

# **Information Exchange Model for Multi-Agent Earthquake/Tsunami Evacuation Simulation**

Claus Aranha<sup>\*</sup>, Hiromu Matsushima<sup>\*\*</sup>, Hitoshi Kanoh<sup>\*</sup>

<sup>\*</sup>Faculty of Engineering, Information and Systems, University of Tsukuba

<sup>\*\*</sup>Graduate School of Science and Information Engineering, University of Tsukuba

(Received: Mar. 15, 2017 Accepted: Dec. 18, 2017)

## **ABSTRACT**

We propose an agent-based simulation system for evacuations after earthquakes and tsunamis. We focus on an improved model of communication among agents, by including a model of speech intelligibility in crowds, and the use of voice to change the evacuation-start behavior. This allows the model to represent the effects of evacuees calling to each other, and of automated emergency broadcast systems. To validate our model, we simulate hypothetical scenarios using data from the Great Hanshin-Awaji Earthquake and the Great East Japan Earthquake and tsunami as the initial conditions. Evacuation start and completion rates from the simulation were similar to those observed in the original events, based on data from post-disaster surveys, and showed the model's ability to serve as a policy modeling tool.

**Keywords:** Simulation, Evacuation, Multi-Agent Systems, Information Exchange

## **1. INTRODUCTION**

Natural disasters such as earthquakes and tsunamis cause enormous harm to people and damage to infrastructure of highly populated areas around the globe. The experiences of the Great Hanshin-Awaji Earthquake in 1995 and the Great East Japan Earthquake in 2011 revealed that the most effective way to mitigate damage from such events is to prepare robust plans for disaster management and relief. One key part of those plans is the evacuation of the civilian population from the affected area.

One issue with the development of disaster management plans is how to evaluate and compare the effectiveness of different policies. Evacuation simulators are a key tool in this task. A good simulator reveals the effects of changes in disaster management policies across a wide array of variables, such as the number of evacuees, intensity of the disaster, and local conditions. This allows planners to quickly try multiple variations of the desired policy, without incurring the cost of full evacuation drills.

However, because of the unpredictability of human behavior and the highly complex nature of natural disasters, the development of useful and accurate evacuation simulators is an ongoing area of research. Accordingly, research has focused on the development of tools for the reproduction of evacuation scenarios, both for earthquake and tsunami disasters (Oki and Osaragi, 2016, Muraki and Kanoh, 2007, Clerveaux et al., 2008, Mas et al., 2012). In these studies, the authors try to bring the evacuation simulation closer to reality by studying and implementing a multitude of factors that contribute to the verisimilitude of the simulation, such as the effects of collapsed buildings on the walking speed of evacuees, the psychology of when an evacuee decides to actually start evacuating, the walking speed and density of evacuees, and so forth.

In this study, we go a step further in this direction, and consider an earthquake and tsunami evacuation simulation where evacuees and emergency services personnel can exchange information about the location of evacuation areas by talking to each other or by shouting over greater distances. This exchange of information influences how the evacuees decide their routes to the evacuation centers, and

how they decide whether to begin evacuation. This addition reflects existing surveys on the behavior of evacuees in large-scale disasters, which indicate that communication between neighbors and nearby evacuation staff is an important factor in the evacuee's decision-making process (Cabinet Office, 1999, 2012).

Our model is based on an agent-based simulation system that focuses on three types of agents: *Evacuees*, *Evacuation Leaders* and *Wireless Broadcast Systems* (WBS). The three types of agents can exchange information about the location of evacuation zones, and keep track of what information they have, and how old it is.

Using the proposed model, we perform evacuation simulations on hypothetical scenarios based on Kobe City during the Great Hanshin-Awaji Earthquake, and Ishinomaki City during the Great East Japan Earthquake and subsequent tsunami. These scenarios use start conditions based on survey and census data of these two historical disasters. We compare the final evacuation ratio, the average evacuation time, and, for the tsunami scenario, the start of evacuation behavior to the observed historical data. Additionally, we show how this model could be used for the analysis of disaster management planning by performing a simulation of the Kobe City scenario using Evacuation Leaders and Wireless Broadcast Systems, which were not available during the original evacuation.

