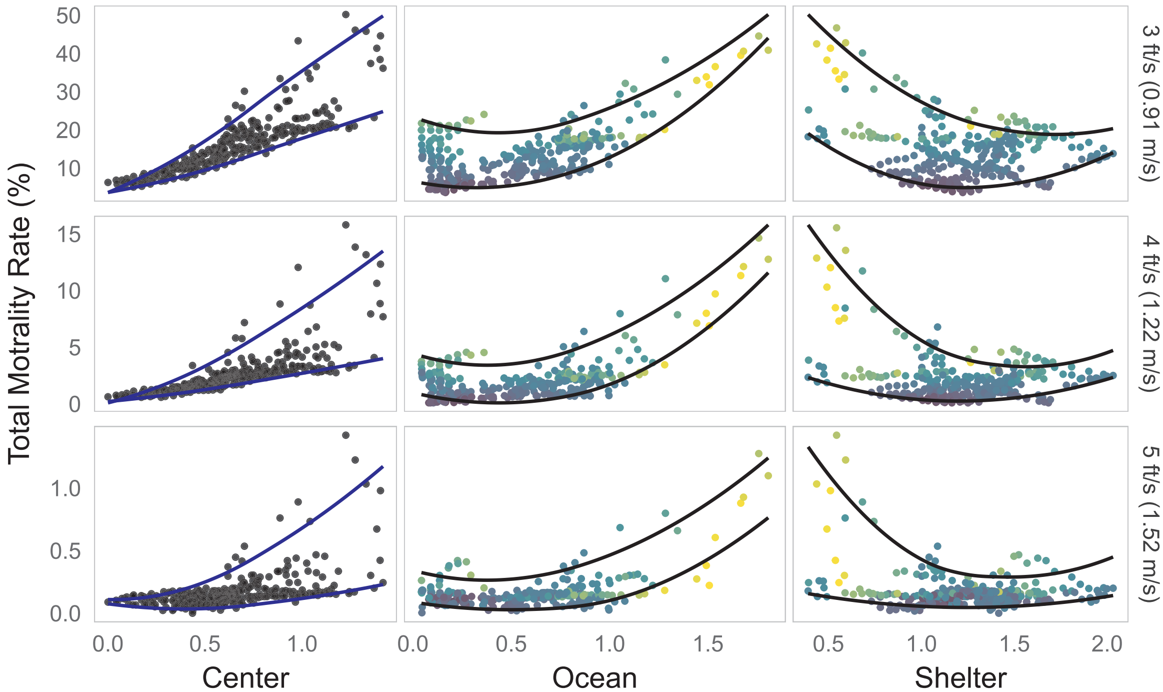



(b) $T^{Min}_{Milling} = 5$ mins

**Fig. 9(a).** Impact of the distance of the shelter to the population centroid, ocean, and the shelters outside of the inundation zone on the total mortality for evacuation cases with 3,4, and 5 *ft/s* (0.91, 1.22, and 1.52 m/s) walking speed and 0, 5, and 10 min of milling time. Curves represent 2 and 98 percentiles. The color on the middle and right panel correlates with the distance of the shelter to the population centroid. The darker the color, the closer to the center of the population.

placement of the vertical evacuation shelters and the vertical evacuation behavior, which both play a significant role in life safety. This study also suggests that the proportion of the people who evacuate vertically is highly correlated with the location of VES. This percentage can be as high as 80% depending on the location of VES, and is non-linearly and negatively correlated with the distance of the VES to the population centroid.

The findings unveiled in this study will help inform the decision-making process to identify the logical locations to place the vertical evacuation shelters to improve life safety and community resilience to the combined earthquake and tsunami hazard. More importantly, the results show that if the shelter is placed at the wrong spot, and the population is advised to evacuate vertically if possible, the evacuation will be tragic. To avoid such consequences, although there are




(c) $T^{Min}_{Milling} = 0$ mins

**Fig. 9(b).** Continued.

generalized findings in this work, the results show that the placement of vertical evacuation shelters are highly case specific. In other words, the topography of the site, expected population distribution, the tsunami inundation, the location of current shelters, the physical and psychological capabilities of the at-risk community, and the attitude of the community towards vertical evacuating can drastically impact the evacuation efficiency. Therefore, pinpointing the logical location for the shelter necessitates such case-specific and high-fidelity modeling and simulations.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