DISASTER MITIGATION

International Journal
Sustainable Future for Human Security
J-SustaiN Vol. 7 No. 2 (2020) 24-34
http://www.j-sustain.com

# *Improving the Evacuation Plan of Coastal Communities using Tsunami Evacuation Simulations: Case Study from Tagajyo, Japan*

**Tomoyuki Takabatake[a*], Tomoya Shibayama[a]**

*[a]Department of Civil and Environmental Engineering, Waseda University, 60-150, 3-4-1 Okubo, Shinjuku-ku, Tokyo, Japan*

*Received: April 21, 2020 / Accepted: July 28, 2020*

## *Abstract*

An evacuation simulation is a helpful tool to evaluate the effectiveness of various countermeasures. To showcase its effectiveness and importance, the present study applied the authors' agent-based tsunami evacuation simulation model to investigate the effectiveness of tsunami countermeasures (i.e., early evacuation, restricting car usage, and combination of these two measures) in an area that was affected by the *2011 Tohoku Earthquake and Tsunami* (namely that of Tagajyo, Japan). As a result, it was found that restricting residents' car usage would be a more effective countermeasure compared with simply encouraging people to immediately start evacuation after feeling the earthquake, which was found to be somewhat ineffective. However, if early evacuation were combined with restricted car use, the risk of residents being hit by a devastating tsunami would be significantly lower. The scenario results, therefore, highlighted the importance of tsunami evacuation simulations in formulating effective evacuation and reconstruction plans for coastal communities. Given the estimated return periods of a devastating tsunami, it is natural to assume that the tsunami-affected areas will gradually change; therefore, to ensure continued community resilience, it is imperative that simulation results be updated according to changes made in the urban landscape of the target city.

**Keywords:** *agent-based approach; tsunamis; evacuation; coastal resilience; reconstruction plan.*

*Corresponding Author*
*Tel.: +81-3-5286-2946; Fax.: +81-3-5286-8296; E-mail: takabatake@aoni.waseda.jp*

*Abbreviations:*

| | |
|---|---|
| L1, L2 tsunami | Level 1, Level 2 tsunami |

## 1. Introduction

Tsunamis are one of the most destructive types of natural disasters, with recent tsunami events such as the *2004 Indian Ocean Tsunami,* the *2011 Tohoku Earthquake and Tsunami*, the *2018 Sulawesi Tsunami* and the *2018 Sunda Strait Tsunami* exemplifying the type of devastation they can cause to coastal communities ([1][2][3][4]). The *2011 Tohoku Earthquake and Tsunami* resulted in massive damage to the eastern coastline of Japan (especially, the Tohoku region) and caused over 18,000 dead or missing [5]. Following this event, a new concept for the classification of tsunami events was proposed in Japan [6]. Tsunamis that occur from every few decades to 100 years and are typically only several meters in height are defined as Level 1 (L1) events, which require the construction hard measures such as breakwaters, levees and seawalls to protect lives and properties. Less frequent (with a return period of more than several hundreds to a thousand year) but significantly higher (typically, over 10 m) tsunamis are defined as Level 2 (L2) events. As it is difficult to protect coastal areas from L2 tsunamis using only hard measures, to reduce damage as much as possible, multiple countermeasures are implemented (combining hard and soft measures, such as land use regulations and evacuation plans).

Based on this classification, tsunami-affected municipalities have developed their own reconstruction plans. Essentially, through a tsunami numerical simulation technique, they first investigate the expected extent of inundation from future L2 tsunamis after considering the effects of newly constructed coastal defenses that could protect them from L1 tsunamis. Many municipalities in areas wherein L2 tsunami simulations have indicated that the inundation depths would exceed 2 m restricted the construction of residential houses and other buildings [7]. A report published by [8] analyzed the reconstruction plans in each of the tsunami-affected municipalities, finding that in most residential areas that would suffer from inundation levels higher than 2 m, it had been decided to relocate to higher ground or to raise the ground level. However, in residential areas with inundation depths lower than 2 m, new coastal defenses were to be constructed and on-site reconstruction adopted, thereby allowing the residents to remain in their original locations. The reasoning behind the "2 m" limit was due to the fact that many of the wooden houses had not been completely washed away when the inundation depths were lower than this height [7]. Although this implies that residents living in the under 2 m inundation zones might be able to save their lives if they were on the second floor or above in a sturdy building, it should nevertheless be noted that tsunami simulation results contain uncertainty, as they were based on several assumptions [9]. Further, the effects of the debris displaced from the seaside areas on the coastal structures that were built inland to prevent tsunami water intrusion were generally not considered. For example, in some coastal areas affected by the *2011 Tohoku Earthquake and Tsunami*, a huge amount of debris, including containers, trees, and vehicles, was pushed inland, causing significant damage to physical structures [10,11]. It has been reported that if tsunami flows include debris, the resulting tsunami plus debris forces are greater than the tsunami forces alone [12-14]. This suggested that some coastal defenses might receive larger forces than expected and could be partially broken, resulting in the tsunami entering the city. Therefore, proper evacuation procedures still play an integral role in saving lives from future L2 tsunamis.

The importance of proper evacuation procedures during a significant tsunami event have been widely recognized. Many coastal communities have been attempting to develop effective evacuation plans and increasing the residents' level of tsunami awareness and preparedness through repeated tsunami evacuation drills and disaster education programs. To help residents become more aware of the importance of these programs and activities and to further strengthen the resilience of coastal communities, it is important to quantitatively determine the degree to which proper knowledge and evacuation behavior can decrease the risks of being caught by a tsunami. An agent-based tsunami evacuation simulation can be used as a powerful approach to quantitatively evaluate the effectiveness of proposed countermeasures, as it can consider a variety of evacuation behavior in detail.

Generally speaking, using a car for tsunami evacuation would cause severe congestion on an evacuation road, and thus it is often considered to be inappropriate. A number of researchers have evaluated the effectiveness of restricting car usage using computer simulations [15-22]. However, only a few studies [20-22] have utilized an agent-based approach, which is believed to be the most effective approach as it can consider a variety of possible evacuation behavior by evacuees, to investigate it. This suggests that performing further simulations, in which the detailed evacuation behavior of pedestrian and car evacuees is considered, is necessary in order to understand the effects of car usage during tsunami evacuation. Especially, although it would be important to investigate the effectiveness of restricting car usage in a coastal area that was affected by *2011 Tohoku Earthquake and Tsunami*, few studies have focused on it.

Previously, the authors had developed an agent-based tsunami evacuation simulation model and simulated the effectiveness of various tsunami countermeasures [23-27]. In the model, a road network, composed of node points and connected links, is used to define the movement of agents. Agents are programmed to move along the links with a defined speed, and whenever they reach a node, they choose which link they will take next. Results of tsunami inundation simulations, which are based on non-linear shallow water equations, are incorporated into the evacuation simulation model. Thus, the number of casualties resulting from a tsunami can be calculated. [23] defined two different types of agents (local residents and visitors) in the model and applied it to simulate the effects of the presence of visitors on total evacuation time in Kamakura City, Japan. In [24], the different questionnaire surveys on evacuation behavior of local residents and visitors were used to express their evacuation behavior more realistically. [25] improved the model of [24] to consider the effects of several countermeasures (e.g. implementing evacuation warnings, evacuation signs), and investigated the effectiveness of them in Kamakura City. [26] applied the model of [23-25] to a coastal city in Vancouver Island (Tofino), and simulated evacuation behavior there. [27] significantly improved the model of [23-25] to consider the detailed behavior of car evacuees. In [27], the model was confirmed to be able to simulate the car congestion which had actually occurred in Tagajyo City, Japan during *2011 Tohoku Earthquake and Tsunami*, relatively well. The present study extends the work of [27] to investigate how proper evacuation behavior during a tsunami event (especially the effects of restricting car usage) would decrease the risks of residents being caught by a tsunami in the same study area (Tagajyo City). Through the case study, the authors aim to demonstrate the importance and effectiveness of tsunami evacuation simulations in improving an evacuation plan for tsunami-affected areas.

