Natural Hazards
https://doi.org/10.1007/s11069-022-05208-y

ORIGINAL PAPER

Evacuation behaviors in tsunami drills

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Received: 23 May 2021 / Accepted: 29 December 2021

Abstract

This paper presents the use of tsunami evacuation drills within a coastal community in the Cascadia Subduction Zone (CSZ) to better understand evacuation behaviors and thus to improve tsunami evacuation preparedness and resilience. Evacuees' spatial trajectory data were collected by Global Navigation Satellite System (GNSS) embedded in mobile devices. Based on the empirical trajectory data, probability functions were employed to model people's walking speed during the evacuation drills. An Evacuation Hiking Function (EHF) was established to depict the speed–slope relationship and to inform evacuation modeling and planning. The regression analysis showed that evacuees' speed was significantly negatively associated with slope, time spent during evacuation, rough terrain surface, walking at night, and distance to destination. We also demonstrated the impacts of milling time on mortality rate based on participants' empirical evacuation behaviors and a state-of-the-art CSZ tsunami inundation model. Post-drill surveys revealed the importance of the drill as an educational and assessment tool. The results of this study can be used for public education, evacuation plan assessment, and evacuation simulation models. The drill procedures, designs, and the use of technology in data collection provide evidence-driven solutions to tsunami preparedness and inspire the use of drills in other types of natural disasters such as wildfires, hurricanes, volcanoes, and flooding.

Keywords Tsunami evacuation · Evacuation drill · Walking speed · Preparedness and resilience · Cascadia Subduction Zone

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Published online: 02 February 2022

1 Introduction

Recent and devastating tsunami events (Mori et al. 2011; Lindell et al. 2015; Sassa and Takagawa 2019) have caused life loss and financial burdens to individuals and communities. Higher evacuation speed and efficiency mean higher survival rate of at-risk populations in low-lying coastal communities, especially for near-field tsunamis with small evacuation time windows (Wang et al. 2016; Raskin and Wang 2017; Williamson and Newman 2019). To reduce the time of evacuations and maximize the survival rate during real events, evacuation drills have been used as an effective simulation for public education and city emergency planning purposes.

Evacuation drills are a method to practice evacuation from risk areas with planned scenarios that mimic realistic hazardous situations. Drills can provide participants "impactful field-based learning experience" (Zavar and Nelan 2020) to be better prepared for future disaster responses. Tsunami evacuation drills have **three functions**: training, assessment, and information. **Training:** The goal of the training is to ensure that drill participants can implement (even improve) any evacuation instructions received through brochures, lectures, videos, other media, or prior experience. For example, participants can implement evacuation plans, such as the planned destination and route choice from previous experience or knowledge. They can also gain or revise evacuation knowledge after drills. **Assessment:** The goal of the assessment is to measure the degree to which the evacuation plans and training materials can evacuate or help the largest number of people possible before a tsunami arrival. With respect to the assessment function, evacuation drills can be viewed as scheduled simulations of actual evacuations. These simulations are designed to enhance evacuation preparedness by identifying gaps in response performances. For example, emergency managers can assess the effectiveness of the signage by investigating whether it can help participants navigate to safety during the evacuation drills. **Information:** The goal of the information is to provide scientific evidence, such as human behaviors in drills, for informing/validating tsunami evacuation modeling and planning studies (Poulos et al. 2018). For instance, walking speed data from an evacuation drill can be used to inform individual movement speed in evacuation simulation models.

An evacuation drill has **two unique features**: controlled and partially realistic. People's responses to a disaster include four sequential components: receiving warnings, decision making, evacuation preparedness, and evacuation movement (Lindell and Perry 2012). The sequence of the four processes can occasionally overlap; however, generally occur in a sequential pattern that allows for predictability in planned evacuation exercises. For example, drill participants will not start to evacuate until they are told of a potential threat. This sequential process in drills is equivalent to people not taking protective action until receiving disaster cues (such as the ground shaking) in real events. Though it is impossible to convey the full stress of a real evacuation due to practical or ethical constraints (Schadschneider et al. 2011), an evacuation drill can provide valuable information reflecting evacuation processes to actual events (Poulos et al. 2018). Evacuation drills, thus, are simulation exercises to replace and amplify real experiences with guided opportunities, often "immersive" in nature, that evoke or replicate substantial aspects of the real world in an interactive fashion.

1.1 Research objectives and questions

This research (1) provides a tsunami evacuation drill template/model/framework for future research and local education programs, and (2) provides empirical evidence of tsunami evacuation walking speed and route choice in evacuation drills. By using a GNSS trajectory dataset, probability functions are employed to model participants' average walking speeds and corresponding probabilities. An Evacuation Hiking Function (EHF), revised from Tobler's Hiking Function (Tobler 1993), is created to describe the relationship between slope and walking speed during evacuation drills. Regression analysis is used to examine what environmental conditions or spatial characteristics affect walking speed during evacuation. Specifically, the research questions include:

1. What are participants' walking speeds and distributions during evacuation drills?
2. How is walking speed affected by elevation change, terrain type, time of day, evacuation distance, time spent during evacuation, and previous experience with evacuation routes?
3. To what extent does milling time (if added before evacuation) impact the potential mortality rate?

1.2 Contribution

Working closely with members of the community, state agencies, and scientists who live and work in Newport, Oregon, we designed a series of evacuation drills for this community. This region provides two formally designated evacuation sites: Safe Haven Hill (SHH) and the Oregon Coast Community College (OCC). The evacuation drills fulfilled the functions of preparedness training, outreach, and education, as well as contributed to our scientific understandings of evacuation behaviors. Residents, potential visitors, students, and researchers engaged in the evacuation drills to better prepare for tsunamis. Moreover, local authorities, agencies, and researchers utilized this opportunity to assess existing evacuation plans and infrastructure (i.e., evacuation signage and shelters).

Empirical evidence was obtained to analyze the walking speed and factors affecting the walking speed in drills. Utilizing the empirical data, the walking speed distributions, and the EHF provide evidence for evacuees' traveling behavior to support tsunami evacuation modeling and emergency planning. In particular, the functions established in this study might provide a more realistic solution for the walking speed assignment for evacuation modeling than in previous studies, such as Lämmel et al. (2010); Mas et al. (2012); Wang et al. (2016); Takabatake et al. (2017); Mostafizi et al. (2019a). Furthermore, the EHF is useful when modelers aim to include the walking-slope relationship in an evacuation model, such as building the cost-distance model by elevations (Wood and Schmidtlein 2012).

Additional components in this study could inform future drills. First, the coordinates and time data were recorded from a downloadable mapping application Strava (©2020) (Strava 2020) on participants' mobile devices. Using the Strava application, we were able to track participants' route choices, locations, and time. Participants' Strava trajectories were incorporated into an agent-based evacuation model. These anonymous route trajectories were processed and visualized during a debrief session. The visualizations of participants results were coupled with pre-computed tsunami inundation dynamics to provide participants a practical understanding of how their evacuation behaviors - such as milling time, walking speed, and choice of routes—affect their ability to "beat the wave" (Priest et al. 2016). Second, we conducted a post-evacuation assessment utilizing a Qualtrics online survey to understand how these organized drills motivate people to prepare for future coastal hazards. Third, in subsequent iterations of the evacuation drills, we added increasing levels of complexity to the decision-making process, such as separating family geospatially at the time of the earthquake, helping injured friends during the earthquake, and nighttime tsunami drills (Cramer et al. 2018).

2 Literature review

Previous tsunami evacuation models (Mas et al. 2012; Wood et al. 2014; Mas et al. 2015; Wang et al. 2016; Priest et al. 2016; Takabatake et al. 2017) were built based on assumptions such as consistent or probabilistic walking speed and shortest route choice. For instance, Wang et al. (2016) and Mostafizi et al. (2019a) assigned a normal distribution to walking speed for individuals in the evacuation simulation. The mean of the normal distribution was based on a study of pedestrians walking on the street in a non-emergency situation (Knoblauch et al. 1996). The authors assumed that the walking speed distribution in a non-emergency situation could somehow represent the walking speed in an emergent tsunami evacuation. Beyond those assigning a probabilistic distribution, Wood and Schmidtlein (2012) used a hiking function (Tobler 1993) to build a cost-distance model for tsunami evacuation. This hiking function was able to capture the impact of slope on walking speed, however, in a non-emergency hiking situation. Overall, existing evacuation models assumed the behaviors in a non-emergency situation could represent behaviors in an emergency evacuation, but this assumption has not been validated by the literature due to a lack of adequate evidence from empirical or experimental evacuation behaviors.