## **2. RESEARCH BACKGROUND**

### **2.1 The role of communication in evacuation procedures**

Local governments conduct studies and surveys after large-scale natural disasters to identify successes and failures in its current disaster management policies. In the evacuation following the Great Hanshin-Awaji Earthquake in 1995, the government survey identified the following issues (Cabinet Office, 1999):

- Many evacuees went to evacuation shelters different from those designated by their residence, leading to delays in assistance from municipalities.
- Some evacuees rushed to the disaster response center instead of their designated evacuation shelters, which hindered the emergency management activities by the municipalities.
- The communication of safety information to the residents was limited, due to the lack of a fixed broadcast system such as the Disaster Wireless Broadcast System (WBS).

According to a different evacuee survey (Foundation for the Center of Fire Fighting Science, 1997), the lack of information regarding evacuation shelters was a common complaint among evacuees. From these surveys, it is clear that a disaster mitigation plan must consider how to effectively transmit information to the population.

After the Great East Japan Earthquake of 2011 and subsequent tsunami, the government's survey showed that evacuees strongly felt that local governments needed to increase their efforts to spread emergency evacuation information (Cabinet Office, 2012). The suggestions included activities such as direct announcements to evacuees, the use of mass media and better use of the Disaster Wireless Broadcast System (WBS) (Inoue, 2012).

From these surveys, we can see that there is room for improvement in the disaster mitigation practices from municipalities, in particular regarding the dissemination of information to evacuees. This raises the issue of how to evaluate proposed changes to evacuation policies. One way to evaluate a new evacuation plan or policy is to perform a large and costly disaster evacuation drill in the real world. This is not feasible in the early planning stages when multiple competing plans are to be compared against each other. Therefore, there is interest in the development of software systems that allow an inexpensive early evaluation of new policy proposals using only computer simulations.

We also observe from these surveys the importance of communication channels to the success of an evacuation effort. In the Great Hanshin-Awaji Earthquake, evacuees had to obtain information about the rescue and shelter efforts from nearby people, or from portable radios. In the Great East Japan Earthquake, it was reported that a number of people only began to evacuate after being prompted by family, neighbors or even in some cases passers-by who were calling out for people to evacuate from the

incoming tsunami (Cabinet Office, 2012). These points motivate us to take special interest in how the communication between evacuees and evacuation personnel is approached in evacuation simulation models.

## **2.2 Multi-Agent Systems for evacuation simulations**

Multi-Agent Systems (MAS) are models composed of multiple intelligent individuals (agents) working on the same environment. After over three decades of research, MAS now come in many different forms, including homogeneous and heterogeneous agents, cooperative or competitive, with or without communication, and various degrees of complexity (Stone and Veloso, 2000).

MAS are extremely powerful and versatile systems for simulating social structures. For example, Bosse et al. (2013) introduced a MAS that simulates a city and its inhabitants, and used it to analyze patterns and mechanisms in crime rate, such as population density and police enforcement. In a similar line, Melo et al. (2005) used MAS to simulate and investigate effective police patrol routes.

In order to be able to perform such simulations, it is necessary to understand the workings of crowds. Borve (2014) surveyed various MAS studies that investigate crowd mechanics, with particular attention to the importance of crowd density. They highlight the use of these simulations for the analysis of human stampedes, riots and evacuations. More recently, Genter and Stone (2016) considered indirect communication between agents, by showing how it is possible to influence the behavior of a flock by inserting “leading” agents that do not communicate directly with the rest of the flock.

The communication between agents in a simulation is a key component in many of these studies. The level of abstraction in the communication model varies greatly. Pynadath et al. (2016) showed a simulation of an Anthrax attack in an American city, and focused on how the exchange of information influences an agent’s beliefs about their environment. In their study, the exchange of information between agents is abstracted to always occur correctly and perfectly. Eck and Soh (2015) proposed a simulation of rescue robots in a disaster scenario. In this case, communication also happens instantly and correctly, but has an associated cost, and the information obtained is not always up-to-date, so the agents may consider exploring the environment instead of exchanging information about it. On the other end of the spectrum, Cafaro et al. (2016) studied the effect of interruption in the exchange of messages (discussion) between two agents. Here each phrase exchanged by the two agents and their timings is represented in the model.