In the following section, the recent progress in agent-based tsunami evacuation is introduced. Section 3 explains about the study area, evacuation modelling approach, numerical conditions, simulated scenarios, and the obtained results. Section 4 discusses important implications of the present study, limitations and future perspectives on tsunami evacuation simulations. Finally, the conclusions will be outlined in Section 5.

## 2. Recent Progress in Agent-based Evacuation Simulations

Although simulating overland inundation resulting from a future L2 tsunami is crucial to formulate a reconstruction plan, evacuation simulations, which can investigate the potential number of casualties that arise from the tsunami and associated evacuation problems, is also an essential step to achieve a tsunami-resilient community. Although other approaches (e.g. GIS approach [28,29]) have been proposed to simulate the behavior of evacuees during an emergency, an agent-based modeling approach appears to be most suitable, as it is able to simulate a variety of complex behaviors and interactions between evacuees realistically [30]. In agent-based approaches, each individual agent is modeled as a decision-making entity that decides on its own movements (e.g., where to evacuate, when to start evacuating, and even changes its choice of route and evacuation speed) [31]. By aggregating each agent's behavior, it is possible to obtain an overall picture of the evacuation process from the interactions between the individual agents.

To date, agent-based modelling approaches have been applied to simulate evacuation process in a variety of emergency situations. For instance, there are a number of studies that have simulated crowd evacuation from a building in the event of fire or earthquake using an agent-based modelling approach [32-39]. Complicated interactions between individual evacuees, such as the exchange of information [33], competitive, queuing, and herding behavior [34] have increasingly been considered in the simulation models. The effects of the environment around evacuees, such as floor layout or damage to the rooms due to an earthquake, on their evacuation behavior, have also been incorporated by some researchers [36,38]. The use of an agent-based approach can also be found in evacuation from river flooding or hurricanes [31,40-44]. In these cases, as the time and length for evacuation are generally longer, evacuees would more likely use a vehicle for evacuation. Thus, a simulation model that considers traffic flow is used to analyze the crowd evacuation from such events [40]. In fact, many of the traffic simulators, mainly used in a transportation engineering field, have adopted an agent-based approach, as shown in [45-48]. To more realistically simulate evacuation behavior in the case of flooding, [31] proposed a simulation model that considers the dynamic response of evacuees to flooding inundation. Recently, the impact of social media and exchange in warning information between neighbors on a total evacuation process has also been investigated by [42,43].

According to [49], one of the first applications of an agent-based tsunami evacuation can be found in [50], which simulated the evacuations from the Okushiri Island's Aonae District in Japan during the *1993 Hokkaido Earthquake*. However, following the *2011 Tohoku Earthquake and Tsunami*, there was a significant increase in the number of studies aiming to simulate tsunami evacuation processes. As observation data and actual survivor evacuation testimonies were partially available after the event, some researchers used tsunami evacuation simulation models to reproduce actual tsunami evacuations [27,51-55]. Especially, [27, 53-55] incorporated the effects of evacuation by car into their simulation model, from which it was found that the models were able to partially reproduce the road congestion observed during the event.

An agent-based tsunami evacuation model has also been applied to assess the potential casualties and problems in a given coastal area [21-27,58-62]. As there is always a certain amount of uncertainty in people's evacuation behavior, [21-23] investigated the impact of evacuation behavior changes on the mortality rate to properly understand the tsunami risks in their specific study area. In contrast, [24] sought to conduct a more realistic tsunami evacuation simulation by utilizing the results of questionnaire surveys about the people's tsunami awareness and preparedness at the time of the tsunami. It is also possible to evaluate the effectiveness of countermeasures in reducing mortality rates using an agent-based tsunami evacuation simulation model. For example, the effects of early evacuation measures on lower tsunami mortality rate were investigated by [59-62]. References [61,62] also investigated the effects of hard measures (elevating the height of a seawall). As alternative agent-based tsunami evacuation applications, [57,58,63] proposed approaches to prioritize road relocations or to optimize the location of evacuation places and routes. [64] made efforts to increase the calculation speeds in a simulation using a parallelization technique.

## 3. Tsunami Evacuation Simulation in Tagajyo, Miyagi Prefecture, Japan

### 3.1 Study Area

Tagajyo, Miyagi Prefecture, Japan, a city of 62,000 residents, was selected as the study area (Figure 1). Tagajyo City [10] reported that during the *2011 Tohoku Earthquake and Tsunami*, more than one-third of the municipal area (approx. 6.62 km$^2$) was inundated, with the maximum inundation depth being 4.6 m, and that 188 people died (though 64 of these were not residents). Historically, this city also suffered significant damage during the *869 Jogan Earthquake and Tsunami*. Tagajyo is close to Sendai, the capital of Miyagi Prefecture, has a large port (Sendai Port), and is the largest industrial city in the Tohoku region. The most significant problem during the 2011 tsunami evacuation was the severe traffic jams, with many survivors claiming that due to there being major traffic jams on the main city roads immediately after the earthquake, many people were caught by the tsunami while stuck in traffic [65,66]. The authors previously simulated the city evacuation process using their tsunami evacuation simulation model and partially succeeded in reproducing the locations where car congestion took place [27]. Therefore, in the present study, the previous model was extended to investigate how an improvement in resident evacuation behavior could decrease tsunami risks.

Following the massive tsunami damage, after discussions with the residents and workers, the Tagajyo City government decided to reconstruct the city in its original location rather than relocating to higher ground or raising the ground level. However, the government also decided to construct multiple new coastal defenses, such as a seawall and a coastal dyke (shown in Figure 1), so that the expected inundation depths from an L2 tsunami would be less than 2 m inside the city. The reconstruction plan also stressed the importance of proper evacuation procedures during L2 tsunamis, by stating that they would endeavor to keep conveying the lessons learned from the disaster to younger generations and implement disaster education programs to strengthen resident disaster awareness and preparedness.


**Figure 1** Map of Tagajyo City, showing the multiple defenses that are under construction: the red line indicates the seawall location, the yellow dashed line shows the coastal dykes, and the black dotted line the land elevation and coastal forests. The red colored area shows the expected inundation from a L2 tsunami. This information was obtained from [11]. The rectangular area surrounded by orange dots shows the extent of the evacuation simulations. Five orange squares indicate the locations of evacuation places used in the evacuation simulations described in the present study.