2.1 Evacuation drill

Numerous studies focused on in-building vertical evacuation behaviors from drills or real events (Proulx 1995; Kretz et al. 2008; Xu and Song 2009; Yang et al. 2012; Qu et al. 2014; Poulos et al. 2018), especially for fire threats with topics of speed, milling time, pedestrian flow and density, evacuation fatigue, and modeling. For example, a study from Finland collected data from 18 evacuation events in different building types ranging from a single hospital ward to a stadium (Rinne et al. 2010). With a large sample size, this study provided empirical evidence of milling time, walking speed, and grouping behavior.

While many studies were developed for in-building fire drills, only a few studies documented tsunami evacuation specifically. Sun et al. (2014) (new version Sun (2020)) used a single-person evacuation drill as an educational method to eliminate people's biased attitudes after the 2011 Great East Japan Earthquake, such as overly optimistic, overly pessimistic, and overly dependent. This study provided a new approach for local authorities to initiate community-level drills for regions with limited resources. Further, the single-person drill attempted to improve personal preparedness from an individual level. The authors concluded that this type of drill could (1) shift the focus of tsunami risk preparedness practice from the community level to the individual level; (2) change "negative attitudes" toward tsunami preparedness; and (3) transform resident's self-view from someone who would need help to someone who would take the initiative in reducing tsunami risks. Sun (2020) emphasized making a multi-screen video to record the evacuation process for future education use; however, this study did not provide an in-depth analysis of human behavior during a tsunami evacuation drill.

Poulos et al. (2018) used an in-building tsunami evacuation drill from a K-12 school to validate the agent-based simulation model for indoor evacuation. This study compared the pedestrian flow and evacuation time in the drills with that in the simulations. The results showed that the error between simulated and actual pedestrian flow rates was 13.5%, and the error between simulated and actual evacuation times was 5.9%. This study provided valuable insight using drill data to validate in-door evacuation simulations. In 2020, Nakano et al. (2020) introduced a "four-way split-screen" evacuation movie method to establish a communication bridge between experts and laymen. The movie clip simultaneously displayed a school evacuation drill and a tsunami inundation. The author argued that this movie clip was a tool to help experts establish scenario-based evacuation strategies and to implement preparedness activities for non-experts. In the same year, Yosritzal et al. (2020) conducted an evacuation drill to analyze the effects on walking speed from age, gender, and walking distance in a community in Indonesia. The authors assigned six observers to record the travel time for 18 evacuees on three designed evacuation routes. This study provided some empirical drill data and discussed the potentials of using the results to inform the evacuation modeling.

In general, current research about tsunami evacuation drills provides an initial understanding of evacuees' behaviors, such as walking speed, factors affecting walking speed, participants' abilities to walk to a higher elevation, and participants' feedback (National Research Council 2011; Cramer et al. 2018).

2.2 Evacuation drill technology

Aforementioned tsunami evacuation drill studies (Sun 2020; Nakano et al. 2020) used cameras to record evacuees' behaviors. For example, the single-person drill study (Sun 2020) applied multiple small-scale artifacts such as video cameras and GPS devices to record the process of evacuation drills. This study used people to document the process. An interviewer and a note taker asked related questions and recorded the evacuees' reactions during the evacuation drills. This process not only provided evacuees a more realistic and real-time scenario but also enabled evacuees to provide immediate feedback on their evacuation efforts. Compared with a post-drill survey procedure, this approach can overcome the issue of losing accuracy of behavior and emotion recollection due to memory decay (Wu 2020). Nevertheless, this approach requires extended inputs including devices, recording labor, and post-drill editing.

Researches have been applying computer graphical simulations to visualize disaster scenarios to improve realistic quality in drills (Chen et al. 2012; Hsu et al. 2013; Farra et al. 2015; Kawai et al. 2015). Virtual Reality (VR) is gaining increasing acceptance because it retains a considerable cost advantage over large-scale real-life drills (Hsu et al. 2013). To improve the traditional VR system assisting tsunami evacuation drills, Kawai et al. (2015) developed a lightweight headset that allowed participants to view digital materials during the evacuation movement. The VR could also generate different scenarios during evacuation. While the authors claimed that they had not fully developed this system, this function could be integrated with existing commercial equipment for evacuation education or training purposes.

2.3 Walking/running speed

Individual traveling speed is a critical factor in building tsunami evacuation models, but it is difficult to determine due to interrelated variables. The walking/running speed varies by individual characteristics (age, mobility, height, weight, etc.) and environment conditions (road surface type, slope, wind, etc.). Depending on the geographic features and urban layout of communities, those residing in tsunami inundation areas may have to travel different distances to safety (Wood and Schmidtlein 2012).

In general, an unimpaired adult's movement speed between 0.6 m/s and 2.0 m/s is commonly observed in field studies. Speed less than 0.6 m/s is considered as an extremely low walking speed (Wu et al. 2019). An unimpaired adult's preferred walking speed is between 1.2 m/s and 1.4 m/s (Mohler et al. 2007; Perry et al. 2010; Wu et al. 2019). Many environmental factors and individual characteristics can affect the walking speed. Bohannon (1997) summarized the comfortable and maximum walking speed for people aged 20 to 80, and also summarized the speed differences between genders and heights. While maximum running speed declines with the increase in age, comfortable walking speed has less variance. Terrain surface type also impacts evacuation walking speed. Gast et al. (2019) found that the preferred speed ($1.24 \pm 0.17m/s$) on a smooth surface is significantly faster than the preferred speed on rough terrain ($1.07 \pm 0.05m/s$). As more information is gathered by the evacuees during the process, the preferred walking speed decreases (Mohler et al. 2007).

Rinne et al. (2010) developed walking speed distributions for in-building drills and found that median speeds for a non-emergency situation were 1.3 m/s for adults, 1.5 m/s for children, and 2.1 m/s for goal-oriented runners. Again, many studies documented walking speed for in-building drills but not for outdoor tsunami evacuation. Fraser et al. (2014) comprehensively reviewed 15 studies and summarized pedestrian walking/running speeds for different age groups to inform evacuation modeling. The different age groups' walking speeds were used in a GIS-based least-cost-distance evacuation model. Though the walking speed spectrum was not created based on empirical tsunami evacuation scenarios, the established speeds by age groups from non-emergency situation are useful to inform evacuation modeling when demographic data are available.

Tobler (1993) built a nonlinear function to describe the relationship between slope and walking speed, $speed = a \times e^{-b \times abs(Slope+c)}$ where estimated parameters are a = 1.67 m/s, b = 3.5, and c = 0.05 (i.e., 2.9°). This function depicts a maximum speed at −2.9°. Tobler's Hiking Function (THF) is widely used in various fields such as recreation planning, rescuing persons, assessment of urban social interaction, pedestrian healthcare facility accessibility, and evacuation route planning (Campbell et al. 2019). Additional researchers (Rees 2004; Campbell et al. 2017; Irmischer and Clarke 2018; Campbell et al. 2019; Davey' et al. 2020) developed different models to represent speed–slope relationship. These existing functions had a peak that represents the maximum travel rate Differences included where the peak point was and how fast the speed decreased on each side of the peak, acted as modifications of the original THF.

Though later research modified THF by different methods or in various scenarios, the original THF has been adopted by studies and preparation implementations because of its practical and simplified features. The THF had a significant contribution to the Anisotropic path modeling (Wood and Schmidtlein 2012; Fraser et al. 2014; Priest et al. 2016). It was used to estimate the evacuees' walking speed and also the minimum "beat-the-wave" speed depending on path distance and slope. Though using the original THF function seems appropriate as a first approximation, the parameters estimated in the THF were estimated in a non-emergency walking scenario rather than an evacuation scenario.

