Journal of Natural Disaster Science, Volume 34, Number 1, 2012, pp41-57

Agent-based Simulation of the 2011 Great East Japan Earthquake/Tsunami Evacuation: An Integrated Model of Tsunami Inundation and Evacuation

Erick MAS*
Anawat SUPPASRI*
Fumihiko IMAMURA*
Shunichi KOSHIMURA*

*International Research Institute of Disaster Science, Tohoku University, Japan

(Received March 31, 2012   Accepted July 12, 2012)

ABSTRACT

The 2011 Great East Japan Earthquake/Tsunami was a magnitude 9.0 Mw event that destroyed most structural tsunami countermeasures. However, approximately 90% of the estimated population at risk from the tsunami survived due to rapid evacuation to higher ground or inland. In this paper, we introduce an evacuation model integrated with a numerical simulation of a tsunami and a casualty estimation evaluation. The model was developed in Netlogo, a multi-agent programming language and modeling environment for simulating complex phenomena. GIS data are used as spatial input information for road and shelter locations. Tsunami departure curves are used as the start time for agents deciding to evacuate in the model. Pedestrians and car drivers decide their own goals and search for a suitable route through algorithms that are also used in the video game and artificial intelligence fields. Bottleneck identification, shelter demand, and casualty estimation are some of the applications of the simulator. A case study of the model is presented for the village of Arahama in the Sendai plain area of Miyagi Prefecture in Japan. A stochastic simulation with 1,000 repetitions of evacuation resulted in a mean of 82.1% (SD=3.0%) of the population evacuated, including a total average of 498 agents evacuating to a multi-story shelter. The results agree with the reported outcome of 90% evacuation and 520 sheltered evacuees in the event. The proposed model shows the capability of exploring individual parameters and outcomes. The model allows observation of the behavior of individuals in the complex process of tsunami evacuation. This tool is important for the future evaluation of evacuation feasibility and shelter demand analysis.

1. Introduction

Evacuation is the most important and effective method to save human lives during a tsunami (Shuto, 2005). An important factor in realistically simulating a major population evacuation during a tsunami is an accurate representation of the timing of people's responses to the emergency (Southworth, 1991). The timing of evacuee responses can have a significant effect on traffic congestion and bottlenecks during the evacuation procedure (Naser & Birst, 2010). It is of course desirable that people leave the danger area immediately after a natural or official warning is received. However, it is a fact that people sometimes are apparently irrational and do not evacuate even when the authorities suggest they should (Riad, Norris & Riback, 1999). Imamura (2009) suggests three steps that can lead to a safe evacuation during an earthquake and tsunami event: first, collecting information and issuing an official warning; second, making the decision to evacuate based on the risk perception and previous experience of the area residents; and third, selecting a proper route and a safe destination for the evacuees. Prior experience and the perception of risk will differ between people. In this study, a tsunami evacuation simulator was developed to explore the individual behavior of start time of evacuation, as well as to make casualty estimation and elucidate issues related to the process of evacuation in the case of tsunami. Tsunami modeling results are integrated into the model to estimate casualty conditions based on the hydrodynamic characteristics of tsunami. The agent-based approach allows for tracking the individual evacuation decision, route, and shelter.

2. The 2011 Great Japan Earthquake and Tsunami

2.1 Overall damage

Japan has experienced many earthquakes and tsunamis throughout its history, particularly along the Sanriku coast. Japan has therefore developed the world's best tsunami countermeasures and evacuation procedures. Before the 2011 event, the area of most concern to seismologists was Miyagi Prefecture, where the calculated probability of the expected Miyagi-oki earthquake occurring within 30 years with a magnitude of 7.5-8.0 Mw was estimated to be 99%, which was the highest earthquake probability in Japan. At 14:46 on March 11, 2011, a massive earthquake occurred offshore at N38.1, E142.9 at a depth of 24 km (JMA, 2011). The earthquake had a magnitude of 9.0 Mw and was followed by many aftershocks and a devastating tsunami. The earthquake was ranked as the fourth most powerful in the world, exceeded only by the 1960 Chile (9.5 Mw), 2004 Sumatra (9.3 Mw), and 1964 Alaska (9.2 Mw) earthquakes. The earthquake was of long duration (approximately 3 min) and the largest observed slip was of approximately 30 m (USGS, 2011). The maximum recorded earthquake intensity was 7, which is the maximum value on the Japanese intensity scale (JMA, 2011). The earthquake early warning system was activated 8 sec after detection of the first P-wave (JMA, 2011), while a tsunami warning was issued 3 min after the earthquake. The initial tsunami warning for Miyagi Prefecture, estimated a 6 m tsunami height; after 24 min, a second warning bulletin was issued increasing the tsunami height estimate to over 10 m (JMA, 2011). The tsunami reached the coastal village of Arahama approximately 1 hr after the earthquake. All told, the tsunami casualties numbered 19,212 dead and missing and more than 50,000 damaged houses and buildings (National Police Agency (NPA), 2012; Suppasri, Koshimura et al., 2012a).

2.2 Tsunami Evacuation

The Japan Meteorological Agency, the Fire and Disaster Management Agency, and the Cabinet Office of Japan conducted a joint survey of 870 evacuees at shelters in Iwate (391), Miyagi (385), and Fukushima (94) in July 2011 (Cabinet Office of Japan, 2011). The results showed that 57% of the interviewees evacuated immediately after the earthquake while 37% had delayed their evacuation. The two main reasons given for evacuation were the strong ground motion (48% of evacuees) and the advice to evacuate given by family members (20% of evacuees) or neighbors (15% of evacuees). Another survey conducted in Kamaishi and Natori Cities found that 60% of 113 interviewees in Kamaishi evacuated in less than 10 min, while in Natori, just 30% of 105 respondents escaped within 20 to 30 min. Based on tsunami waveform data recorded during the event (Hayashi, Tsushima, Hirata, Kimura & Maeda, 2011) and clocks observed in the field confirming the arrival time of waves (Muhari, Imamura, Suppasri & Mas, 2012; Suppasri, Mas et al., 2012b), the estimated tsunami arrival times in Kamaishi and Natori were approximately 30 min and 67 min, respectively (Yalciner et al., 2011). It was observed that a large number of evacuees from the coast left by car, especially from low-topography areas like the Sendai plain.

3. Tsunami Modeling

3.1 Tsunami source model

The tsunami source was modeled assuming an instantaneous displacement of the sea surface identical to the vertical sea floor displacement. Ten sub-fault segments based on the Tohoku University Source Model version 1.1 (Imamura et al., 2011) were used for the initial surface deformation (Fig. 1). The parameters are shown in Table 1.

3.2 Numerical model setup

The source model presented above was used to numerically simulate the tsunami entering the village of Arahama in the Sendai plain in Miyagi Prefecture. Tohoku University's Numerical Analysis Model for Investigation of Near-field Tsunamis (TUNAMI model) was used as the modeling tool (Imamura, 1995). A set of non-linear shallow water equations, (Eq. 1 to Eq. 3), were discretized by the staggered leap-frog finite difference scheme, with bottom friction expressed using Manning's formula and set to be constant across the whole domain.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0, \tag{1}$$

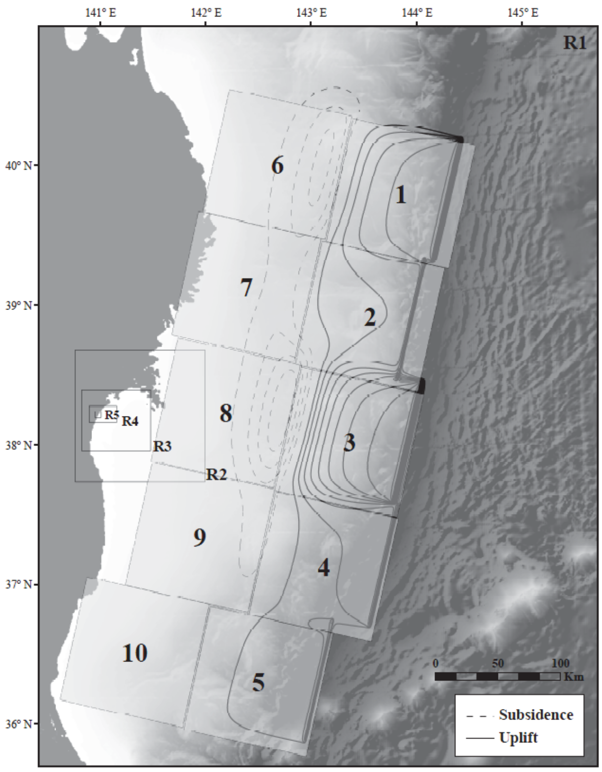

Figure 1 Tohoku University Tsunami Source Model version 1.1 of the 2011 Great East Japan Earthquake. The five regions show the nested grid setting for the numerical simulation.