### 3.2 Modeling the Evacuation Behavior of Pedestrian and Car Evacuees

The tsunami evacuation simulation model used in the present study is developed based on a well-known agent-based modelling platform, *Artisoc 4.0* ([67]). As a variety of functions, which are helpful for users to express complex evacuation behavior, is available in it, many researchers (especially in Japan) have used this platform to construct their agent-based evacuation models [68,69].

As severe car congestion was observed in the study area during the 2011 event, it was important to model both the car and pedestrian evacuation behaviors. Therefore, the authors' simulation model for the study area expressed these two behaviors in different ways. For instance, as it was assumed that pedestrian evacuees would go to the closest evacuation place using the shortest route, the simulation model adopted a Dijkstra algorithm [70] to calculate the shortest route from each initial evacuee's location to the evacuation place. In contrast, considering the tendency that a car evacuee would prefer to take a wider road during evacuation [71], the modified Dijkstra algorithm, which was originally proposed by [72] and can consider the preference of car evacuees to choose wider roads, was adopted for the route choice of a car evacuee. While the general Dijkstra algorithm calculates the shortest route by simply using the length of each road, the modified Dijkstra algorithm calculates "the cost" of each route using evacuee preference information based on road width and length. More specifically, when the road width is narrower than the car evacuee preference, the original length is used to calculate the road cost. However, when it is wider than the preferred width, the length of the road is reduced using a reduction factor, which can also be determined in the model, with the reduced length being used to determine the road cost. As it was possible to obtain the costs for each road using this procedure, the route with the "lowest cost" from the initial car evacuee location to the evacuation place was obtained. It was also assumed that each car evacuee would take the lowest cost route to go to the evacuation places, and when there were more than two evacuation places, they were assumed to go to the closest evacuation place based on "the cost". It should be noted that although in reality an evacuee would change his/her route when they encountered congestion, a possible change in evacuation route was not considered in the simulations.

Moving speed is also different between pedestrian and car evacuees. The moving speed of a pedestrian is known to be influenced mainly by the age of the pedestrian and the level of road congestion [73]. In the simulation model, it was defined to change according to the age of evacuees and the crowd density on the road, following the works of [51,54,71] (Figure 2). Obviously, infants cannot move at a speed of 1.19 m/s. However, in an emergent situation, they would be carried by their parents, which means that the moving speed of an infant would be equal to the evacuee who carries him/her. In the present simulations, as an infant is assumed to move together with older evacuees (<65 years of age), the authors set his/her moving speed to be equal to that of <65 years of age. It is also noted that the model considers the effects of the presence of vehicles on the moving speed of a pedestrian, when both the pedestrians and vehicles are on the same roads (i.e. there is no separation of road space for pedestrians and vehicles, something typical in many smaller Japanese roads, due to the absence of sidewalks). This influence was considered by counting one vehicle as ten evacuees when calculating the crowd density following [71].

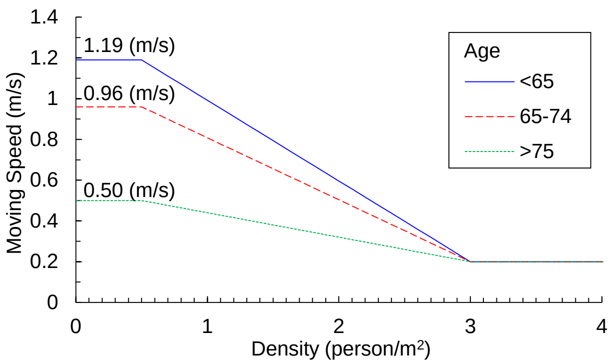


**Figure 2** Moving speed of pedestrian agents.

The moving speed of a car evacuee was defined by considering the other car evacuee in front. Namely, the idea of an Intelligent Driver Model (IDM) [74], expressed with the following equations, was adopted in the authors' simulation model.

$$\frac{dv_i(t)}{dt} = a\left\{1 - \left(\frac{v_i(t)}{v_{max}}\right)^4 - \left(\frac{DG}{\Delta x_i(t)}\right)^2\right\} \tag{1}$$

$$DG = s_0 + Tv_i(t) + \sqrt{\frac{v_i(t)\left(v_{i+1}(t) - v_i(t)\right)}{2\sqrt{ab}}} \qquad (2)$$

where $v_i(t)$, $v_{i+1}(t)$ are the moving speeds of the car and the other car in front of it at time $t$; $a$ is the maximum acceleration; $b$ is the maximum deceleration; $v_{max}$ is the desired maximum velocity; $DG$ is the desired gap between the car and the car in front; $\Delta x_i$ is the actual gap; $s_0$ is the minimum gap; and $T$ is the safe time headway. Here, $a$, $b$, $s_0$ and $T$ are constant values, which were determined based on [74], and $v_{max}$ is defined to change according to the width of a road (30 m/s for road width less than 3 m, 50 m/s for road width between 3 and 5.5 m, and 60 m/s for a road width greater than 5.5 m). In addition, when a car evacuee comes close to an intersection, it was defined to decrease its speed or stop according to the movement of other cars near the intersection (see [27] for further information). It should be noted that although the presence of pedestrians would also influence the moving speed of vehicles in a real situation, such effects were not considered in the present study.

## 3.3 Numerical Conditions

The numerical conditions used for the simulations were set based on the information of Tagajyo City before the *2011 Tohoku Earthquake and Tsunami*. The initial location of each evacuee was set based on the 2010 census data, in which the population distribution of residents is available. In addition, to consider the number of people working at the port area before the earthquake struck, the authors counted the number of cars that was parked at the port in a satellite image taken around 1 year before the event. In total, 13,450 evacuees were considered in the present simulation. The age distribution of agents was also determined from the 2010 census data as follows: 5% (Age 0–4), 10% (5–14), 65% (15–64), 11% (65–74), 9% (75–). Considering that many of the children would evacuate together with a parent, evacuees of age 0-4 and 5-14 were assumed to move together with older evacuees, who are initially located close to them.

The road network data of Tagajyo City, which was used as the possible routes that could be taken by evacuees, were obtained from [75]. The data provided is GIS data, and contains the information about the details of each road (e.g. length, width and type).

## 3.4 Simulated Scenarios

As explained earlier, the evacuation process in Tagajyo during the *2011 Tohoku Earthquake and Tsunami* had been previously simulated using the previously developed tsunami evacuation simulation model [27]. Therefore, the present study extended this work by investigating what would happen if the evacuees had displayed proper evacuation behaviors during the event, for which four different scenarios were considered, as shown in Table 1.

**Table 1** Summary of simulated scenarios

| Simulated scenarios | Evacuation start time | Car usage ratio |
|---|---|---|
| Scenario 1 (Baseline scenario) | Observed evacuation time | 56% (actual percentage) |
| Scenario 2 (Early Evacuation) | 5 min after the earthquake | 56% |
| Scenario 3 (Limiting car usage ratio) | Observed evacuation time | 0% |
| Scenario 4 (Early evacuation & Limiting car usage ratio) | 5 min after the earthquake | 0% |

The first scenario was a baseline scenario, which was based on the actual evacuation behavior in Tagajyo during the *2011 Tohoku Earthquake and Tsunami*. The results of a fact-finding survey [76] that summarized the actual evacuation times for 5,524 survivors over the entire tsunami-affected area were used to determine the evacuation start time in the baseline scenario. Namely, the authors expressed it using the Rayleigh distribution and mean evacuation start time among 5,524 survivors (22 min). The car usage ratio was also set based on this fact-finding survey. As more than half the evacuees (55%) in the entire tsunami-affected area evacuated by car, the baseline scenario assumed this same percentage. It was assumed that when evacuees are initially located in a residential area, three people would ride one car. In contrast, when they are initially located near the industrial area (near Sendai port in Figure 1), one person is assumed to ride each car.