While evacuation methods have been developed, they are rarely used by local practitioners due to a lack of systematically consistent data or information (Løvholt et al. 2014). Thus, we provide an example of organizing evacuation drills with a practical way to record detailed evacuation data and also provide empirical evidence to augment other approaches.

3 Methodology and data collection

3.1 Study site

The Cascadia Subduction Zone (CSZ) megathrust is a 1000 km long dipping fault that runs from northern California, United States up to Northern Vancouver Island, British Columbia. It is about 100–160 km off the Pacific coast shoreline (Thatcher 2001; Nelson et al. 2006), as shown in Fig. 1. A magnitude 9 (M_w9) CSZ earthquake can pose significant threats to coastal communities in the U.S. Pacific Northwest (Wood et al. 2020), and its likelihood of occurring in the next 50 years is 7–25% (Goldfinger et al. 2012). It will generate a near-field tsunami with waves of ten meters or more (wave elevation at shoreline above Mean Higher High Water) striking coastal communities within 20–40 minutes (Gonzalez et al. 2009; Goldfinger et al. 2012; Priest et al. 2013). According to a study from the United States Geological Survey (USGS) (Wood 2007), the tsunami inundation zones in Oregon threaten approximately 22,201 residents and an average of 53,713 day-use visitors. The potential casualties in Oregon are between 600 and 5000 (Oregon Seismic Safety

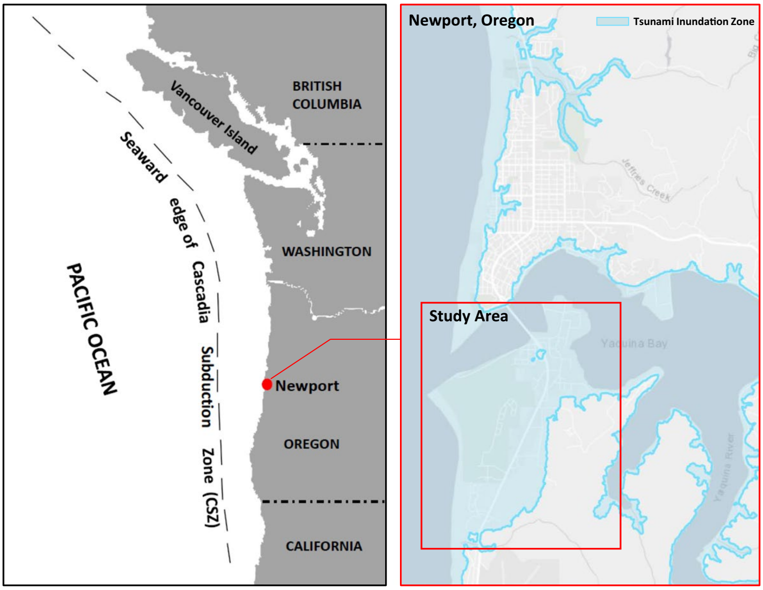


Fig. 1 Study area in Cascadia Subduction Zone and its impact area, revised based on (Thatcher 2001). (Newport, OR: 44.610550, -124.060313 WGS-84)

Policy Advisory Commission 2013), not to mention the impact in California, Washington, United States and Vancouver Island, British Columbia.

The city of Newport, Oregon, United States with 10,854 residents (2019 Census), has a high number of employees (1455) exposed to the tsunami hazard (Wood et al. 2010, 2015). As shown in Fig. 2, restaurants, local marine facilities, and state or national agencies [National Oceanic and Atmospheric Administration (NOAA), Oregon Department of Fish & Wildlife (ODFW), Oregon Coast National Wildlife Refuge (OCNWR), Oregon Coast Aquarium (OCA)] are located in the low-lying inundation area in the south part of Newport. South Beach State Park and surrounding facilities attract an average of 1,135,584 visitors per year and have the second-highest annual average number of day-use visitors among the 66 parks along the Oregon Coast (Wood 2007). This recreation site is at an inundation risk with the added concern of out-of-area visitors having less evacuation knowledge than local residents. In addition, this study site covers a large variance of elevation (0-50 meter), land uses (recreational, commercial, and residential areas), and terrain types (sandy beach, forests, natural trails, and paved roads). Two high ground sites exist in the study area—Safe Heaven Hill (SHH) and Oregon Coast Community College (OCC)—as shown in Fig. 2. While SHH is surrounded by an inundation zone, it has a higher elevation (>21 meters)

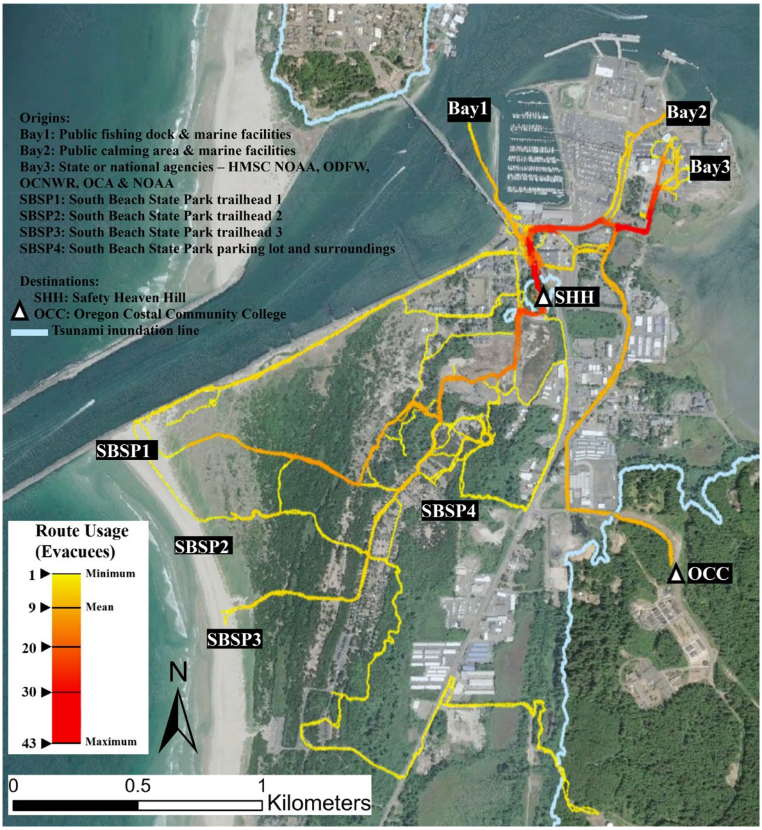


Fig. 2 Tsunami evacuation route choice and tsunami inundation area in Newport, OR, USA(State of Oregon Department of Geology and Mineral Industries 2012)

than surrounding flat land and serves as a vertical evacuation site facilitating a rapid evacuation from the low-lying South Beach State Park and the harbor area in Newport (Oregon Office of Emergency Management 2016). OCC is located inland with high elevation and serves as a horizontal evacuation site providing ample space for a refuge. Given this context, this region offers a unique case study location that provides both vertical and horizontal evacuation sites for evacuation drills.

3.2 Evacuation drills process

To understand the variables influencing evacuation, drills were conducted with different origins and destinations, scenarios, time of day, and participants having different occupations. We invited participants from schools, government agencies, and non-profit education organizations. The public was also allowed to register on-site. Different days of the year were also selected to cover various seasons and weather without keeping participants in extreme weather or hazardous conditions. Evacuating by foot is officially promoted during tsunami evacuation in Oregon by state education and outreach programs (State of Oregon Department of Geology and Mineral Industries 2012). All participants in our study were asked to evacuate by foot as fast as possible during evacuation drills to better simulate a real evacuation situation.

Figure 2 illustrates the evacuation origins, destination, and route choice, and choice density of the drills. Three sites around the bay and four sites within the SBSP were selected as origins to represent the heterogeneous land-use locations, including recreational activity locations, work locations, and parking locations. Two high ground areas, SHH and OCC, were selected as the evacuation destinations (State of Oregon Department of Geology and Mineral Industries 2012).