Table 1 Dimension of the faults and tsunami source parameters for the 2011 Tohoku Earthquake

No.	Long (deg)	Lat (deg)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Length (km)	Width (km)	Slip (m)
1	144.507	40.168	1.0	193.0	14.0	81.0	100.0	100.0	20.00
2	144.200	39.300	1.0	193.0	14.0	81.0	100.0	100.0	10.00
3	143.939	38.424	1.0	193.0	14.0	81.0	100.0	100.0	35.00
4	143.682	37.547	1.0	193.0	14.0	81.0	100.0	100.0	10.00
5	143.070	36.730	1.0	193.0	14.0	81.0	100.0	100.0	7.50
6	143.394	40.367	24.2	193.0	14.0	81.0	100.0	100.0	1.00
7	143.100	39.496	24.2	193.0	14.0	81.0	100.0	100.0	3.00
8	142.853	38.620	24.2	193.0	14.0	81.0	100.0	100.0	4.00
9	142.609	37.744	24.2	193.0	14.0	81.0	100.0	100.0	2.00
10	142.009	36.926	24.2	193.0	14.0	81.0	100.0	100.0	2.00

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=$$
$$-gD\frac{\partial \eta}{\partial x}-\frac{gn^2}{D^{\frac{7}{3}}}M\sqrt{M^2+N^2}, \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=$$
$$-gD\frac{\partial \eta}{\partial y}-\frac{gn^2}{D^{\frac{7}{3}}}N\sqrt{M^2+N^2}. \tag{3}$$

Here:

$$M=\int_{-h}^{\eta} udz\,;\; N=\int_{-h}^{\eta} vdz\,;$$
$$D=\eta+h.$$

M and N are the discharge flux in the x and y directions, respectively, η is the water level, and h is the water depth above the mean sea level.

Bathymetric and topographic data were obtained from the Central Public Disaster Prevention Council of Japan. Grid sizes vary from 405 m, 135 m, 45 m, 15 m, and 5 m in five regions of a nested grid system as shown in Fig. 1.

4. Evacuation Modeling

Tsunami hydrodynamic models have significantly contributed to the scientific and engineering investigation of tsunamis. However, understanding social science and risk management is necessary for a complete modeling of the problem. Evacuation is probably the most important and effective method to save human lives (Shuto, 2005) and more emphasis has recently been put on social science in understanding tsunami mitigation. Thus, modeling tsunamis is part of modeling evacuation from a tsunami. However, human behavior is very complex and is the most difficult aspect of the evacuation process to simulate (Gwynne, Galea, Owen, Lawrence & Filippiddis, 1999). Human behavior includes complex problem solving (Gagne, Wager, Golas & Keller, 2004), and individual characteristics with both aspects are difficult to capture in mathematical equations (Pan, Han, Dauber & Law, 2007). In this study, we developed a tsunami evacuation model considering the outputs described above. The model of evacuation uses an "agent"-based approach. This means that the model assumes that there are thousands of individual agents who each have their own characteristics that follow simple rules in moving toward a few different goals.

4.1 Overview of the model

The model for tsunami evacuation was developed in Netlogo, a multi-agent programming language and modeling environment for simulating complex phenomena (Wilensky, 2001). Hundreds or thousands of agents can operate concurrently to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interactions. The model uses GIS data as spatial input and, if available, the population spatial distribution. Tsunami characteristics are introduced as raster files at each tsunami numerical time step during the simulation. Input parameters of scenario, model view, and outputs are observed during the simulation in real time. Outputs are exported into file reports. A snapshot of the model interface is shown in Figure 2.

4.2 Start time of evacuation

To realistically simulate a tsunami evacuation event, it is important to accurately represent the timing of responses to the emergency (Southworth, 1991; Suzuki & Imamura, 2005). The timing of evacuee responses can have a significant effect on traffic congestion and bottlenecks during an evacuation (Naser & Birst, 2010). Moreover, it is expected that human damage will decrease if there are more early evacuations (Sugimoto, Murakami, Kozuki & Nishikawa, 2003). Past simulation efforts on the evacuation of humans from tsunamis have considered timing using many approaches that have resulted in differing estimates of casualties and congestion points. Three main approaches to start time have been used in prior tsunami evacuation modeling work. The first approach is an "all together" evacuation based on scenarios where the entire study population starts evacuating a certain number of minutes, such as 0 min or 5 min, after the warning (Suzuki & Imamura, 2005; Sugimoto, Murakami, Kozuki & Nishikawa, 2003; Fujioka, Ishibashi, Kaji & Tsukagoshi, 2002; Ohhata, Kagami & Takai, 2005; Post et al., 2009; Meguro & Oda, 2005). However, such instantaneous group behavior has never been recorded in past events. In general, individuals from a large at-risk population never start their

Figure 2 Snapshot of the interface of the developed tsunami evacuation simulator. Parameter input panel (left), view screen (center), and output graphs (right) can be observed together during simulation.

evacuations at the same time due to individual decisions. The second approach is similar to the previous one, but fixed start times are assigned to groups or areas based on survey results (Imamura, Suzuki & Taniguchi, 2001; Saito & Kagami, 2005). This is a special case of the first approach where the whole population is divided into smaller groups and the average starting time of the group is obtained from questionnaires distributed in the area. Although this may lead to better approximations for the evacuation process of a large population, the use of one questionnaire result may not explain the complexity and uncertainty of human behavior or the initial spatial condition of the population. The third approach is a more sophisticated approach that introduces psychological parameters obtained from questionnaires and treats people individually with respect to displaying rational behavior (Sato, Kono, Koshimura, Yamaura & Imamura, 2008; Mas, Imamura & Koshimura, 2011). For this third approach, however, the definitions of parameters and values for the simulation are difficult to assess for a large population. In this paper, we will introduce a fourth approach modified from the emergency, urban, and traffic planning fields in which departure times are determined from sigmoid curves describing the population (Lindell & Prater, 2007).

4.3 Questionnaire surveys

Tsunami evacuation models often use data provided by questionnaire surveys to establish average evacuation start times or an estimated distribution of evacuation decision times. The need for these data is common to researchers and stakeholders, but conducting surveys and updating survey data usually faces budget and time constraints, leading to delayed decisions for new mitigation actions. According to Naser & Birst (2010), surveys that are designed to collect data describing actual travel or evacuee behavior are classified as Revealed Preference (RP) surveys, while hypothetical behavior in the future is obtained through Stated Preference (SP) surveys. Hence, RP surveys are related to past tsunami experiences, while SP surveys collect data on how the evacuee would respond to a hypothetical situation in the future. Both survey types attempt to obtain estimates of the human behavior during an emergency; however, the use of one questionnaire result may not explain the complexity and uncertainty of human behavior or the initial spatial condition of the population. Moreover, there is a frequent variation in the level of awareness and risk perception of individuals resulting from recent experience, public information, or education. As a result, previous estimations of evacuation times in past surveys may change in time. Changes could also arise because events have now been forgotten or there might now be more estimates (Tatano, 1999).

4.4 Tsunami evacuation departure times

To address the complexities and variabilities of human behavior and preferences regarding evacuation times, a set of distributions of departure times can be used to include all possible behaviors in the population. Such an approach requires a definition of suitable distribution parameters. Researchers developing state-of-the-art techniques for modeling evacuation departure times in large-scale events such as hurricanes or nuclear accidents have used sigmoid curves to describe the population load rate into the evacuation network (Lindell & Prater, 2007; Southworth, 1991; Tweedie, Rowland, Walsh, Rhoten & Hagle, 1986). In this work, we used several RP and SP surveys of tsunami evacuation and compared them with the theoretical Rayleigh distribution (Eq. 4), which is similar to the shape proposed by Tweedie, Rowland, Walsh, Rhoten & Hagle (1986) for regional evacuation in a hurricane.

$$F(t) = 1 - e^{-\frac{t^2}{2\sigma^2}}, \tag{4}$$

$$\mu = \sigma\sqrt{\frac{\pi}{2}}. \tag{5}$$

Here:

F(t) is the Rayleigh cumulative distribution of the decision rate for evacuation of the population at time t. The parameter σ is the continuous scale parameter of the Rayleigh distribution. This scale parameter or mode of distribution can be related to the distribution mean μ (Eq. 5).

Table 2 shows the results of correlations and values of the distribution mean compared to the reported or estimated tsunami arrival times in RP or SP surveys, respectively.