The second scenario assumed an early start of evacuation for all evacuees. Therefore, in this scenario, all evacuees were assumed to understand the importance of early evacuation and start evacuation within 5 minutes after the earthquake. The value of 5 minutes was determined according to [77], which is a guideline for an effective tsunami evacuation plan, and recommends to set the start time for evacuation to be 2 - 5 min when investigating a city's tsunami evacuation plan with a computer simulation. To focus on the assessment of the effectiveness of such an early evacuation, other numerical conditions such as the car usage ratio remained the same as in the baseline scenario. The third scenario assumed an evacuation start time based on the results of the fact-finding survey (i.e., the same as the baseline scenario) and reduced the car usage ratio under the assumption that residents knew that car usage would cause severe congestion and it would be better to avoid using vehicles for the evacuation. In the present study, to investigate the effects of minimizing the car usage ratio, it was assumed that nobody would use a vehicle to evacuate. The fourth scenario was a combination of the second and third scenarios; that is, all residents were assumed to start evacuating 5 min after the earthquake, with nobody using their vehicles to go to the evacuation places. By comparing the results of these four scenarios, it was possible to determine the effectiveness of the different evacuation behaviors in the study area.

As evacuation simulations incorporate some stochastic elements, even when running the same scenario, the results (total evacuation time in this case) changes slightly each time it is run. Thus, in the present study, the same scenario was repeated 20 times, and the averaged evacuation time for each scenario was obtained. In addition, using these 20 simulation repeats, the mean percentage of the population who finished their evacuation within 30 min and 60 min with 95% confidence intervals were also obtained.

## 3.5 Results

Figure 3 compares the snapshots of evacuation simulations for all the scenarios. These snapshots correspond to the results of the first run of 20 times repetitions for each scenario (snapshots are not significantly different among the same scenario, and thus the authors simply chose the result of the first run to display). In the present simulations, 5 locations were set as evacuation places (where evacuees go), considering the predicted extent of the inundation and actual evacuation places during the *2011 Tohoku Earthquake and Tsunami* (obtained from [76]). All of the 5 places are outside of the inundation area for the case of the *2011 Tohoku Earthquake and Tsunami* and located on higher ground. Some of the evacuees who are initially located inside the extent of the evacuation simulation domain (see Figure 1), might actually proceed to other evacuation places. However, as the tsunami hazard map published by Tagajyo City [78] instructs residents to go to higher grounds, the authors simply used these evacuation places for the simulations.

For the case of scenario 1 (baseline scenario), severe car congestion (many red colored car agents) happened along the roads connected to the evacuation places (see Figure 3(a)). Previously, the authors confirmed that this simulated car congestion reproduced well that which was actually observed in the study area in 2011. Severe car congestion was also found in the results of scenario 2 (early evacuation scenario). As all the evacuees started evacuation 5 min after the earthquake with 55% using a vehicle, the level of congestion is actually more severe 10 min after the earthquake than compared with scenario 1 (compare snapshots at 10 min of Figure 3(a) and (b)). This severe car congestion lasted more than 1 hour after the earthquake. For the case of Scenario 4, as all evacuees started evacuation 5 min after the earthquake on foot, more evacuees were found on the road than at 10 min after the earthquake in Scenario 3. However, almost all of them were also diminished from the map (indicated that they had


**Figure 3** Comparison of snapshots of tsunami evacuation simulations

finished their evacuation) 60 min after the earthquake in both scenarios.

Figure 4 shows the percentage of evacuees who completed their evacuation (i.e., reached the evacuation places) at time progresses. Table 2 shows the percentage of population who reached evacuation places within 30 min (and 60 min) after the earthquake with 95% confidence level. As shown, in Scenario 1 around 23% of evacuees had not completed their evacuation within 60 min of the earthquake due to the severe car congestion. Although more people reached evacuation places within 30 min in Scenario 2, 23% of the evacuees did not complete their evacuation within 60 min. When the car usage ratio was reduced (Scenario 3), the evacuees reached more quickly one of the evacuation places than in Scenario 1. If all evacuees started evacuating 5 min after the earthquake and no one used vehicles (Scenario 4), the evacuation time for all evacuees significantly reduced. For instance, 79.31 (±0.12)% had finished evacuating within 30 min of the earthquake, and 98.25 (±0.06)% within 60 min (see Table 2). As the city was inundated approximately 60 min after the *2011 Tohoku Earthquake and Tsunami*, Scenario 4 indicated that if people had evacuated promptly after they had felt the ground shaking and not used their vehicle for the evacuation, more than 98% of them would have survived the tsunami (with 95% confidence).

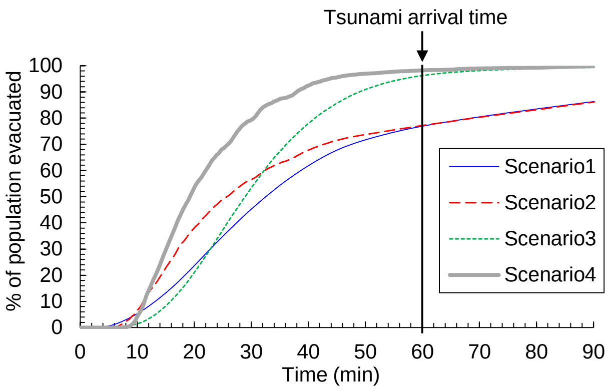


**Figure 4** Percentage of evacuees who reached evacuation places with respect to time. A vertical line shows the arrival time of the tsunami.

**Table 2** Summary of simulated results

| Simulated scenarios | % of population who reached evacuation places within 30 min after the earthquake (95% confidence level) | % of population who reached evacuation places within 60 min after the earthquake (95% confidence level) |
|---|---|---|
| Scenario 1 | 45.24% (±0.23%) | 76.92% (±0.37%) |
| Scenario 2 | 56.52% (±0.36%) | 77.18% (±0.43%) |
| Scenario 3 | 53.37% (±0.17%) | 96.23% (±0.09%) |
| Scenario 4 | 79.31% (±0.12%) | 98.25% (±0.06%) |

## 4. Discussion

Essentially, it is not easy to understand or evaluate the effectiveness of soft countermeasures (such as disaster education and evacuation plans) on tsunami risk mitigation. However, the present study showcases that there is a possibility to evaluate their effectiveness using a tsunami evacuation simulation model. The application of the authors' tsunami evacuation simulation model in this study found that restricting the car usage ratio in Tagajyo would be more effective than prompting everyone to evacuate early (at least if/when a L2 tsunami arrives to the city). Recently, many researchers have been reported higher level of awareness and preparedness about coastal disasters around the world [79-81]. Thus, it could be assumed that many people would start evacuating relatively early in case of a future earthquake and tsunami. However, the present study indicated that unless people stop using their vehicles to evacuate, the tsunami risks would not significantly decrease in the study area, which should be emphasized in the city's reconstruction plans. In contrast, if encouraging early evacuation is combined with restricting car usage the risks of residents being caught in a L2 tsunami were significantly reduced. This information could assist disaster risk managers to draft more effective evacuation plans as, based on the results, residents would become more aware of the areas where the car congestion would most likely occur and the importance of obeying the suggested evacuation procedures. Therefore, it could be concluded that tsunami evacuation simulations could be valuable disaster prevention educational tools. Although not investigated in the present study, as the expected inundation depth from future L2 tsunami would be less than 2 m in Tagajyo, guiding vulnerable people (e.g., elderly, disabled, and infants) to evacuate to the closest vertical evacuation place (i.e., tsunami shelter) might also be a promising type of countermeasure. Furthermore, tsunami evacuation simulations can be helpful in optimizing the locations of such vertical evacuation places (see [57]).