Figure 3 illustrates the evacuation drill procedure. Across the six drills, participants were asked to register and provide basic demographic and evacuation knowledge information, including downloading the Strava app, before being sent to start locations. We assigned participants to four starting points that represent popular trail-heads in the SBSP area (SBSP1, SBSP2, SBSP3, and SBSP4) and three starting points that represent popular working and recreation locations in the Yaquina Bay area (Bay1, Bay2, and Bay3), as shown in Fig. 2. At a predetermined time, participants were told to imagine a CSZ earthquake, pause (simulates the decision time, but is not captured by Strava app), start the Strava app, and then evacuate to SHH or OCC. After each evacuation drill, a debrief and evaluation session was held on-site. Participants were then invited to submit their downloaded Strava evacuation data and complete an online Qualtrics questionnaire.

One key component to this drill process is providing near real-time results to participants immediately after the drills and encouraging them to evaluate their evacuation behaviors and decisions. Specifically, the research team downloaded participants' evacuation trajectory data and overlaid it to the tsunami inundation model (see Sect. 3.4) (Park et al. 2013; Wang et al. 2016; Mostafizi et al. 2019a). The visualization of the comparison was shown to participants to encourage them to evaluate their route choices and walking speeds. For instance, participants were shown whether they would be caught by a tsunami if they evacuated on the routes and with the speeds they used in the drills. Participants saw their collective route choices (we did not identify particular individuals on screen to protect privacy) and how their decision making affected whether they could reach safety (Cramer et al. 2018).

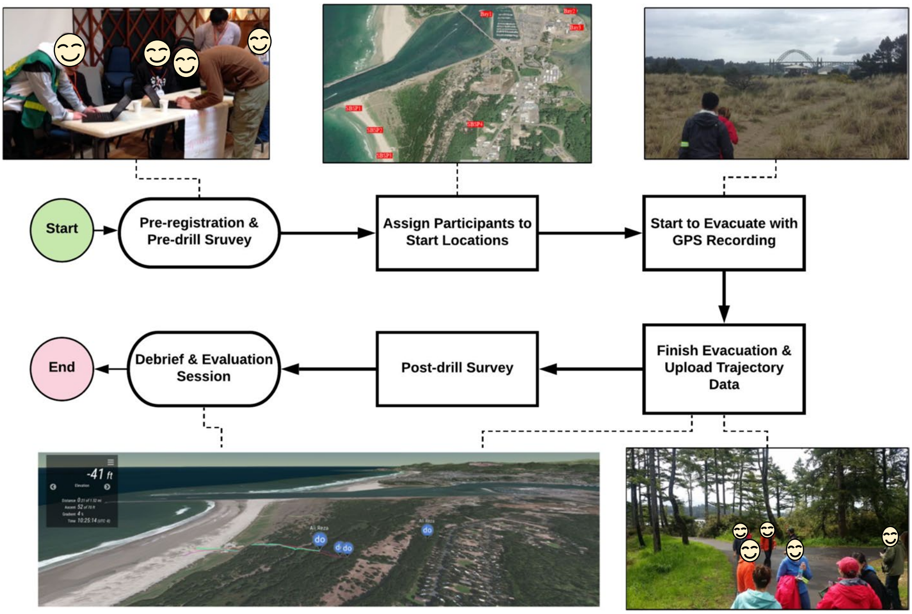


Fig. 3 Evacuation drill process

The official drills were conducted 6 times from 02/18/2017 to 08/10/2017. The dates were selected to accommodate participant availability. The weather of the six dates covered sunny, cloudy, and slight rain. We did not organize drills in winter to enhance participants' safety. Table 1 documents the number of samples collected for each drill. Within the total 136 participants, 87 uploaded trajectory data and 74 are valid for analyzing. Thirty-one participants conducted voluntary post-drill surveys. Details of the six drills are documented below:

1. *02/18/2017* Oregon State University (OSU) students and professors participated in the first official drill.
2. *05/11/2017* Participants included OSU students and professors, staff from Oregon Parks and Recreation Department (OPRD), Teen Community Emergency Response Team (CERT) from a local junior high school, Hatfield Marine Science Center (HMSC), and general public volunteers.
3. *06/16/2017* Participants included OSU students and HMSC staffs.
4. *06/29/2017* OSU Summer Undergraduate Research Fellowship (SURF) program students and professors were the main participants. This drill required participants to give up cell phone and maps and evacuate based on their own knowledge and on-site evacuation signs. Letters in envelopes were giving to participants for different role-playing scenarios (Fishing from Shore, Whale Watcher, Looking for sea shells. Details can be found in the supplement material).
5. *07/13/2017* (night drill) Participants included Research Experiences for Undergraduates (REU) students, Sea grant scholars, and HMSC staff.
6. *08/10/2017* (night drill) Participants included REU students, Sea Grant students, and OMSI staff. Letters in envelopes were given to participants in different role-playing scenarios.

Table 1 Evacuation drill data collection

Date	Totals	Origin–>Destination			Occupation groups				Trajectory data		Survey
		Bay–>SHH	Bay–>OCC	SBSP–>SHH	OSU student faculty	HMSC OPRD State Agency	REU Sea grant	Others public	Total Strava	Valid Strava	Post-drill Survey
1. 2017.02.18	13	0	0	13	13	0	0	0	8	7	0
2. 2017.05.11	39	26	0	13	6	27	0	6	23	20	12
3. 2017.06.16	11	0	11	0	4	7	0	0	9	9	8
4. 2017.06.29	28	0	0	28	28	0	0	0	11	3	11
5. 2017.07.13[a,b]	19	19	0	0	2	2	14	1	17	16	0
6. 2018.08.10[a]	26	19	0	7	1	10	14	1	19	19	0
Totals	136	64	11	61	54	46	28	8	87	74	31

[a]Drill was done at night;[b]drill was done using scenarios

There was diversity among the volunteer participants which included college students, teachers, state and local government personnel, and a range of age and gender demographics. The HMSC, OPRD, and State agency groups represented those who were familiar with the evacuation routes, as they were required to walk the routes as part of their job orientation. It was important to include participants who do not reside in Newport and are less familiar with the evacuation destinations and routes. Participants in the fourth, fifth, and sixth drills consisted of students involved in undergraduate research [SURF, REU, and Oregon Sea Grant students], and we increased the complexity of scenarios of the drills. Please see supplement materials for details of those designed scenarios. In those scenarios, an envelope was given to participants to describe different options to mimic possible behaviors and activities, then participants chose their course of action, for instance, choosing to evacuate to higher ground directly or meet family first before evacuate. Due to limited data points of the last drill, results are not statistically analyzed, yet are documented in the supplement material for information and future research.

3.3 GNSS trajectory

Global Navigation Satellite System (GNSS) [Sometime refers to Global Positioning System (GPS)] enables mobile devices to track and map participants' locations. GNSS data can contribute to human movement, behavior, and route choice research (Chen et al. 2020b). It has been used in disaster studies such as risk mitigation (Ai et al. 2016) and decision making (Zerger and Smith 2003). In this study, participants used the Strava app in their own GNSS-enabled mobile devices to record the latitude (y), longitude (x), elevation (z), and time during evacuation (t). Slope is calculated using Δz (change in elevation) divided by $\sqrt{\Delta x + \Delta y}$ (Euclidean distance) between two data points. While the data could be impacted by the mobile devices or Satellite connection signal, this study showed that 74/87 (85%) of participants' trajectory data are valid (partially recorded data and data not in the study area are considered as invalid). GNSS-enabled mobile devices are easy to access and may be affordable for small jurisdictions to repeat the drills.

3.4 Tsunami inundation and participants' milling time

Besides the evacuation travel process, two other critical components affect the success of an evacuation: how a tsunami inundates and how long evacuees spend before evacuation (Lindell et al. 2019). This study, therefore, incorporated (1) tsunami inundation, (2) milling time, and (3) the empirical drill evacuation GNSS trajectories into an Agent-based Tsunami Evacuation Model (ABTEM) created by the OSU research team (Wang et al. 2016; Mostafizi et al. 2017, 2019a) to articulate the effectiveness of participants' evacuation.