As can be observed in Fig. 3a and Fig. 3b, there is a higher correlation between the recorded arrival times of tsunamis with the preparation times from RP surveys compared to the estimated arrival time and the preparation times stated in SP surveys.

This means that an SP survey might be obtaining from respondents what it is considered to be the "correct" answer, which is a fast evacuation. An RP survey may show instead that at least half of the population at risk waited until the tsunami had nearly arrived before they started their evacuation. This apparently irrational behavior of some people in delaying their evacuation activity has been observed in other events and confirmed by several videos available on the web for this latest tsunami event. Based on Fig. 3, one might be tempted to rely on the distributions of previous revealed preference surveys for input into the evacuation model. However, due to individuality of

Table 2 RP and SP questionnaire surveys correlated to Rayleigh distributions

No	Survey Type	Country	City	Event	Survey	No of respondents	Arrival Time (min)	Mean time (min)	Correlation	NRMSE	Reference	Wave Height
1	SP	Japan	Arahama	-	[?].07.2000	1073	45	7	0.964	11%	(Suzuki T et al, 2005)	-
2	SP	Japan	Miyagi	-	[?].10.2002	1460	45	11	0.992	11%	(Hayakawa T. et al, 2003)	-
3	SP	Thailand	Phuket	-	18.03.2009	46	90	13	0.968	12%	(Suppasri, A., 2010)	-
4	SP	Japan	Matsushima	-	01.06.2009	750	45	15	0.994	4%	(Shishido, N., 2010)	-
5	SP	Peru	La Punta	-	20.09.2010	128	25	7	0.988	6%	This study	-
6	SP	Peru	La Punta	-	10.09.2011	127	25	5	0.994	4%	This study	-
1	RP	Japan	Sanriku	02.11.1989	14.11.1989	1778	25	21	0.998	3%	(Saito, T., 1990)	0.56
2	RP	Japan	Okushiri	12.07.1993	[?].01.1994	182	7	6	1.000	3%	Online (*)	20.00
3	RP	Japan	Hokkaido	26.09.2003	[?].03.2005	2500	16	10	0.991	6%	(Hiroi, O. et al, 2005)	1.30
4	RP	Indonesia	Padang	12.09.2007	29.10.2007	29	45	26	0.988	6%	GTZ (2007)	0.90
5	RP	Indonesia	Padang	30.09.2009	07.11.2009	98	15	19	0.998	3%	GTZ (2009)	0.27
6	RP	Japan	Kamaishi	11.03.2011	28.04.2011	61	20	17	0.983	8%	NPO CeMI (2011)	8.00

(*) http://www.drgeorgepc.com/Tsunami1993JAPANOkushiri.html

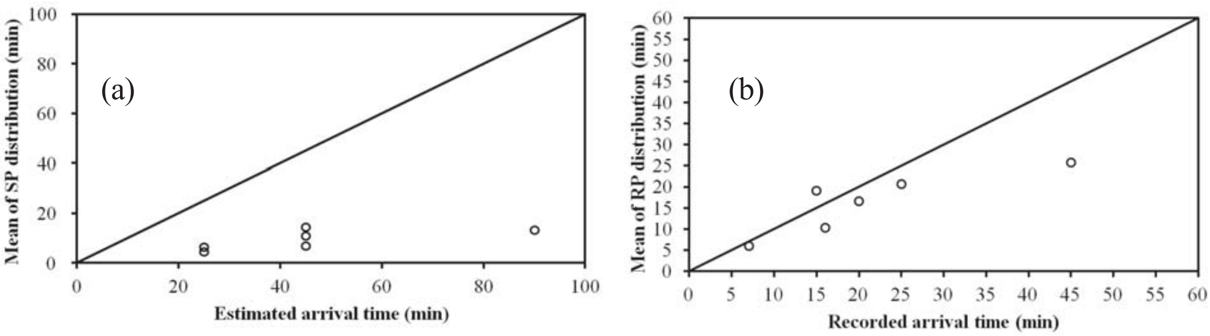

Figure 3 (a) Stated Preference surveys; (b) Revealed Preference surveys.

behavior, we cannot neglect the stated preference surveys because some individuals might actually follow the stated preferences. A better approach, therefore, is to assume a behavior bounded by the SP and the RP results.

It is the case that many areas desiring a tsunami risk assessment might not have had a tsunami recently, meaning that RP surveys might not be available. In this case, based on the results explained before, stakeholders may apply SP surveys and estimate the arrival time of a tsunami through numerical simulations. The final boundary distributions of behavior are obtained from these two methods.

4.5 Agent architecture

We model individuals as agents having the minimum necessary ability to process information and execute their evacuation by simple behaviors or decisions broken into layers. The layers are described below.

a) Layer 0: The evacuation decision, with times assigned randomly based on the departure time distributions discussed above
b) Layer 1: The shelter decision has two alternatives available in the scenario: One alternative is to go to the closest shelter, while the other alternative is to choose any shelter. Other models have traditionally used the nearest shelter condition, but in many cases, the preference is not necessarily the nearest shelter.
c) Layer 2: Pathfinding: As a method of finding a route that was not necessarily the best or closest, we used the A* (A star) algorithm on grid spaces. This is the most popular graph search algorithm and is also used in the video game industry (Anguelov, 2011).
d) Layer 3: Speed adjustment: Speed variability is assumed to be a one-tailed normal distribution with density based on the field of view for the agent and a maximum value of 1.33 m/s for pedestrians and 30 km/h (8.33 m/s) for cars (Meister, 2007; Suzuki & Imamura, 2005). The field of view for the agent is a 60° cone with a 5 m radius for pedestrians and a 10 m radius for vehicles.

4.6 Agent movement

A large number of both pedestrian and car agents move around the streets in the model. This means that collision avoidance should be included in the model. Agents move in a continuous grid space according to their actual speed. An agent does not necessarily “jump” from the center of a grid square to another center (integer coordinates), but may step on borders or other parts of a grid square between the center and the borders (real coordinates). To allow agents to move, a certain number of agents are allowed in an area based on the spatial accuracy or grid size. If a pedestrian requires a 1 m^2 personal area, 25 pedestrians can theoretically “fit” in a 5 m x 5 m grid. However, due to the dynamic movement of agents and the consideration of personal space between individuals, the grid area is not filled as would be suggested by theory. We used the predictive collision avoidance method proposed by Karamouzas, Heil, van Beek & Overmars (2009) and tested the movement of pedestrians from the area via a corridor (Helbing, 1991). We count the number of agents in a 5 m x 5 m area moving along a 1 m x 1 m grid-size corridor in a time step; the results show that the maximum capacity of the grid is 70% of its total area (Fig. 4). Therefore, we established a congestion condition of no more than 70% of the grid space used for pedestrians. A similar approach determined that the congestion condition for cars was 7%. Thus, a maximum of 18 pedestrians are allowed in a 5 m x 5 m grid, which is the limit for defining a crowd condition. This means that agents who would be modeled as wanting to enter a crowded space must wait until another agent has left the space and made room. The crowded condition for cars allows a maximum of two cars on a 5 m x 5 m grid.

4.7 Casualty estimation

We modeled casualties using the experimental results of Takahashi, Endoh & Muro (1992). The results provided a binomial casualty condition (safe or fall) depending on the flow depth (cm) and flow velocity (cm/s). The results of this experiment were used as a reference for the characterization of human stability against hydrodynamic forces; it reflects the interaction of the human body with flow features such as the depth and velocity that the tsunami may also present. A binomial logistic regression was performed to obtain the casualty probability as a function of flow characteristics. The results are shown in Fig. 5 and Eq. 6.