As tsunami evacuation simulations include uncertainties, it is important to perform a sensitivity analysis and to check how the simulated results would react to different parameter settings such as different moving speed of evacuees [26]. As it had already been confirmed that the simulation model can simulate the movement of car evacuees reasonably in the study area [27], it is more important to investigate the sensitivity of the results to the different moving speed of pedestrian evacuees. In the present study, the authors simply investigated the effects of decreasing and increasing the moving speed of pedestrian evacuees. To investigate the effects of slower moving speeds, 80% of the original moving speeds was used, while 120% of them was used for effects of faster moving speeds. The effects of changing moving speed were reflected by assuming that pedestrian evacuees would take 1.25 (=1/0.8) times longer to complete their evacuation for the slower moving speeds, and 0.83 (=1/1.2) for the faster moving speeds. Table 3 shows the calculated percentages of evacuees who finished their evacuation within 60 min after the earthquake for each scenario and moving speed. Overall, the simulated results did not vary significantly across the different pedestrian moving speeds. Thus, the results of the sensitivity analysis confirmed that the conclusions drawn in this study remain the same even if the effect of uncertainties on pedestrian moving speed are considered (i.e., restricting the car usage would be an effective countermeasure for the study area).

**Table 3** Percentages of population who reached evacuation places within 60 min after the earthquake for original slower and faster moving speeds of pedestrian evacuees

| Simulated scenarios | Original moving speeds of pedestrian evacuees | Slower moving speeds of pedestrian evacuees | Faster moving speeds of pedestrian evacuees |
|---|---|---|---|
| Scenario1 | 76.92% | 74.23% | 77.80% |
| Scenaro2 | 77.18% | 76.42% | 77.54% |
| Scenario3 | 96.23% | 89.14% | 98.34% |
| Scenario4 | 98.25% | 96.58% | 98.99% |

However, there were some limitations to these results of the tsunami evacuation simulations. The authors acknowledge that the dynamic decisions about route changes that evacuees might make were not considered in the present simulation model. For instance, a car driver might change their route when encountering severe car congestion; however, this behavior was not considered in this study. The effects of road blockages on evacuation behavior were also not considered. Earthquakes that cause severe ground shaking often result in building collapses, road liquefactions, and fires [82]. Therefore, future studies could also investigate the impacts of such road blockages on evacuation efficiency.

Another important limitation regarded the validation of the results using the tsunami evacuation simulation model. To the authors' knowledge, no existing tsunami evacuation simulation model has been perfectly validated. Essentially, as it has been almost impossible to collect the actual evacuation behaviors of all evacuees during the tsunami event, there is not enough available data for a comprehensive validation [49]. Therefore, disaster risk managers and residents should view the simulated results as a "good estimate" rather than an "exact estimate." In that sense, it is important to conduct tsunami drills based on the simulated results to confirm the effectiveness of the countermeasures in the field (though it is difficult to perfectly confirm such effectiveness, as almost all of the residents would need to participate in the evacuation drill to do so).

To increase the resilience of coastal communities, it is important to update tsunami evacuation simulations at regular intervals. Generally, over time, the population, age distributions, and city layouts change in a given area; therefore, it is necessary to conduct tsunami simulations using updated city information to confirm the effectiveness of the countermeasures and to communicate the results to residents. If a coastal area receives a certain number of visitors, modeling visitor behavior, which appears to be different from that of residents [83,84], is also necessary.

## 5. Conclusions

This study applied the authors' agent-based tsunami evacuation simulation model to investigate the effectiveness of tsunami countermeasures (i.e., early evacuation, restricting car usage, and combination of these two measures) in an area that was affected by the *2011 Tohoku Earthquake and Tsunami*. It was found that restricting residents' car usage would significantly decrease the risks of people encountering a L2 tsunami. If early evacuation were combined with restricted car use, the risk of residents being hit by the following L2 tsunami would be further reduced.

The scenario results highlighted the importance and effectiveness of tsunami evacuation simulations in constructing effective evacuation and reconstruction plans of coastal communities. However, as tsunami evacuation simulations have started to be actively studied since the *2011 Tohoku Earthquake and Tsunami*, all tsunami evacuation behaviors have not yet been perfectly modeled, and therefore, further studies are needed to improve the simulation models. Given the estimated return periods for L2 tsunamis, it is natural to assume that the areas that could potentially be affected by tsunamis would gradually change. Therefore, to ensure that the resilience of a community gradually improves over time it is imperative that the simulation results are updated according to changes in the target city to ensure its long-term sustainable development.

## Acknowledgements

This research was supported by Japan Science and technology Agency (JST) as part of the Belmont Forum Grant Number JPMJBF2005, and the JSPS KAKENHI Grant Number JP1915104. The present work was performed as a part of activities of Research Institute of Sustainable Future Society, Waseda Research Institute for Science and Engineering, Waseda University.

## References

[1] Mori N, Takahashi T, The 2011 Tohoku Earthquake Tsunami Joint Survey Group, Nationwide post event survey and analysis of the 2011 Tohoku Earthquake Tsunami. *Coast Eng. J.* 2012; **54**(1):1250001 (27 pages).

[2] Mikami T, Shibayama T, Esteban M, Takabatake T, Nakamura R, Nishida Y, et al. Field survey of the 2018 Sulawesi Tsunami: inundation and run-up heights and damage to coastal communities. *Pure and Applied Geophysics* 2019; **176**(8):3291-3304. https://doi.org/10.1007/s00024-019-02258-5

[3] Stolle J, Krautwald C, Robertson I, Achiari H, Mikami T, Nakamura R, et al. Engineering lessons from the 28 September 2018 Indonesian Tsunami: debris loading. *Canadian Journal of Civil Engineering* 2020; **47**(1):1-12. https://doi.org/10.1139/cjce-2019-0049

[4] Takabatake T, Shibayama T, Esteban M, Achiari H, Nurismanc N, Gelfi M, et al. Field survey and evacuation behaviour during the 2018 Sunda Strait Tsunami, *Coastal Engineering Journal* 2019; **61**(4):423–443. https://doi.org/10.1080/21664250.2019.1647963

[5] National Police Agency of Japan. Damage report of 2011 Tohoku Earthquake and Tsunami, 2020.

https://www.npa.go.jp/news/other/earthquake2011/pdf/higaijokyo.pdf. Accessed 29 March 2020.