- *Tsunami inundation layer* Tsunami inundation time series data was developed by Park et al. (2013) and represented an extreme scenario generated by a $M_w 9$ Cascadia Subduction Zone event. We used a 0.5-meter water depth as the threshold to indicate that participants were caught by the wave.
- *Milling time* All participants evacuated immediately during the drills, while in the real events people tend to spend time on decision making, collecting and confirming information, collecting necessities, contacting family, or picking up family before evacuation (Lindell and Perry 2012). Those psychological and physical tasks can be repre-

sented by the aforementioned milling time people spend before evacuation. Due to the scope of this study, drill participants did not experience the actual milling process, so the GNSS data only recorded the evacuation movement. Thus, to understand how the milling time affects the drill evacuation results, a sensitivity analysis of the milling time was conducted in the ABTEM. Specifically, we included different artificial milling time (0–40 min.) before each participant's GNSS trajectory to analyze the effect of milling time on mortality rate [percentage of participants caught by tsunami based on the inundation model from Park et al. (2013)].

By varying milling time, this analysis demonstrated whether and where evacuees would be caught by waves based on their current walking speeds and route choices when exposed to a near-field tsunami caused by the M9 earthquake in CSZ.

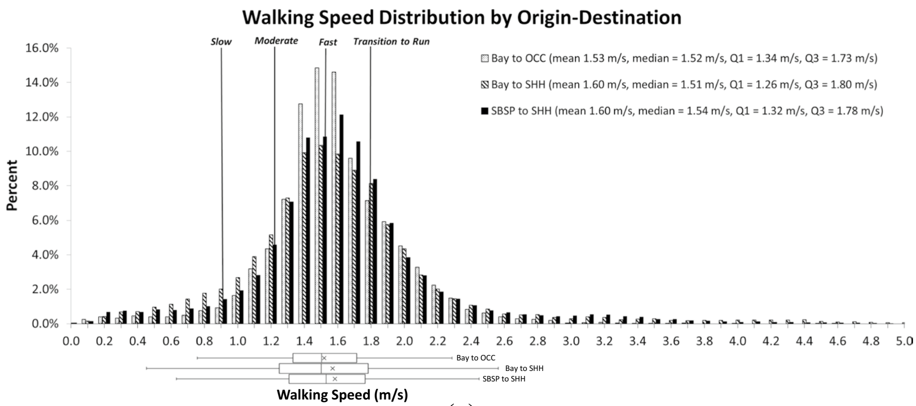
4 Results and discussion

4.1 Walking speed distribution during evacuation

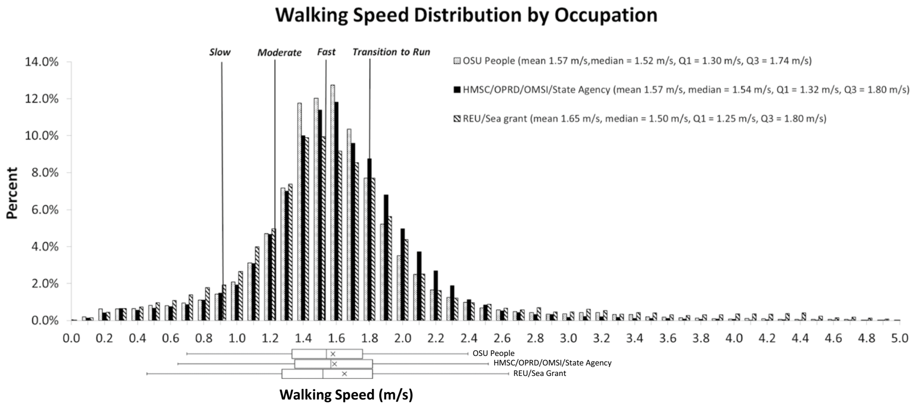
Walking speed during the evacuation drill had a mean of 1.58 m/s and a standard deviation of 0.62, as shown in Fig. 4. The mean walking speed was slightly faster than the "fast" walking speed (1.52 m/s) for unimpaired adults observed in previous literature (Wood and Schmidtlein 2012; Fraser et al. 2014). Most of the time (83%) during the evacuation drills, people walked faster than a "moderate" walking speed of 1.22 m/s (Knoblauch et al. 1996; Langlois et al. 1997). As expected, the results indicate that on average people moved faster in the drills than in normal situations.

Figure 4 illustrates the walking speed distribution categorized by origin–destination and by groups of people with different occupations. While the boxplots illustrate no obvious difference in walking speed between groups, the average value and the regression analysis show a relatively clearer pattern: Participants evacuating from Bay to OCC, on average, moved more slowly than others ($\beta = 0.04$, $p < 0.01$), as shown in Fig. 4a. The total evacuation distance from Bay to OCC was also longer than the other evacuation scenarios (for example, from Bay to SHH and from SBSP to SHH). For occupation groups, REU and Sea Grant students tended to evacuate faster than the others ($\beta = 0.21$, $p < 0.01$), as shown in Fig. 4b. Those students were on average younger than other groups of people, and the age was, according to previous studies, negatively correlated with the walking speed (Gast et al. 2019).

We employed probability methods to model the average walking speed from the drills. These fitted probability models can inform evacuation simulation and modeling research. Probability models were fitted using package "tdistrplus" in R (Delignette-Muller and Dutang 2015). Based on the right-skewed shape of the average walking speed of participants, three distributions were selected as candidates for the model fitting process: Log-logistic, Gamma, and Burr distributions, as shown in Fig. 5. Figure 5b demonstrates that all three estimated models fit the empirical data well for the range below 2 m/s. A reasonable explanation is that this dataset provided more data points for the range below 2 m/s than the other ranges. Because the majority of participants (93%) evacuated with the average speed at the range from 1.2 to 2.0 m/s, those functions can describe the overall data accurately. Log-logistic function shows the best goodness-of-fit statistics of the three candidates, as illustrated in Table 2. Thus, the Log-logistic function is selected to model people's



(a)



(b)

Fig. 4 Walking Speed Distribution by **a** Origin–destinations and **b** Roles. Walking speed threshold: Slow = 0.91 m/s (Langlois et al. 1997; Knoblauch et al. 1996); Moderate = 1.22 m/s (Langlois et al. 1997; Knoblauch et al. 1996); Fast = 1.52 (Wood and Schmidtlein 2012; Fraser et al. 2014); Transition to Run = 1.79 m/s (Fraser et al. 2014). In box plots: Q1 = 25th percentile; Q3 = 75th percentile; Min. and Max. lines indicate Q1-1.5IQR and Q3+1.5IQR, respectively; Crosses indicate means

average walking speed during the tsunami evacuation drills. The Log-logistic distribution has a cumulative density function:

$$F(x) = \frac{1}{1 + (x/\gamma)^{-\delta}} \tag{1}$$

where $F(x)$ represents the cumulative probability of having speed less or equal to x. Maximum likelihood estimation shows that estimated $\gamma = 12.3267$ and $\delta = 1.5490$. Therefore, the function can be simplified as:

$$F(x) = \frac{0.0045}{0.0045 + x^{-12.3267}}. \tag{2}$$

This walking speed function with the best-estimated parameters can be used to inform the individual's walking speed for tsunami evacuation modeling, as evidenced in Mostafizi