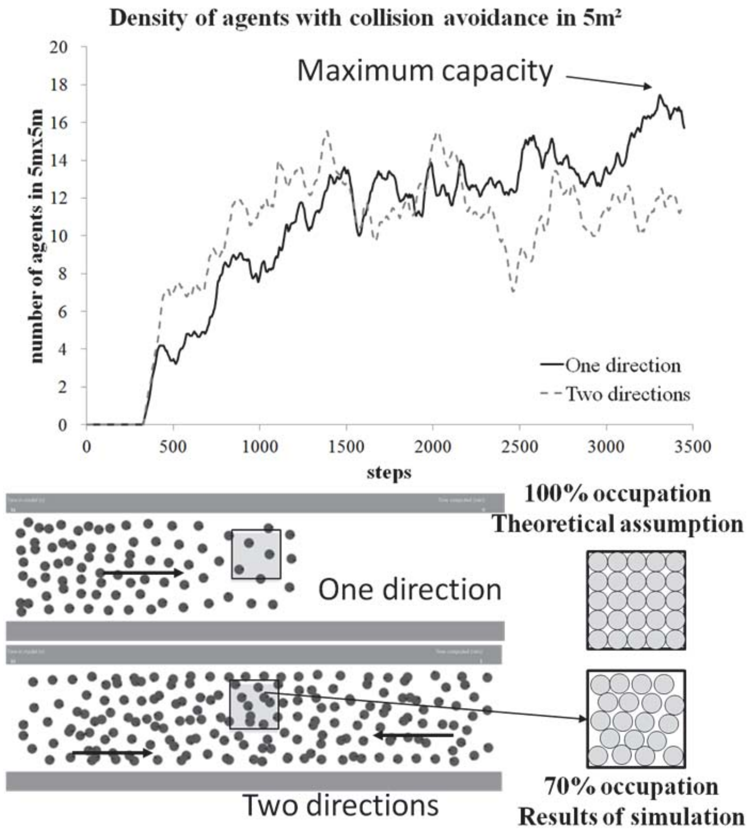

Figure 4 The corridor test (Helbing, 1991) using the predictive collision avoidance method (Karamouzas et al., 2009) to find the maximum capacity of agents in a certain area as a congestion parameter for bottleneck calculation. In the dynamic condition of agents, only 70% of the total area is used for movement with collision avoidance.

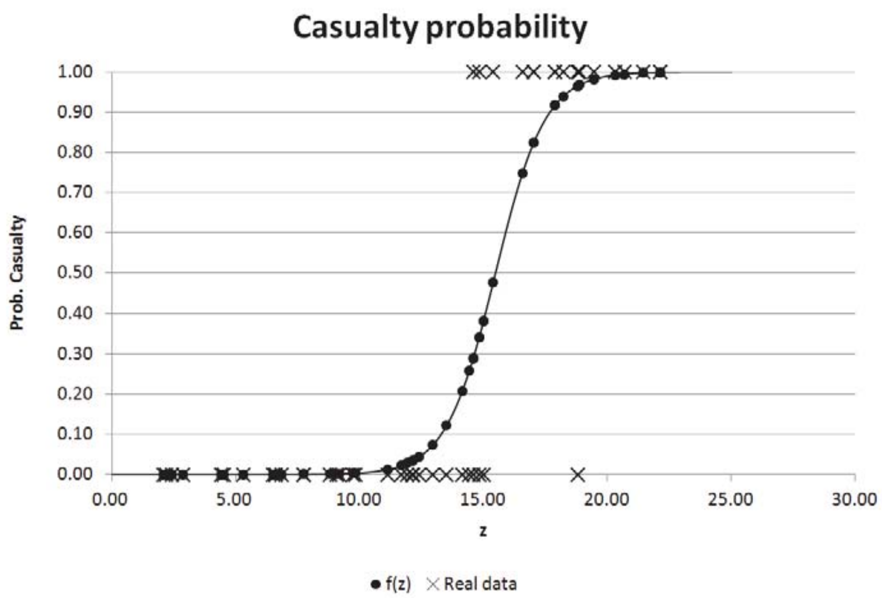

Figure 5 Binomial logistic regression model from experimental data in Takahashi et al. (1992).

$$f(z) = \frac{1}{1+e^{(15.48-z)}}. \tag{6}$$

Here:
$z=\beta_0+\beta_1 * h+\beta_2 * u.$
$\beta_0 = -12.37$; $\beta_1 = 22.036$; $\beta_2 = 11.517$.
h = *tsunami inundation depth*.
u = *tsunami velocity*.

The experimental data are limited to depth and velocity intervals of h [0.28, 0.85](m) and u [0.50, 2.00](m/s). Values for tsunami features above these ranges cannot be probabilistically calculated with the developed binomial function. Therefore, the model applies the binomial function to the estimation of casualties when the tsunami conditions are within range, and when the depth is greater than 0.85 m, the trapped agent is considered to be a casualty.

Casualties were also estimated for cars and agents in cars. While there have been cases where evacuees were found safe inside a car after a tsunami, in the majority of cases, passengers caught by a tsunami do not survive because they drown in the car or succumb due to debris impact. Based on Yasuda & Hiraishi (2004), a value of 0.50 m of inundation depth is considered sufficient for a driver lose control of the vehicle and in many cases, the car begins to float. Thus, when a car is trapped in a tsunami inundation depth greater than 0.50 m, it is considered to be a casualty with all of its passengers (four by default).

4.8 Outputs in model

Model outputs are presented in three ways: a) model view; b) reporters; c) files. The model view shows the movement of agents and tsunami propagation. Reporters show the simulation results of the number of saved agents or casualties, plots of shelter demand, and the evacuation rate. Files report the total simulation step by step in text, image, and video format.

5. Case Study: Arahama Village

Arahama is a populated village in Wakabayashi Ward of Sendai City in Miyagi Prefecture, Japan. Arahama is located between the Natori and the Nanakita Rivers, 6 km south of the Port of Sendai. A total of 2,704 residents lived in this area; after the 2011 tsunami, the Sendai City Bureau reported a total of 2,421 residents (Census, 2011). The population reduction of 283 might be the maximum number of casualties because after the earthquake, the local media reported that between 200 and 300 victims had been found in the area. The tsunami arrived in Arahama 1 hr after the earthquake with a maximum wave height of 10 m. The tsunami inundated 5 km inland, approximately ten times the expected Miyagi-oki tsunami. Arahama does not have many highly reinforced concrete buildings, so the only official tsunami evacuation building in the area is Arahama Elementary School, which has four stories and an accessible roof. It remained standing after the earthquake and provided tsunami shelter for approximately 520 evacuees (NGA, 2011). Figure 6 shows the synthetic waveform produced by numerical simulation of the tsunami 350 m offshore and at a 7.5 m depth in front of Arahama. From the numerical simulation, the estimated arrival time of the first peak of the tsunami wave was 69.5 min; this estimate was confirmed by video footage and agreed with stopped clocks found in the area (Suppasri, Koshimura et al., 2012a). For instance, a clock found inside the one-story gymnasium at Arahama Elementary School had stopped at 15:56, 70 min after the earthquake (Fig. 7a), while a second clock found in the surrounding residences had also stopped at 15:56 (Fig. 7b). In an elevated children's playground in Arahama Adventure Park, 2 km south of the Elementary School, a third clock found inside the information office had stopped at 15:58 (Fig. 7c). At this location, the tsunami height was 2 m while in other places in the Arahama area, the tsunami height reached 7 to 8 m. The office was apparently protected by the hill that split the tsunami wave in two directions. Finally, a fourth example was at Higashi-Rokugo Elementary School, located 2 km further inland. In this location, a clock had stopped at 16:03, 77 min after the earthquake (Fig. 7d).

5.1 Spatial and tsunami data

Local spatial data for the simulation were provided by the Geospatial Information Authority of Japan (GSI) in a shape format and converted for the model into a 5 m x 5 m grid raster. Tsunami data were taken from the output of calculations in the smallest domain shown previously (Fig. 1 & Fig. 2).

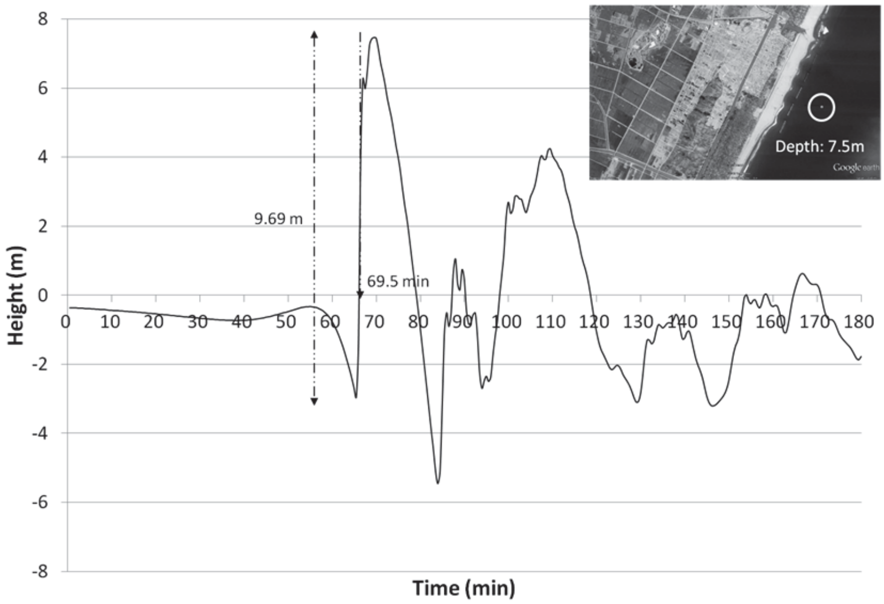

Figure 6 Synthetic waveform of a tsunami 350 m offshore of Arahama village (7.5 m sea depth). Arrival time: 69.5 min; height: 9.69 m.