[6] Central Disaster Prevention Council, Technical Investigation Committee. Report of the committee for technical investigation on countermeasures for earthquakes and tsunamis based on the lessons learned from the "2011 off the Pacific coast of Tohoku Earthquake", 2011. http://www.bousai.go.jp/kaigirep/chousakai/tohokukyokun/pdf/Report.pdf. Accessed 29 March 2020.

[7] Ubaura M. Changes in land use after the Great East Japan Earthquake and related issues of urban form. In: Santiago-Fandino V, Sato S, Maki N. Iuchi K. editors. *The 2011 Earthquake and Tsunami: Recostruction and Restoration -Insights and Assessment after 5 years-*, Switzerland: Springer International Publishing AG; 2018, p. 183–203.

[8] Ministry of Land, Infrastructure, Transport and Tourism (MLIT). A survey on approached to reconstruct tsunami-affected area (summary), 2012. https://www.mlit.go.jp/common/000209868.pdf. Accessed 29 March 2020.

[9] Takabatake T, St-Germain P, Nistor I, Stolle J, Shibayama T. Numerical modelling of coastal inundation from Cascadia Subduction Zone tsunamis and implications for coastal communities on western Vancouver Island, Canada, *Natural Hazards*, 2019; **98**:267-291. https://doi.org/10.1007/s11069-019-03614-3

[10] Tagajyo City. Reconstruction plan of Tagajyo City, 2011. http://www.city.tagajo.miyagi.jp/ganbaro/kurasi/daishinsai/torikumi/documents/sa-ke-index_keikaku.pdf. Accessed 29 March 2020.

[11] Naito C, Cercone C, Riggs HR, Cox D. Procedure for site assessment of the potential for tsunami debris impact. *J. Waterw. Port Coast. Ocean Eng.* 2014; **140**:223–232. doi:10.1061/(ASCE)WW.1943-5460.0000222

[12] Stolle J, Takabatake T, Mikami T, Shibayama T, Goseberg N, Nistor I, Petriu E. Experimental investigation of debris-induced loading in tsunami-like flood events. *Geosciences* 2017; **7**:74. https://doi.org/10.3390/geosciences7030074

[13] Mauti G, Stolle J, Takabatake T, Nistor I, Goseberg N, Mohammadian A. Experimental Investigation of Loading due to Debris Dams on Structures *J. Waterw. Port Coast. Ocean Eng.* 2020; **146**: 04020029. doi:10.1061/(ASCE)HY.1943-7900.0001731.

[14] Hamano G, Ishii H, Iimura K, Takabatake T, Stolle J, Esteban M, Shibayama T. Evaluation of force exerted by tetrapods displaced by tsunami on caisson breakwater return wall *Coast Eng. J.* 2020; **62**(2):170-181. https://doi.org/10.1080/21664250.2020.1723194

[15] Shimamoto H, Schmöcker J-D, Nagao, B, Nakamura T, Uno N, Yamazaki H. Evaluation of tsunami evacuation planning consideringvehicle usage and start timing of evacuation. *Transportmetrica A: Transport Science*, 2018; **14**(1-2):50-65. https://doi.org/10.1080/23249935.2017.1290708

[16] Wood N, Jones J, Peters J, Richards K. Pedestrian evacuation modeling to reduce vehicle use for distant tsunami evacuations in Hawai ʻi. *Int. J. Disaster Risk Reduct.* 2018; **28**:271-283.

[17] Fukuda T, Okushima M. Traffic simulation for evacuation planning at the outbreak of tsunami in local city. *Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management)* 2014; **70**(5):I_85-I_92. https://doi.org/10.2208/jscejipm.70.I_85

[18] Takei H, Okumura M. Risk of being caught by tsunami and traffic accident risk in vehicle-pedestrian mixed evacuation. *JSTE Journal of Traffic Engineering* 2018; **4**(1): A_129-A_137. https://doi.org/10.14954/jste.4.1_A_129

[19] Ando H, Kurauchi F, Sugiura S. Optimal facility investment design based on bimodal tsunami evacuation planning model. *Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management)* 2018; **74**(4): 306-319. https://doi.org/10.2208/jscejipm.74.306

[20] Fujiu M, Takada K, Nakayama S, Takayama J. Analysis of countermeasures for car evacuation against tsunami using traffic-micro simulation. *Journal of Japan Association for Earthquake Engineering* 2016; **16**(8): 8_135-8_144. https://doi.org/10.5610/jaee.16.8_135

[21] Wang H, Mostafizi A, Cramer LA, Cox D, Park H. An agent-based model of a multimodal near-field tsunami evacuation: Decision-making and life safety, Transportation Research Part C Emerging Technologies 2016; 64:86–100. doi: 10.1016/j.trc.2015.11.010.

[22] Mostafizi1 A, Wang1 H, Dong S. Understanding the multimodal evacuation behavior for a near-field tsunami, Transportation Research Record 2019; 2673:480-492. https://doi.org/10.1177/0361198119837511

[23] Takabatake T, Shibayama T, Esteban M, Ishii H, Hamano G. Simulated tsunami evacuation behavior of local residents and visitors in Kamakura, Japan. *International Journal of Disaster Risk Reduction*, 2017; **23**:1–14. https://doi.org/10.1016/j.ijdrr.2017.04.003

[24] Takabatake T, Shibayama T, Esteban M, Ishii H. Advanced casualty estimation based on tsunami evacuation intended behavior: case study at Yuigahama Beach, Kamakura, Japan. *Natural Hazards* 2018; **92**(3):1763-1788. https://doi.org/10.1007/s11069-018-3277-0.

[25] Takabatake T, Esteban M, Nistor I, Shibayama T, Nishizaki S. Effectiveness of hard and soft tsunami countermeasures on loss of life under different population scenario. *Int. J. Disaster Risk Reduct.*., 2020; **45**:101491. https://doi.org/10.1016/j.ijdrr.2020.101491

[26] Takabatake T, Nistor I, St-Germain P. Tsunami evacuation simulation for the District of Tofino, Vancouver Island, Canada. *Int. J. Disaster Risk Reduct.* 2020; 101573. https://doi.org/10.1016/j.ijdrr.2020.101573

[27] Takabatake T, Fujisawa K, Esteban M, Shibayama T. Simulated effectiveness of a car evacuation from a tsunami. *Int. J. Disaster Risk Reduct.*, 2020;101532. https://doi.org/10.1016/j.ijdrr.2020.101532

[28] Sugimoto T, Murakami, H, Kozuki, Y, Nishikawa, K. A human damage prediction method tsunami disasters incorporating evacuation activities. *Nat. Hazards* 2003; **29**(3):587–602, http://dx.doi.org/10.1023/A:1024779724065.

[29] Wood NJ, Schmidtlein, MC. Community variations in population exposure to near-field tsunami hazards as a function of pedestrian travel time to safety. *Nat. Hazards*, 2013; **65**(3):1603–1628. http://dx.doi.org/10.1007/s11069-012-0434-8.