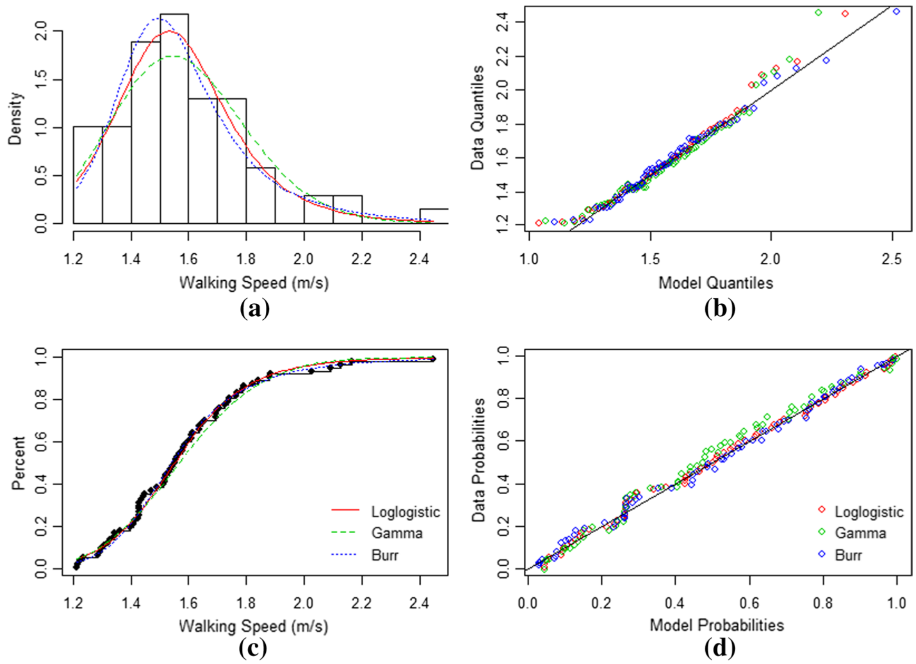


Fig. 5 Model fitting for average walking speed

Table 2 Statistics for model comparison

Goodness-of-fit statistics	Models		
	Log-logistic	Gamma	Burr
Kolmogorov–Smirnov	0.07	0.07	0.06
Cramer–von	0.03	0.07	0.03
Anderson–Darling	0.26	0.53	0.21
Akaike's information criterion	−5.98	−3.53	−5.62
Bayesian information criterion	−1.51	0.94	1.08

et al. (2019a) and Mas et al. (2012). The emergency management practitioners can also use this function to estimate the pedestrians' evacuation travel time and assess the current evacuation plans. However, this function does not represent all situations and all population segments due to the limited sample size and representativeness. Using walking speed for each population segment was summarized in Fraser et al. (2014) and might be more useful when the demographic data and elevation data are available. This limitation of our walking speed function will be discussed in Sect. 6 in detail.

4.2 Slope–speed

Figure 6 shows that the majority of time the participants were walking on a terrain with a slight positive slope (incline). A few data points on top of the y-axis describe the sprint

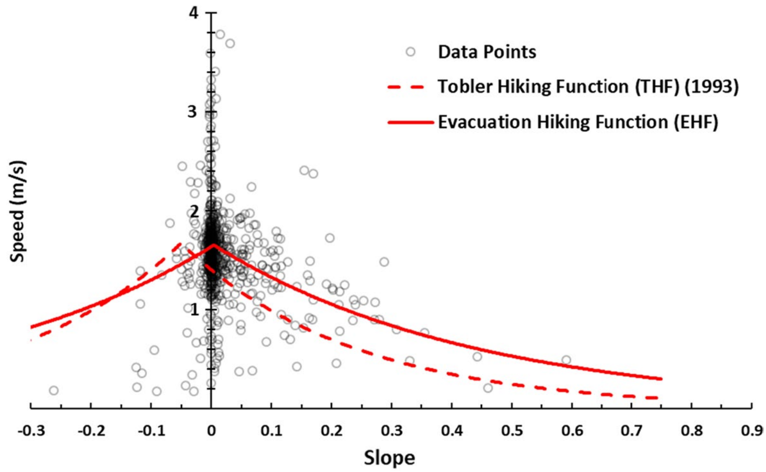


Fig. 6 The impact of Slope on Speed during Evacuation

movement of some participants during the drills (included in data analysis). The distribution of the data points shows a nonlinear relationship between the slope and the walking speed. To model this nonlinear relationship, we fitted an Evacuation Hiking Function (EHF) with three estimated parameters using the nonlinear least square method. This function was created based on Tobler's Hiking Function (THF) but with three different estimated parameters. The estimated function of EHF is:

$$Speed = 1.65 \times e^{(-2.30 \times abs(Slope - 0.004))}. \tag{3}$$

The fitted EHF ($R^2 = 0.10$, MAE = 0.31) produced less error than the THF ($R^2 = 0.06$, MAE = 0.37) when applied to this drill dataset. The THF shows that the peak walking speed (1.67 m/s) occurs on a slight downhill slope of −0.05 (−2.86°), whereas the EHF shows the peak appears on the approximately flat slope of 0.004 (0.23°) in the evacuation drills. Some data points appearing above the peak point indicate that evacuees sometimes run at a fast speed [a speed from 1.79 to 2.11 m/s is the common transition from walk to run (Mohler et al. 2007; Fraser et al. 2014)] on flat areas during the drills. Indeed, we observed some participants started with a fast run at the beginning of the evacuation drills.

The estimated walking speed at the positive slope of the EHF is faster than the speed of the original THF, consistent with expectations. It is likely that participants moved faster under the pressure of an emergency evacuation situation than a non-emergency hiking scenario. There are limited data points at negative slope (due to participants evacuating uphill most of the time) which creates the difficulty in determining the usefulness of this model for the negative slope range. Nevertheless, the positive slope section of the function is more useful in practice because of the assumption that people move uphill most of the time in a real tsunami evacuation.

In the regression analysis, as shown in Table 4, the slope (change in elevation divided by change in horizontal distance) shows a negative impact ($\beta = -0.78$, $p < 0.01$) on the walking speed during the evacuation drills, and is consistent with the results from EHF when the slope > 0. The multiple linear regression is suitable to justify this relationship because the majority of data points are located at a slope > 0 (Slope > 0 means participants evacuated uphill.), so the slope–speed relationship is approximately monotonic. In some rare communities where evacuees have to move downhill before going uphill, using the EHF would be more useful and reliable than a multiple linear regression analysis to capture the non-monotonic slope–speed relationship.

4.3 Space-time trajectory

Figure 7 illustrates the relationship between time and the shortest distance to destination (the shortest surface distance from every point on evacuation paths to destinations) for each participant. Depending on the variables (such as origins, destinations, walking speed, and route choice), the space-time trajectory can be different for participants. The initial point (when the trajectory line intersects with the y-axis) represents the distance to the planned destination when a participant is at the start location. The end point represents the distance to the planned destination when a participant reaches the evacuation point.

The majority of participants of the group that evacuated from Bay to SHH took less time than the other two groups due to relatively shorter distance to the destination. Participants who evacuated from Bay to OCC had longer total evacuation distance than participants of the other two groups. However, some of participants even arrived at the destination sooner than other participants that evacuated from SBSP to SHH. Indeed, the space-time figure shows that some participants who evacuated from SBSP to SHH moved in the opposite direction from the destination sometime during the evacuation drills, which resulted in the late arrival. Two participants who evacuated from SBSP to SHH spent a longer time than others (total 35 and 37 minutes). Their space-time trajectories ascended from 15 to 20 minutes and then declined again, which indicates that they walked in the opposite direction to the destination or wandered around during the evacuation but eventually went in the correct direction. Two other participants (two red outliers) evacuated to neither SHH nor OCC, so the two trajectory lines depart from the destinations. The two participants reported to researchers that they initially planned to evacuate to SHH, but lost their way and then evacuated to the direction they believed to be safe. We verified that the destination they evacuated to was outside of the tsunami inundation zone; however, their data points were excluded from the analyses for data consistency purposes.

4.4 Terrain, night/day, time spent, and distance to destination

In addition to the factors discussed in the previous sections, variables such as terrain surface type, night/day, time spent during evacuation, and distance to destination also have a potential impact on the walking speed during the evacuation drills. A regression analysis was applied to investigate the impact of those factors, as shown in Table 4. Descriptions of factors included in the regression analysis are summarized in Table 3.