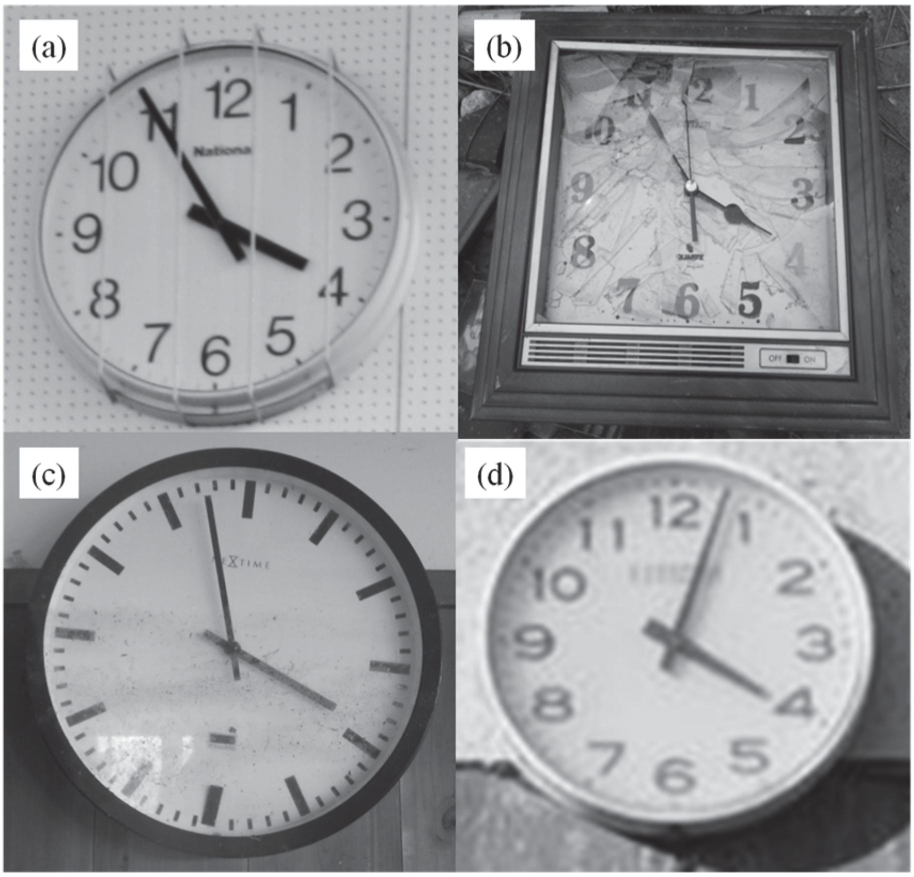

Figure 7 Possible evidence of the tsunami arrival time from stopped clocks. The time agrees with video footage, witnesses' accounts, and numerical simulation of tsunami arrival time. a) Arahama Elementary School gymnasium (15:56); b) Arahama village (15:56); c) Adventure Park (15:58); d) Higashi-Rokugo Elementary School (16:03).

5.2 Population data

It is very difficult to determine the exact number of evacuees at the moment of an earthquake. However, an estimation of a possible number of agents in the area is considered. It is not within the scope in this paper to fully reproduce the evacuation of March 11th, but to introduce the model's capabilities with the available data for a real event. The model was applied to 84% of the Arahama residential area, so 84% of the population of 2,704 (2,271) was considered. Of this group of evacuees, 72% were taken to be in-car evacuees based on the questionnaire results by Suzuki & Imamura (2005) (Fig 8). Assuming there were four passengers per car, 410 cars were modeled plus 631 pedestrians.

5.3 Hazard map, shelters, and routes

Before the 2011 event, Miyagi Prefecture and Sendai City were expected to be subjected to a 7.5 to 8.0 Mw magnitude earthquake within 30 years with a 99% probability of occurrence. In this projection, the predicted damage area was the northern part of Tohoku, the Sanriku coast; while the Sendai plain might be inundated less than 1 km inland with a nearly 3 m tsunami height. The hazard map prepared for this projection is shown in Fig. 9. The delimited area included no more than 500 m of shoreline. The large magnitude of the Great East Japan Earthquake produced a tsunami with an unprecedented height that reached approximately 5 km inland, ten times the predicted inundation. Witness accounts and rescue teams stated that the majority of Arahama evacuees were found in Arahama Elementary School, which was a designated evacuation building. The rest of the population was evacuated by car along two main roads, as shown in Fig. 9. The first evacuation road (Exit 1) was the Prefectural Road No. 137, while the second road (Exit 2) was an alternative road towards the inland area. Both pedestrians and cars in our model were allowed to evacuate to the evacuation building in the area, but only cars were allowed to evacuate via the nearest road to inland areas.

5.4 Stochastic simulation

The use of a multi-agent paradigm or agent-based model typically requires stochastic elements (Ormerod & Rosewell, 2009). Consequently, a set of runs was conducted to obtain average outputs for parameters of interest. We conducted several trials to observe the convergence of estimated values over a large number of repetitions. Therefore, 1,000 simulation repetitions were conducted with random initial spatial distributions of pedestrians and cars. The evacuation start time decision was based on a randomly selected value in a distribution bound between results from Suzuki et al. (2005) and the recorded arrival time of the tsunami on March 11th (67 min), with a distribution mean of 7 min (Fig. 10).

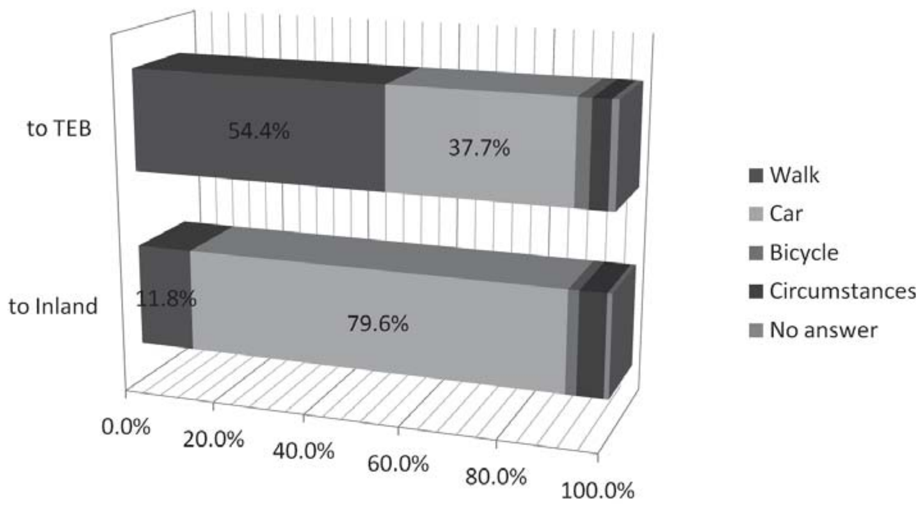

Figure 8 Questionnaire results of evacuation mode preferences, from Suzuki et al. (2005). (TEB: tsunami evacuation building)

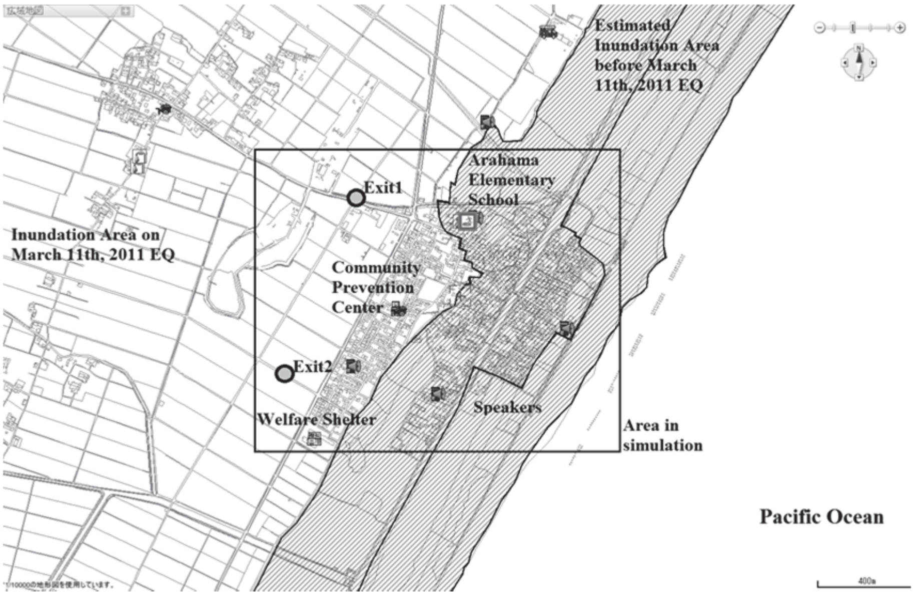

Figure 9 Tsunami hazard map before the 2011 tsunami. Actual inundation includes the total area shown in the graph. The inset square shows the area of simulation. Also, Exit 1, Exit 2, and the tsunami evacuation building (TEB) of Arahama Elementary School are annotated. (Sendai City website: http://www.city.sendai.jp/s-map/bousai.html)