[30] Na, HS, Banerjee, A. Agent-based discrete-event simulation model for no-notice natural disaster evacuation planning. *Computers & Industrial Engineering* 2019; **129**:44-55. https://doi.org/10.1016/j.cie.2019.01.022

[31] Dawson RJ, Peppe R, Wang M. An agent-based model for risk-based flood incident management. *Nat. Hazards* 2011; **59** (1):167–189. https://doi.org/10.1007/s11069-011-9745-4

[32] Owen M, Galea ER, Lawrence, PJ. The exodus evacuation model applied to building evacuation scenario. *J. Fire Prot. Eng.* 1996; **8** (2):65–86. https://doi.org/10.1177/104239159600800202

[33] Pelechano N, Badler N. Modeling crowd and trained leader behavior during building evacuation. *IEEE Computer Graphics*

*and Applications* 2006; **26**(6):80–86. https://doi.org/10.1109/MCG.2006.133

[34] Pan X, Han C, Dauber K, Law K. A multi-agent based framework for the simulation of human and social behavior during emergency evacuations. *AI Soc* 2007; **22**(2): 113-132.

[35] Löhner, R. On the modeling of pedestrian motion." Applied Mathematical Modelling. 2010; **34**(2):366–382. https://doi.org/10.1016/j.apm.2009.04.017

[36] Ha V, Lykotrafitis G. Agent-based modeling of a multi-room multi-floor building emergency evacuation. *Physica A: Statistical Mechanics and its Applications* 2012; 391:2740–2751. https://doi.org/10.1016/j.physa.2011.12.034

[37] Wagner N, Agrawal V. An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. *Expert Systems with Applications* 2014; **41**:2807–2815. http://dx.doi.org/10.1016/j.eswa.2013.10.013

[38] Liu Z, Jacques CC, Szyniszewski S, Guest JK, Schafer BW, Igusa, T, Mitrani-Reiser J. Agent-based simulation of building evacuation after an earthquake: coupling human behavior with structural response. *Nat. Hazards Rev.* 2016; 17(1):1-14. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000199

[39] Liu H, Liu B, Zhang H, Li L, Qin X, Zhang G. Crowd evacuation simulation approach based on navigation knowledge and two-layer control mechanism. *Information Sciences* 2018; **436–437**, 247–267. https://doi.org/10.1016/j.ins.2018.01.023

[40] Chen X, Zhan FB. Agent-based modelling and simulation of urban evacuation: relative effectiveness of simultaneous and staged evacuation strategies. *Journal of the Operational Research Society* 2008; **59**(1):25-33. https://doi.org/10.1057/palgrave.jors.2602321

[41] Liu Y, Okada N, Takeuchi Y. 2008. Dynamic route decision model -based multi-agent evacuation simulation- case study of Nagata Ward, Kobe. *Journal of Natural Disaster Science*, 2008; **28**(2):91–98. https://doi.org/10.2328/jnds.28.91

[42] Nagarajan M, Shaw D, Albores P. Disseminating a warning message to evacuate: A simulation study of the behaviour of neighbours. *European Journal of Operational Research*, 2012; **220**: 810–819. http://dx.doi.org/10.1016/j.ejor.2012.02.026

[43] Du E, Cai X, Sun Z, Minsker B. Exploring the role of social nedia and individual behaviors in flood evacuation processes: an agent-based modeling approach. *Water Resources Research* 2017; **53**:9164–9180. https://doi.org/10.1002/2017WR021192

[44] Du E, Rivera S, Cai X, Myers L, Ernest A, Minsker B. Impacts of human behavioral heterogeneity on the benefits of probablistic flood warnings: an agent-based modeling framework. *Journal of the American Water Resources Association* 2017; **53**(2):316-332. https://doi.org/10.1111/1752-1688.12475

[45] Lammel G, Grether D, Nagel K. The representation and implementation of time-dependent inundation in large-scale microscopic evacuation simulations. *Transp. Res. Part C* 2010; **18**:84–98. https://doi.org/10.1016/j.trc.2009.04.020

[46] Bradley M, Bowman JL, Griesenbeck B. SACSIM: an applied activity-based model system with fine-level spatial and temporal resolution. *J. Choice Modell*, 2010; **3**(1):5–31. https://doi.org/10.1016/S1755-5345(13)70027-7

[47] Pendyala RM, Kitamura R, Kikuchi A, Yomamoto T, Fujii S. Florida activity mobility simulator. *Transp. Res. Rec.* 2005; **1921**: 123–130.

[48] Stadtfeld C. NetSim: A Social Networks Simulation Tool in R., 2019. https://rdrr.io/rforge/NetSim/ Accessed 29 March 2020.

[49] Mas E, Koshimura S, Imamura F, Suppasri A, Muhari A, Adriano B. Recent advances in agent-based tsunami evacuation simulations: case studies in Indonesia, Thailand, Japan and Peru, *Pure Appl. Geophys.* 2015; **172**(12): 409–3424. http://dx.doi.org/10.1007/s00024-015-1105-y.

[50] Usuzawa H., Imamura F, Shuto N. Development of the method for evacuation numerical simulation for tsunami events. *Annual Meeting of the Tohoku Branch Technology Research Conference, Japan Society of Civil Engineers* 1997; 430–431. http://library.jsce.or.jp/jsce/open/00322/1997/1997-0430.pdf.

[51] Kumagai K. Validation of tsunami evacuation simulation to evacuation activity from the 2011 off the pacific coast of Tohoku earthquake tsunami. *Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management)*, 2014; 70(5):187–196. (in Japanese). https://doi.org/10.2208/jscejipm.70.I_187

[52] Mas E, Suppasri A, Imamura F, Koshimura S. Agent-based Simulation of the 2011 Great East Japan Earthquake/Tsunami Evacuation: An Integrated Model of Tsunami Inundation and Evacuation. *Journal of Natural Disaster Science*, 2012; 34(1):41–57. doi:10.2328/jnds.34.41.

[53] Makinoshima F, Imamura F, Abe Y. Development of tsunami evacuation simulation considering ped-car interaction-validation in the 2011 evacuation event at Kesennuma city-. *Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)* 2015; 71(2):1645–1650. (in Japanese). https://doi.org/10.2208/kaigan.71.I_1645

[54] Makinoshima F, Imamura F, Abe Y Behavior from tsunami recorded in the multimedia sources at Kesennuma City in the 2011 Tohoku tsunami and its simulation by using the evacuation model with pedestrian - car interaction. *Coastal Engineering Journal* 2016; **58**(4):1640023 (28 pages). doi:10.1142/S0578563416400234.

[55] Nishihata T, Moriya Y, Anno K, Imamura F. Modeling of car evacuation from tsunami attacking and evaluation for accompanied traffic jam. *Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)*, 2012; **68**(2):1316–1320. (in Japanese). https://doi.org/10.2208/kaigan.68.I_1316

[56] Di Mauro M, Megawati K, Cedillos V, Tucker B. Tsunami risk reduction for densely populated Southeast Asian cities: analysis of vehicular and pedestrian evacuation for the city of Padang, Indonesia, and assessment of interventions, *Nat. Hazards* 2013; **68**(2): 373–404, https://doi.org/10.1007

[57] Mostafizi A, Wang H, Cox D, Dong S. An agent-based vertical evacuation model for a near-field tsunami: choice behavior, logical shelter locations, and life safety, *Int. J. Disaster Risk Reduct.* 2019; **34**(3):467–479. https://doi.org/10.1016/j.ijdrr.2018.12.018.