A hypothesis suggests that the roughness of a terrain correlates to the walking speed. The results support this hypothesis. In the drills, evacuees' walking speed on the rough terrain (sand, non-paved trail, or natural trail surface) is on average 0.11 m/s slower ($\beta = -0.11$, $p < 0.01$) than the walking speed on the smooth surface terrain (paved trail, side-walk, or motorized vehicle lane). This finding is consistent with previous research (Schmidtlein and Wood 2015; Gast et al. 2019). The result also provides empirical evidence for the evacuation modeling by varying land cover types. Schmidtlein and Wood (2015) explored how different land cover types influence anisotropic least-cost-distance model outcomes. In their study, for instance, dirt/gravel/grass/sand lands were assigned

Table 3 Variable description

Variables	Unit	Description	Min.	Max.	Mean	Std.
Time	Seconds	–	0.00	2348.00	601.42	443.24
Elevation	Meter	-	1.45	45.29	9.006	7.18
Terrain	–	1: Land surface type sand or dirt/gravel trail; 0: Asphalt	0.00	1.00	0.05	0.22
Agency	–	1: Participant from HMSC, OPRD, and state agency; 0: Otherwise	0.00	1.00	0.32	0.47
REU	–	1: Participants being REU or Sea Grant student (younger than other groups); 0: Otherwise	0.00	1.00	0.20	0.40
Night	–	1: Evacuate at nigh; 0: Evacuate in the day	0.00	1.00	0.30	0.46
SBSP to SHH	–	1: Evacuate from South Beach State Park to Safety Heaven Hill; 0: Otherwise	0.00	1.00	0.46	0.50
Bay to OCC	–	1: Evacuate from Newport Bay area to Oregon Coast Community College; 0: Otherwise	0.00	1.00	0.19	0.40
Shortest Distance*	Meter	The shortest surface distance from every point on evacuation paths to destinations for each evacuee	0.00	2436.07	837.07	590.75
Slope	–	(Vertical elevation change) / (horizontal distance change) during one second time interval	−16.48	9.43	0.02	0.11

*Theoretical shortest distance may not reflect the actual route choice for each participant, but can serve as a proximity to destination

std.: Standard Deviation

Table 4 The impact of variables on speed

Variables	Coefficients	Std. error	Standardized coefficients
(Constant)	1.86	0.02	–
Time (seconds)	−0.0002***	0.00001	−0.17
Elevation (meter)	−0.004***	0.0004	−0.05
Terrain (natural)	−0.11***	0.01	–
Agency	0.006	0.006	–
REU	0.21***	0.01	–
Night	−0.21***	0.01	–
SBP to SHH	0.08***	0.01	–
BAY to OCC	0.04**	0.01	–
Shortest distance (meter)	−0.0001***	0.00001	−0.10
Slope	−0.78***	0.02	−0.14

Dependent variable: walking speed. Model is significant at 0.001 level ($F = 370, p < 0.00$).

Significance level: *0.05, **0.01, ***0.001

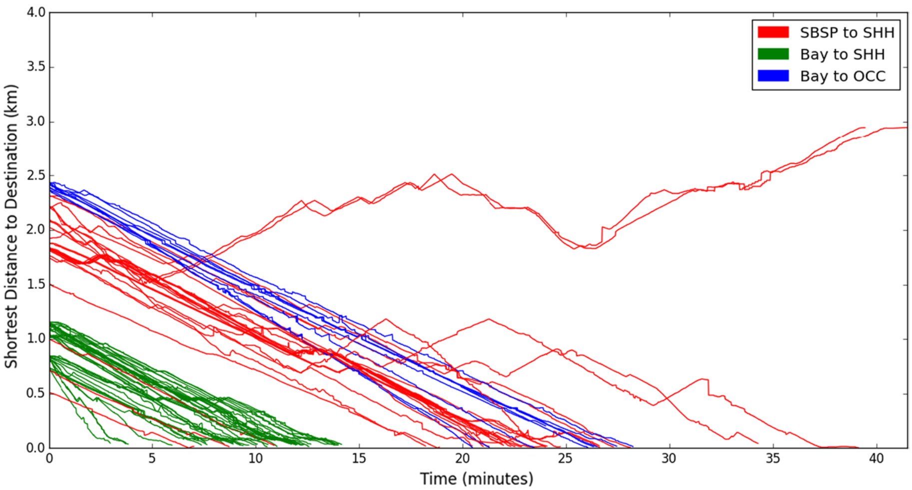


Fig. 7 Space-time trajectory for each participant during evacuation

with a lower walking speed value than paved roads. Schmidtlein and Wood (2015) admitted that analysts need to arbitrarily decide which speed value (proxies) is assigned to which land cover type, but the empirically derived values on land cover from actual evacuations would be ideal. The empirical relationship from this present study is closer to this "ideal." For example, evacuation walking speed on the rough surface is 0.11 m/s slower than on the smooth surface in the drills, and this information can be used to inform a simplified dichotomy of walking speeds by the land cover types in evacuation models.

Walking speed is impacted by evacuating in the day or at night. The result indicates that evacuees moved more slowly at night than in the day by 0.21 m/s on average ($\beta = -0.21$, $p < 0.01$). A rationale assumption involves lower visibility of routes and evacuation signage at night, so participants spent more time on navigating or looking for routes and intersections. This finding is consistent with the conclusion from a self-assessment study (Sun and Sun 2020) that people need longer mobilization time and longer clearance time to reach safety at night.

The **time spent** during the evacuation drills has negative impacts on the walking speed by controlling other variables constant, as expected. The result shows that every increase of one standard deviation in time (443 s) is associated with 0.17 *m/s* decreases in the walking speed (standardized $\beta = -0.17$, $p < 0.01$) on average. It may be explained by the fatigue after more time spent on evacuating uphill (Pelechano and Malkawi 2008), but future research should confirm this impact.

An interesting finding is the negative association between the shortest distance to destination and walking speed. This study calculated the shortest distance from every point on the evacuation route to destinations for each evacuee. An evacuee may not follow this theoretical shortest route; however, it indicates how far away the evacuee is to a destination if taking the shortest route. Every increase of one standard deviation in the distance to destination is associated with 0.10 *m/s* decreases in the walking speed (standardized $\beta = -0.10$, $p < 0.01$) on average. In other words, an evacuee moved faster when being closer to the destination, even controlling the time spent during the evacuation drills. It should be noted that the R^2 of the fitted model is low, likely due to a large amount of inherently unexplainable variation. Nevertheless, the regression method serves as an exploratory analysis in this study rather than an in-depth analysis, especially given our inability to consider endogeneity issue where independent variables may correlated with omitted variables (Greene 2012), such as age, gender, stamina, and physical characteristics.

4.5 Milling time impact

Figure 8 illustrates the percent of evacuees caught by the tsunami when milling time varies, if participants took the walking speeds and route choices from the drills in a real event. The X-axis represents the amount of artificial milling time that is added before evacuation. For example, $x = 10$ means the participants spent 10 minutes before evacuation and then started to evacuate based on their empirical drill trajectory. The corresponding $y = 13\%$ when $x = 10$ means that 13% of participants evacuating from SBSP to SHH would be caught by the tsunami if participants spent 10 minutes milling before evacuation. A more immediate impact occurs on the mortality rate (4% at time = 0) for evacuees from SBSP to SHH than the other two groups when milling time increases.

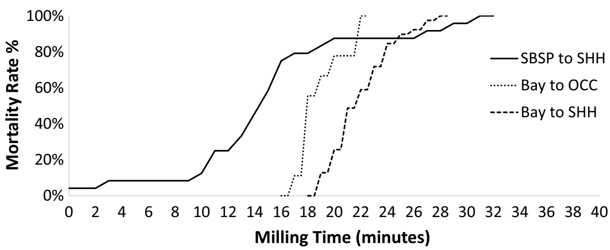


Fig. 8 The impact of milling time on mortality

This can be explained by the fact that the origins at SBSP are located closer to the ocean than other two groups (Origins at Bay). This result indicates that encouraging early evacuation can save lives but not all, especially for those residing around SBSP. Local authorities may consider other factors to decrease the evacuation time, such as increasing walking speed and familiarity of evacuation routes. While preparedness programs of earthquake and tsunami in Washington (WGS 2021), Oregon (DOGAMI 2020), and California (Cal OES 2021) encourage people to evacuate by foot to account for infrastructure failure and congestion, exceptions can be made for those residing in areas where walking maybe not be feasible for reaching safety on time (see Wood and Schmidtlein (2012) for identifying those areas) by facilitating off-road transportation. Additional concern can be raised when certain numbers of vehicles on the road delay the overall travel time. The optimal (lowest mortality) ratio of evacuating by foot and car is documented in Mostafizi et al. (2019b). However, previous studies showed that half of CSZ residents intended to evacuate by car even though authorities promote otherwise (Chen et al. 2021a, b; Buylova et al. 2020).