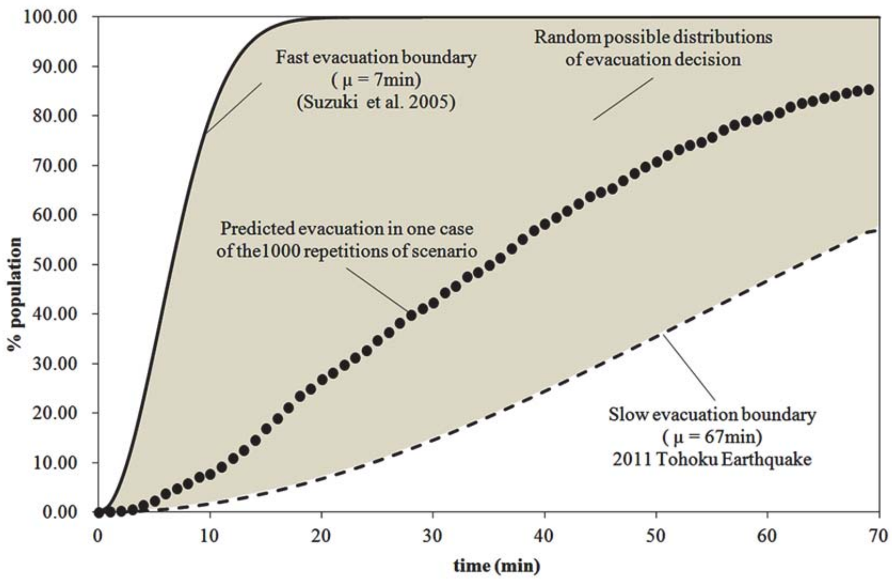

Figure 10 Boundary distributions for the start time decision of evacuation from a tsunami. Fast evacuation is determined by the questionnaire answers, while slow evacuation is based on the arrival time of the tsunami calculated by numerical simulation. Inside the area bound by the two extreme expected behaviors is a distribution of evacuation decisions from the 1,000 repetitions of stochastic simulation.

5.5 Results and discussion

Each simulation provides information comprising the number of evacuees sheltered plus the number of evacuees who have passed one of the exits (“safe”), the number of evacuees trapped by the tsunami with more than a 50% probability of falling (“casualty”), and the number of evacuees in tsunami evacuation buildings (TEBs). The average, standard deviation (SD) and other statistical values for the set of repetitions are shown in Table 3. The results show that

82.1% (SD=3.0%) of the population was safely evacuated. The apparent preferences for evacuation shelters are balanced between the three given options. An average of 21.9% (SD=0.5%) decided to evacuate to the tsunami evacuation building (TEB), while nearly 30.1% (SD=2.9%) and 30.0% (SD=2.8%) preferred to exit the area through Exit 1 and Exit 2, respectively. According to local media and the city census results before and after the earthquake, approximately 90% of the population was saved from the tsunami, as approximately 283 casualties were found in the area and 520 evacuees were sheltered in the Arahama Elementary School building. It is difficult to obtain the exact values observed with the stochastic simulation developed in this study; however, the average estimations of survivors and evacuees at the TEB show that the model has good capability of reproducing a suitable representation of decisions and casualty estimations in the area. The relative error of predicted values and the official information for the real event was 43% for the casualty estimation (model: 406, data: 283), 4% for the number of evacuees sheltered at the tsunami evacuation building (model: 498, data: 520), and 7% for the rest of the population evacuating inland (model: 1,367, data obtained as the difference between casualties and those sheltering with the 2,271 modeled: 1,468). Due to the uncertainty in the initial population distribution and the possible use of non-official buildings as shelters, the casualty estimation cannot be accurately predicted despite the improved results shown in Mas, Imamura & Koshimura (2012) compared to other methods of simulation. Figure 10 shows one of the 1,000 simulations of randomly selected values for the evacuation decisions of all agents within the given boundaries. The average distribution follows a sigmoid shape. By the time the tsunami arrived (t=67 min), a total of 85% of the population had already decided to evacuate. An important characteristic of micro simulations is the capability to explore the behavior of the model variables at the individual level. For example, the simulation allows a focus on the departure times shown in Fig. 10 for the entire population involved in the scenario, taking into consideration the casualty outputs in the model. A graph of one simulation showing sheltered evacuees' departure times ("survivors") next to the evacuation start times for agents caught by the tsunami ("casualties") is shown in Fig. 11. The influence of late departure times on the casualty estimation is clear. The majority of casualties decided to start their evacuation after approximately 53 min with some even evacuating after 70 min. By contrast, most of the survivors decided to evacuate after much less time. Some agents who started evacuating after 53 min made it to their shelter due to their specific distance to the shelter or having rapid modes of evacuation. We divided the modes of evacuation for the sheltered evacuees into pedestrians and cars and show in Table 4 the average distance to the shelter, the start time of evacuation, the time of evacuation considering only their travel time to the shelter, the total evacuation time, and the average speed. The size of the model area means that the average distance to the shelter is approximately 500 m. Because we have used the random seed number and the same algorithm to decide departure times for pedestrians and cars, the start time of evacuation values are similar. However, as expected, the time of evacuation (ToE) is shorter for cars than for pedestrians in accordance with the given speed rules. The total evacuation time is almost the same because of the great influence of the departure time. The average pedestrian speed of 1.10 m/s agrees with the maximum value of 1.33 m/s developed above. The average car speed of 5.03 m/s (18.11 km/h) was also consistent with the maximum value given by the model rule. The average speed values are lower than the maximum model rules, due to the dynamic condition of increasing and decreasing speed from bottlenecks and crowd conditions.

It is important to go beyond the final simulation outcomes for sheltered evacuees or residents evacuating through exit points and to evaluate the demand on resources during the evacuation process. A step-by-step tracking of the demand for shelters over time and the traffic flow through exits is possible and useful for resource management for supporting evacuation. Due to the stochastic characteristic of this simulation, it is difficult to show the set of 1,000 outputs. Figure 12 shows one of the repetition outputs. In this case, 30 min after the earthquake, only 37.2% of the population has reached their goal, 8.3% to the TEB, and 13.6% and 15.3% to Exit 1 and Exit 2, respectively. Bottleneck conditions in every repetition are shown in a final snapshot of each simulation (Fig. 13). Traffic was generally observed on the main roads leading to the exit points, at the entrance of the tsunami evacu-

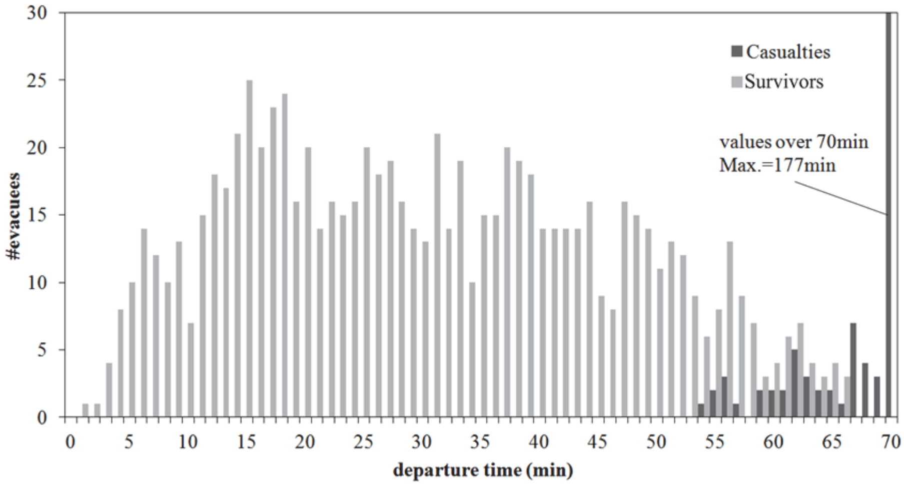

Figure 11 Departure times of agents and their final condition as survivor or casualty. The influence of faster evacuation is clear in the graph.

ation building, and near the bridge at the channel. Although these bottlenecks were not all present all at the same time in a given simulation, bottlenecks were observed at some point in at least one of the repetitions. All of these bottlenecks should be identified as critical points. Future work will involve exploring an adequate representation of the entire set of outcomes to facilitate the understanding of the evacuation process.