[58] Mostafizi A, Wang H, Cox D, Cramer LA, Dong S. Agent-based tsunami evacuation modeling of unplanned network disruptions for evidence-driven resource allocation and retrofitting strategies, *Natural Hazards* 2017; **88**(3):1347-1372. https://doi.org/10.1007/s11069-017-2927-y

[59] Johnstone WM, Lence BJ. Assessing the value of mitigation strategies in reducing the impacts of rapid-onset, catastrophic floods, *J. Flood Risk Manag.* 2009; **2**(3):209–221. https://doi.org/10.1111/j.1753-318X.2009.01035.x.

[60] Johnstone WM, Lence BJ. Use of flood, loss, and evacuation models to assess exposure and improve a community tsunami response plan: Vancouver Island, *Nat. Hazards Rev.* 2012; **13**(2): 162–171. https://doi.org/10.1061/(ASCE)NH.1527- 6996.0000056.

[61] Koyanagi Y, Arikawa T. Study of the tsunami evacuation tower using the tsunami evacuation simulation, *J. Japan Society of Civil Eng, Ser. B2 (Coastal Engineering)* 2016; **72**(2):1567–1572, https://doi.org/10.2208/kaigan.72.I_1567 (in Japanese).

[62] Uno Y, Shigihara Y, Okayasu A. Development of crowd evacuation simulation for risk evaluation of human damage by

tsunami inundation, *J. Japan Society of Civil Eng, Ser. B2 (Coastal Engineering)* 2014; **71**(2):1615–1620, https://doi.org/10.2208/kaigan.71.I_1615 (in Japanese).

[63] Kitamura F, Inazu D, Ikeya T, Okayasu A. An allocating method of tsunami evacuation routes and refuges for minimizing expected casualties, *International Journal of Disaster Risk Reduction* 2020; **45**:101519. https://doi.org/10.1016/j.ijdrr.2020.101519

[64] Makinoshima F, Imamura F, Abe Y. Enhancing a tsunami evacuation simulation for a multi-scenario analysis using parallel computing, *Simulation Modelling Practice and Theory* 2018; **83**:36-50. https://doi.org/10.1016/j.simpat.2017.12.016

[65] NHK, Remembering 3.11 Great East Japan Earthquake Archive 2013, http://www9.nhk.or.jp/archives/311shogen/en/. Accessed 7 April 2020.

[66] Kahoku Shinpo, Retrospective 3.11 testimony -Sudden turbid flow attacking the main road-, 2017, https://www.kahoku.co.jp/special/spe1168/20170213_01.html Accessed 7 April 2020.

[67] KOZO KEIKAKU ENGINEERING Inc. artisoc4. https://mas.kke.co.jp/en/artisoc4/. Accsessed 29 March 2020.

[68] Kosaka Y, Nomura N, Oto A, Miyajima M. Analysis on tsunami evacuation by using multi agent system ~case study of Wajima district in Wajima City~, *J. Jpn. Soc. Civil Eng. Ser. A1 (Structural Engineering & Earthquake Engineering (SE/EE))* 2017; **73**(4):I_1010–I_1017, https://doi.org/10.2208/jscejseee.73.I_1010. (in Japanese).

[69] Jiang D, Murao O. Consideration of tsunami risk reduction effect focusing on tourists' evacuation time in Katase-Nishihama and Kugenuma district, Fujisawa city, *J. Soc. Saf. Sci.* 2017; **31**:117–124, https://doi.org/10.11314/jisss.31.117. (in Japanese).

[70] Dijkstra EW. A Note on Two Problems in Connection with Graphs, *Numerical Mathematik* 1959; **1**:269–271.

[71] Goto Y, Affan M, Nurdin YA, Yuliana DK, Ardiansyah. Tsunami evacuation simulation for disaster education and city planning, *J. Disaster Res.* **2012**; 7(1):92–101.

[72] Jacob S, Aguilar L, Wijerathne L, Hori M, Ichimura T, Tanaka S. Agent based modeling and simulation of tsunami triggered mass evacuation considering changes of environment due to earthquake and inundation, *Journal of Japan Society of Civil Engineers, Ser. A2 (Applied Mechanics (AM))*, 2014; **70**(2): I_671-I_680. https://doi.org/10.2208/jscejam.70.I_671

[73] Fraser SA, Wood NJ, Johnston DM, Leonard GS, Greening PD, Rossetto T. Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling, *Nat. Hazards Earth Syst. Sci.* 2014; **14**:2975–2991., https://doi.org/10.5194/nhess-14-2975-2014.

[74] Treiber M, Hennecke A., Helbing D. Congested Traffic States in Empirical Observations and Microscopic Simulations, *Phys. Rev. E* 2000; **62**:1805-1824. 10.1103/PhysRevE.62.1805.

[75] Geospatial Information Authority of Japan, Download service for data of basic map (Kiban Chizu), 2016. https://fgd.gsi.go.jp/download/menu.php. Accessed on 8 April 2020.

[76] Archive of the Recovery Support, 2012. http://fukkou.csis.u-tokyo.ac.jp/. Accessed on 15 May 2019.

[77] Fire and Disaster Management Agency. Report of the committee for the manual for promoting tsunami evacuation measures, 2013, 194p. (in Japanese)

[78] Tagajyo City. Tagajyo City Tsunami Hazard Map. 2018. http://www.city.tagajo.miyagi.jp/bosai/kurashi/bosai/bosai/documents/english_ver.pdf. Accessed on 18 June 2020.

[79] Takabatake T, Mäll M, Esteban M, Nakamura R, Kyaw TO, Ishii H, Valdez JJ, Nishida Y, Noya F, Shibayama T. Field Survey of 2018 Typhoon Jebi in Japan: Lessons for Disaster Risk Management, *Geosciences* 2018; **8**(11):412. https://doi.org/10.3390/geosciences8110412

[80] Harnantyari AS, Takabatake T, Esteban M, Valenzuela P, Nishida Y, Shibayama T, Achiari H, Rusli, Marzuki AG, Marzuki GFH, Aránguiz R, Kyaw TO. Tsunami awareness and evacuation behaviour during the 2018 Sulawesi Earthquake tsunami, *International Journal of Disaster Risk Reduction* 2020; **43**:101389. doi.org/10.1016/j.ijdrr.2019.101389

[81] Esteban M, Bricker J, Carlos Arce RS, Takagi H, Yun N, Chaiyapa W, Sjoegren A, Shibayama T. Tsunami awareness: a comparative assessment between Japan and the USA, *Natural Hazards* 2018; **93**(3):1507-1528. https://doi:10.1007/s11069-018-3365-1

[82] Horikawa N, Osaragi T. Earthquake disaster simulation system: integration of models for building collapse, road blockage, and fire spread, *J. Disaster Res.* 2016; **11**(2):175–187. https://doi.org/10.20965/jdr.2016.p0175.

[83] Carlos-Arce RS, Onuki M, Esteban M, Shibayama T. Risk awareness and intended tsunami evacuation behavior of international tourists in Kamakura City, Japan, *Int. J. Disaster Risk Reduct* 2017; **23**:178–192. https://doi.org/10.1016/j.ijdrr.2017.04.005.

[84] Yasuda T, Hatayama M, Shimada H. National questionnaire survey of surfers awareness about tsunami evacuation, *Safety Science Review* 2016; **2016**:61–80 (in Japanese).