A steep rise in mortality rate between 10 and 15 minutes indicates that 10 min is a critical milling time for people to evacuate from SBSP to SHH. For the other two groups evacuating from the Bay, milling time shows no impact on mortality rate until 15 min; however, the sharp increase curve from 15 to 25 min indicates that the impact rises dramatically during this time range. When adding more than 30 min of milling time before the evacuation, all participants would be potentially caught by the tsunami wave if they used the same walking speed and route choice from the drills.

4.6 Participants' feedback

This section summarizes the post-drill survey results regarding participants' attitudes, behaviors, opinions, and lessons learned as a part of the evacuation drills. The feedback from participants reflects the training purpose of the drills and indicates potential issues of evacuation strategies. The majority (87%) of participants stated that the drill was useful and they felt more prepared to evacuate to a safe zone after the drills. An overwhelming majority of respondents believed the drill was useful regarding (1) learning about evacuation time (100%), (2) improving their ability to evacuate to safe zones (87%), and (3) learning how to improve evacuation effectiveness (68%). Most respondents (70%) who evacuated from SBSP pointed out a difficulty in finding clear evacuation signage. Examples of participant comments include: *"I feel that the signage around the route that I used was not clear, I tried following the signs but I did not make it to Safe Haven Hill," "...There are not many evacuation signs in the trail..." and "I think they should really really really improve the signs at the Newport Campsite (SBSP)...."*

Most participants stated that they would prepare a "to-go" disaster kit (58%), make an evacuation plan (61%), and participate in additional evacuation drills (71%). Because the post-drill survey was voluntary, some participants opted out of the responses, which resulted in a small number of respondents ($n = 31$). Thus, there was not enough data to do a statistical assessment of the participants' responses; however, we were fortunate to gather enough information to illustrate the important usefulness of utilizing on-the-ground participant information. It indicated opportunities for route signage improvement, evacuation behavior, and the importance of the drill as an outreach and educational program.

5 Conclusion

This research organized tsunami evacuation drills across heterogeneous evacuees in a coastal city in the Cascadia Subduction Zone and could serve as a tsunami evacuation drill template/model/framework for preparedness improvement. This study also provided evidence of tsunami evacuation behaviors by using a spatial trajectory dataset collected by GNSS embedded mobile devices. The results include the following:

1. In general, the walking speed has a distribution with a mean of 1.58 m/s and a std. of 0.62 during the evacuation. An evacuation walking speed function, using Log-normal distribution, was created based on the empirical data to describe the probability of mean walking speed (Sect. 4.1). This function can be used to inform the individual's average walking speed for tsunami evacuation modeling studies.
2. The Evacuation Hiking Function was built based on Tobler's Hiking Function with three estimated parameters to model the relationship between the walking speed and the slope in evacuation drills. This function can also be applied to evacuation modeling studies such as calculating cost-distance.
3. The evacuation walking speed is negatively associated with slope (Sect. 4.2), time spent during evacuation, rough terrain surface, walking at night, and distance to destination (Sect. 4.4). Participants who evacuated from the Bay to SHH (Sect. 4.4) and REU students (younger age group) were found to move faster than others (Sects. 4.4 and 4.1).
4. 10–15 min is a critical milling time for people to evacuate in this community (Sect. 4.5).

The feedback from participants indicated the evacuation drill could potentially serve as an effective educational activity to discover the preparedness gaps for both participants and emergency planners. Overall, the results from this study can be used for public education, evacuation plan assessment, and supporting evacuation simulation or models. Results from this study indicate that involving local participants in tsunami drills would enhance our scientific modeling endeavors, increase local preparedness knowledge, and enhance the role of agency, thereby contributing to a culture of preparedness and, ultimately, community resilience (Cramer et al. 2018).

6 Limitations, future work, and recommendations

Participants in the drills are not exposed to the same level of stress that evacuees experience in a real event, so the walking speed observed in this exercise should not be assumed to be higher than that in a real evacuation (Schadschneider et al. 2011). In other words, people may receive more motivation (from the environment, peers, or themselves) to move faster in a real event. Future studies can develop a calibration factor between the speed in real evacuations and evacuation drills. For example, one can record the walking speed in real events and the walking speed in drills from the same community, and measure the difference between the two walking speeds as a calibration factor. The factor may be generalized to guide simulation for other communities. Human evacuation performance could also be impacted by topological and geological difference between communities. For example, lower-lying communities with large flat areas require evacuees to walk further in distance to reach safe zones. Researchers or local emergency managers may organize drills in their own towns/cities to better achieve the education and assessment purposes.

Due to the long time input for participants to finish the whole drill process, which typically requires half to one day, randomly inviting local residents to participate could result in a demographic representativeness bias. For example, retired seniors are more likely to participate than others because of time availability. Therefore, this study proactively invited participants with various demographics and knowledge backgrounds to mitigate the representativeness issue. Our results were built on the diversity of the volunteer participants who represent a range of age, gender, and other demographics, such as college students, teachers, and government personnel. However, some biases, still, can be generated from the invitation sampling process rather than a random process. Future work can either (1) provide demographic information to explain how a sample represents a population; or (2) choose a random sampling method and at the same time simplify or shorten the drill process to reduce the time requirement for participants.

Further research can also investigate the mobile phone GNSS signal issue. Given the exploratory nature of these drills, we used participants' owned devices to record evacuation trajectories. Within the 87 cases from participants who submitted Strava data, 13 were either corrupted or incompleted due to the weak signal or device dysfunction, therefore were deleted from the dataset. Future research can provide other types of devices to mitigate this issue.

Another limitation involves the survey and basic registration. Participants were encouraged to take an online survey after the evacuation drill, but the demographic information was voluntary, with some participants opting out of such responses. As noted above, the drill portion of this study was utilized primarily to ground-truth the process and the evacuation models. We were fortunate to gather enough information to illustrate the important usefulness of utilizing on-the-ground participant information; however, there was not enough survey data to do a comprehensive assessment of the participants. Future research can also collect demographic, knowledge, and physical information (weight, height, and general health levels) at the pre-registration site. Such information may also affect the walking speed in the evacuation drills. Future work can also divide the impact factors to more categories for regression analysis and examine the further impact of each category. For example, while terrain in this study is dichotomized to natural/paved surfaces, future study can divide the terrain to multiple categories such as the example in Schmidtlein and Wood (2015).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-022-05208-y.

Acknowledgments The authors would like to acknowledge the funding support from the Oregon Sea Grant program #NA140AR4170064 and the National Science Foundation through grants: #1563618, #1826407, #1902888, #1952792, #2044098 #2052930, and #2103713. Any opinions, findings, and conclusion or recommendations expressed in this research are those of the authors and do not necessarily reflect the view of the funding agencies. The authors are also grateful to the generous support and collaborations from Oregon Parks and Recreation Department, the Hatfield Marine Science Center (HMSC) to conduct the drills at the South Beach State Park, Newport, OR and use the HMSC facility for the night drills. We are also thankful to each and every drill participant for their contributions in particular the group of local junior high school students, their participation has provided a great example on how K-12 students' risk perceptions can be changed through evacuation drills.

Declarations

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval This project was approved by the Oregon State University Human Research Protection Program (HRPP) and Institutional Review Board (IRB) and follows the regulations to protect participants, with projects reference number 6779 and 7349.

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