6. Conclusions

An integrated tsunami and evacuation simulator was introduced. The TUNAMI model and the Tohoku University Source Model version 1.1 was the tsunami modeling tool applied to the evacuation scenario for the 2011 Great Tohoku Earthquake and Tsunami. The evacuation model of evacuation was developed in NetLogo considering the influence of human behavior and individual characteristics on when an individual starts evacuation. The analysis of several questionnaire surveys with a statistical distribution showed

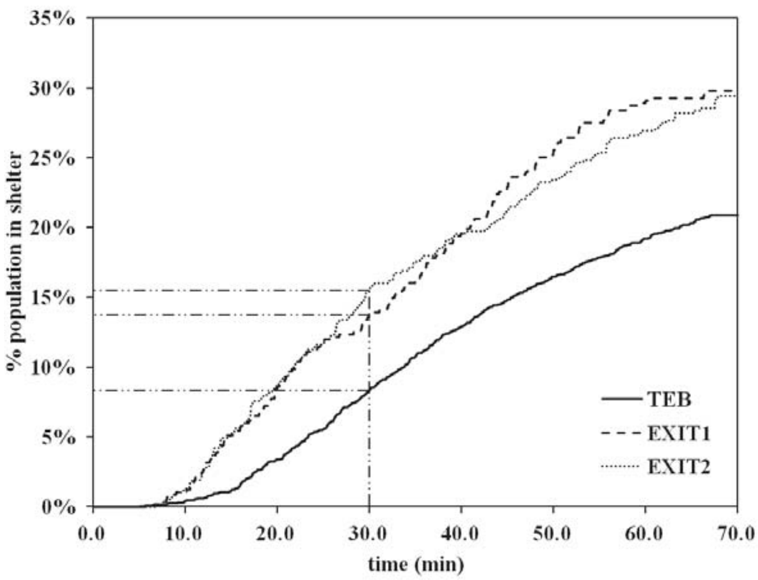

Figure 12 The curves show the loading of evacuees into the shelter (TEB) and through exits (Exit 1 and Exit 2) during the time of evacuation. After 30 min of simulation, less than 40% of population had found their way to the shelter or out of the computation area.

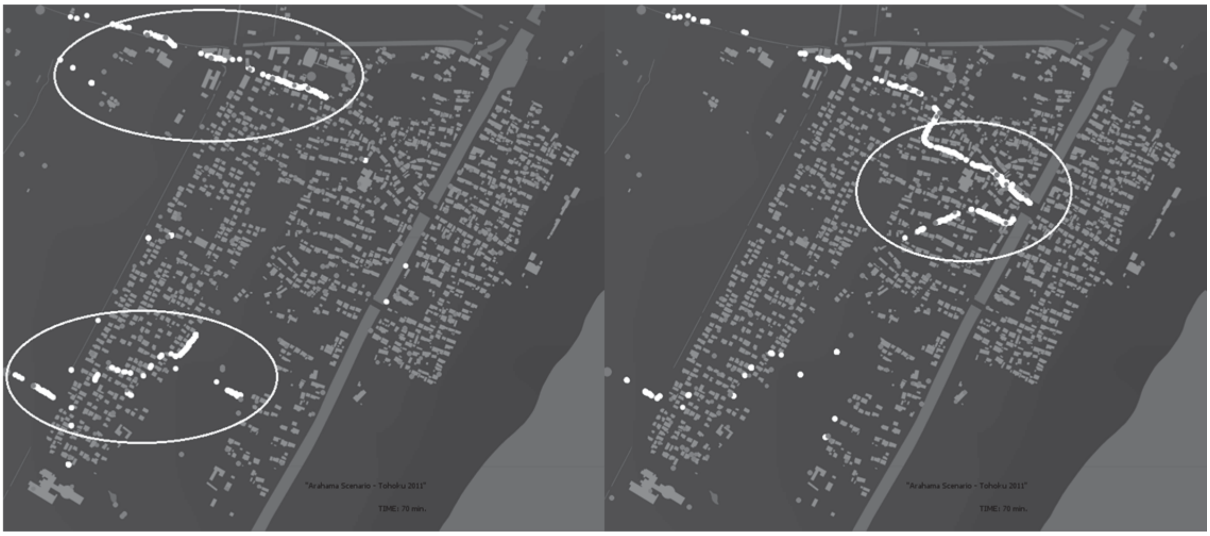

Figure 13 Representative snapshots of two different repetitions of simulation. Bottlenecks can be observed in the circled areas. Near the exit points, the evacuation building and a bridge connecting two areas are separated by a channel.

that stated preferences surveys indicated an expected fast evacuation by respondents, while revealed preference surveys showed a later distribution of evacuation start times. In this study, we have used human behavior data from questionnaires of stated preferences and features of tsunamis obtained by numerical simulation, such as the arrival time, to construct boundary distributions for a stochastic simulation of evacuation decisions. Tsunami hydrodynamic conditions were used for the casualty estimation. A case study was conducted through simulation of the Arahama evacuation in the 2011 Great Tohoku Earthquake and Tsunami. The case study shows the capability of the model of exploring individual parameters and outcomes. Evacuation models like the one introduced here allows for studying the behavior of individuals in the complex process of tsunami evacuation.

Acknowledgements:

The authors acknowledge the support of the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT) as well as the support of the Japan Science and Technology Agency (JST) through the Science and Technology Research Partnership for Sustainable Development (SATREPS-PERU). We express our deep appreciation to the Willis Research Network (WRN), the Pan-Asian/Oceanian tsunami risk modeling and mapping project, and Tokio Marine Nichido Fire Insurance Co., Ltd. through the International Research Institute of Disaster Science (IRIDeS) at Tohoku University.

Bibliography

Anguelov, B. (2011). *Video Game Pathfinding and Improvements to Discrete Search on Grid-based Maps*. Master Thesis. University of Pretoria.

Cabinet Office of Japan. (2011). Lessons from the Great East Japan Earthquake. Report on the Survey of Tsunami and Earthquake Countermeasures, 1-91.

Census. (2011). *Sendai City web page*. Retrieved November 15, 2011, from census data: http://www.city.sendai.jp/kikaku/seisaku/toukei/jinkou/jinkou-kakusai.html.

Fujioka, M., Ishibashi, K., Kaji, H. & Tsukagoshi, I. (2002). Multi Agent Simulation Model for Evaluating Evacuation Management System against Tsunami Disaster. *J. Archit. Plann. Environ. Eng., AIJ* 562, 231-236.

Gagne, R. M., Wager, W. W., Golas, K. & Keller, J. M. (2004). *Principles of Instructional Design* (5th edition). Wadsworth Publishing Co. Inc.

GTZ. (2009). *30 Minutes in the City of Padang: Lessons for Tsunami Preparedness and Early Warning from the Earthquake on September 30, 2009*. GTZ.

GTZ. (2007). *Early Warning Experiences in Padang after First Bengkulu Earthquake on September 12, 2007*. GTZ.

Gwynne, S., Galea, E., Owen, M., Lawrence, J. & Filippidis, L. (1999). A Review of the Methodologies Used in Evacuation Modeling. *Fire and Materials* 23, 383-388.

Hayakawa, T. & Imamura, F. (2002). Model of the Determination of Tsunami Evacuation and Its Application. *Journal of Japan Society for Natural Disaster Science* 21 (1), 51-66.

Hayashi, Y., Tsushima, H., Hirata, K., Kimura, K. & Maeda, K. (2011). Tsunami Source Area of the 2011 off the Pacific Coast of Tohoku Earthquake Determined from Tsunami Arrival Times at Offshore Observation Stations. *Earth, Planets and Space* 63(7), 809-813. doi:10.5047/eps.2011.06.042.

Helbing, D. (1991). A Mathematical Model for the Behavior of Pedestrians. *Behavioral Science* 36, 298-310.

Hiroi, O., Nakamura, I., Fukuda, M., Nakamori, H., Sekiya, N., Mikami, S. et al. (2005). *Evacuation Activities at the Tokachi Earthquake, 2003*. Tokyo University.

Imamura, F. (1995). Review of Tsunami Simulation with a Finite Difference Method. In *Long-Wave Runup Models,* 25-42. World Scientific.

Imamura, F., Suzuki, T. & Taniguchi, M. (2001). Development of a Simulation Method for the Evacuation from the Tsunami and Its Application to Aonae, Okushiri Is., Hokkaido. *Japan Society for Natural Disaster Science* 20 (2), 183-195.

Imamura, F. (2009). Dissemination of Information and Evacuation Procedures in the 2004-2007 Tsunamis, Including the 2004 Indian Ocean. *Journal of Earthquake and Tsunami* 3 (2), 59-65.

Imamura, F., Koshimura, S., Murashima, Y., Akita, Y. & Shintani, Y. (November 11, 2011). The 2011 East Japan off the Pacific Coast Earthquake and Tsunami. *Tohoku University Source Model version 1.1*. Sendai, Miyagi, Japan: Disaster Control Research Center.

JMA. (2011). *Japan Meteorological Agency*. Retrieved June 12, 2011, from The 2011 off the Pacific Coast of Tohoku Earthquake: http://www.jma.go.jp/jma/en/2011_Earthquake.html.

Karamouzas, I., Heil, P., van Beek, P. & Overmars, M. (2009). A Predictive Collision Avoidance Model for Pedestrian Simulation. In A. Egges, R. Geraerts & M. Overmars, *Motion in Games* 5884, 41-52.

Lindell, M. K. & Prater, C. S. (2007). Critical Behavioral Assumptions in Evacuation Time Estimate Analysis for Private Vehicles: Examples from Hurricanes Research and Planning. *Journal of Urban Planning and Development*, 18-29.

Mas, E., Imamura, F. & Koshimura, S. (2011). Modelling the Decision of Evacuation from Tsunami based on Human Risk Perception. *Tohoku Branch Annual Meeting*. Sendai: Japan Society of Civil Engineering (JSCE).

Mas, E., Imamura, F. & Koshimura, S. (2012). Tsunami Departure Curves for Evacuation Simulation. A New Approach to Model the Human Behavior in Tsunami Evacuation (under review).

Meguro, K. & Oda, K. (2005). Development of Evacuation Simulator for Tsunami Disaster Mitigation. *Production Research* 57 (4), 343-347.

Meister, J. (2007). *Simulation of Crowd Dynamics with Special Focus on Building Evacuations*. Hamburg: Master Thesis. University of Applied Sciences.

Muhari, A., Imamura, F., Suppasri, A. & Mas, E. (2012). Tsunami Arrival Time Characteristics of 2011 East Japan Tsunami Revealed from Eyewitness, Evidences and Numerical Simulation. *Journal of Natural Disaster Science* (this issue).

National Police Agency (NPA). (2012). Damage Report National Police Agency Japan (January 30, 2012), 1-2. Retrieved from http://www.npa.go.jp/archive/keibi/biki/higaijokyo.pdf.

Naser, M. & Birst, S. C. (2010). *Mesoscopic Evacuation Modeling for Small to Medium-Sized Metropolitan Areas.* North Dakota State University.

NGA. (2011). *The 2011 Great Tohoku Earthquake and Tsunami Damage Report No. 12.* Japan: National Governors' Association.

NPO CeMI. (2011). *Questionnary Survey of the Tohoku Area, Offshore of the Pacific Earthquake.* CeMI NPO.

Ohhata, D., Kagami, H. & Takai, N. (2005). *Application of Multi Agent System to Simulation of Evacuation Behavior from Tsunami. A model of Kushiro, Hokkaido.* Architectural Institue of Japan. Collection of Academic Lecture Synopses F-1. Urban Planning, Architectural, Economics, and Housing Issues.

Ormerod, P. & Rosewell, B. (2009). Validation and Verification of Agent-Based Models in the Social Sciences. In F. Squazzoni, *Epistemological Aspects of Computer Simulation in the Social Sciences* 5466, 130-140. Berlin: Springer.

Pan, X., Han, C., Dauber, K. & Law, K. (2007). A multi-agent Based Framework for the Simulation of Human and Social Behavior during Emergency Evacuations. *AI & amp Society* 22 (2), 113-132.

Post, J., Wegscheider, S., Muck, M., Zosseder, K., Kiefl, R., Steinmetz, T. et al. (2009). Assessment of Human Immediate Response Capability Related to Tsunami Threats in Indonesia at a Sub-national Scale. *Natural Hazards and Earth System Sciences* 9, 1075-1086.

Riad, J. K., Norris, F. H. & Riback, R. B. (1999). Predicting Evacuation in Two Major Disasters: Risk Perception, Social Influence, and Access to Resources. *Journal of Applied Social Psychology* 29 (5), 918-934.

Saito, T. (1990). Questionnaire Survey of Human Behaviors and Consciousness on the Tsunami of the 1989 Sanriku-Oki Earthquake. *Japan Society for Natural Disaster Science* 9 (2), 49-63.

Saito, T. & Kagami, H. (2005). Simulation of Evacuation Behavior from Tsunami Utilizing Multiagent System. A Case Study of Aonae, Okushiri Island. *J. Archit. Plann., AIJ* 597, 229-234.

Sato, T., Kono, T., Koshimura, S., Yamaura, K. & Imamura, F. (2008). An Evacuation Model Incorporating Cognitive Dissonance: Introduction of Psychological Elements to Evacuation Simulating. *Institute of Social Science* 10.

Shishido, N. (2010). *Study on the Evaluation Method of Human Loss Considering the Tsunami Evacuation Process*. Sendai, Japan: Master thesis. Tohoku University.

Shuto, N. (2005). Tsunamis: Their Coastal Effects and Defense Works. *Scientific Forum on Tsunami, Its Impact and Recovery*, 1-12. Thailand: Asian Institute of Technology.

Southworth, F. (1991). *Regional Evacuation Modeling: A State-of-the-Art Review.* Oak Ridge National Laboratory (ORNL).

Sugimoto, T., Murakami, H., Kozuki, Y. & Nishikawa, K. (2003). A Human Damage Prediction Method for Tsunami Disasters Incorporating Evacuation Activities. *Natural Hazards* 29, 585-600.

Suppasri, A. (2010). *Tsunami Risk Assessment to Coastal Population and Building in Thailand.* Sendai, Japan: PhD Thesis. Tohoku University.

Suppasri, A., Koshimura, S., Imai, K., Mas, E., Gokon, H., Muhari, A. & Imamura, F. (2012a). Damage Characteristic and Field Survey of the 2011 Great East Japan Tsunami in the Miyagi Prefecture. *Coastal Engineering Journal* 54(1), 1-30.

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K. & Imamura, F. (2012b). Developing Tsunami Fragility Curves from the Surveyed Data of the 2011 Great East Japan Tsunami in Sendai and Ishinomaki Plains. *Coastal Engineering Journal* 54(1), 1-16. doi:10.1142/S0578563412500088.

Suzuki, T. & Imamura, F. (2005). Simulation Model of the Evacuation from a Tsunami in Consideration of the Resident Consciousness and Behavior. *Japan Society for Natural Disaster Science* 23 (4), 521-538.

Takahashi, S., Endoh, K. & Muro, Z. (1992). *Experimental Study on People's Safety against Overtopping Waves on Breakwaters.* Rept. of Port and Harbour Res. Inst., Vol. 31, No. 4, 3-29.

Tatano, H. (1999). Risk Perception and Investment for Disaster Mitigation by Individual Households. *IEEE International Conference on Systems, Man and Cybernetics*, 1003-1006.

Tweedie, S., Rowland, J., Walsh, S., Rhoten, R. & Hagle, P. (1986). A Methodology for Estimating Emergency Evacuation Times. *Social Science Journal* 23 (2), 189-204.

USGS. (2011). *US Geological Survey*. Retrieved March 20, 2011, from Magnitude 9.0 Near the Coast of Honshu, Japan:
http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/.

Wilensky, U. (2001). Modeling Nature's Emergent Patterns with Multi-agent Languages. *EuroLogo*.

Yalciner, A. C., Ozer, C., Zaytsev, A., Suppasri, A., Mas, E., Kalligeris, N. et al. (2011). Field Survey on the Coastal Impacts of March 11, 2011 Great East Japan Tsunami. *WCCE-ECCE-TCCE Joint Conference 2—Seismic Protection of Cultural Heritage*, 123-140. Antalaya, Turkey.

Yasuda, T. & Hiraishi, T. (2004). Experimental Study of Tsunami Inundation in Coastal Urban Area. *Fourteenth International Offshore and Polar Engineering Conference* , 740-746. Toulon, France: International Society Offshore and Polar Engineering.