In recent years, MAS and agent-based simulations have been used extensively in the simulation of disaster, evacuation and rescue scenarios. Ren et al. (2009) lists a large number of studies where the simulation of evacuees was used to understand and prepare for disasters. We see two main groups of applications for disaster simulation: applications that focus on the rescue personnel, and applications that focus on the evacuees.

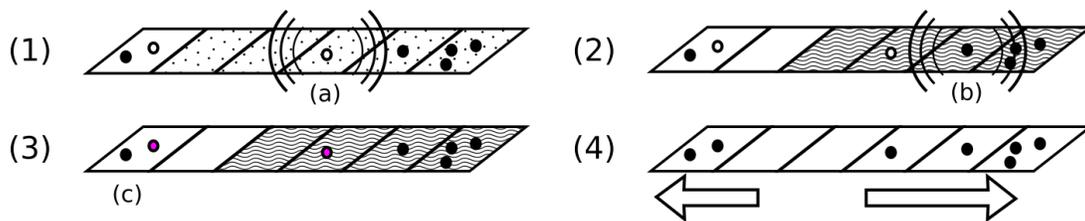
In the first group, agents represent rescue workers, or sometimes robots. Morishita et al. (2002) and Noda et al. (2002) are two examples of studies in this group. Both of them pay special attention to the communication protocol among the rescue agents in order to guarantee a well-coordinated rescue operation. Beck et al. (2016) described a MAS for planning search and rescue in the wake of the recent Haiti hurricane. Singh et al. (2011) reviewed many other studies in this group, and highlighted the importance of communication among rescue personnel.

In the second group, agents represent evacuees, although sometimes evacuation personnel agents are also included. Shinoda et al. (2002) discussed that one of the main problems of simulations focusing on evacuees is that they require a number of agents’ orders of magnitude above simulations focusing only on rescue personnel agents. To reduce this burden, many studies try to find efficient ways to model parts of the evacuation. The movement of crowds is a common concern. Boukas et al. (2015) and Sirakoulis (2014) used cellular automata to represent the crowd, while Yamashita et al. (2014) represented the members of a crowd as individual agents and studied the effects of density on the evacuee’s movement speed. Oki and Osaragi (2016) described a system to reflect how the destruction of buildings due to fire might block evacuation routes. Recently, Wolshon et al. (2015) introduced a very large-scale traffic simulator to study highway policies during major hurricanes in the United States. Their system could simulate over half a million vehicles, by using individually simple agents.

Regarding the simulation of tsunami evacuations, Clerveaux et al. (2008) proposed a tsunami evacuation simulator and discussed the importance of information transmission between evacuees and evacuation personnel, due to the very short timeframes involved. However, their study does not specify to what degree the information exchange is modeled in the simulator. Mas et al. (2012) also proposed a tsunami scenario simulator. Their study considers the necessity of quick evacuation in tsunami scenarios, and models the conditions when evacuees decide to actually begin evacuation using a stochastic behavior function.

In this context, we are interested in developing a simulator for earthquake and tsunami evacuation scenarios based on a Multi-Agent System, where the focus is on the simulation of pedestrian and car-based evacuees as agents, and on the interactions between the evacuees and the evacuation personnel, including the exchange of information through voice.

This study is based on the agent-based simulation system proposed by Muraki and Kanoh (2007). Their system uses MAS to represent evacuees, and car navigation system data to allow the simulation of city-sized evacuation areas with tens of thousands of agents. In this study, we extend their system in several ways: inclusion of tsunami evacuation scenarios; message exchange among agents through voice, including an intelligibility model that limits the exchange of messages in crowded areas; agent neighborhood familiarity, where some agents do not know the location of the nearest vacant shelter, and need to receive this information from evacuation personnel or other evacuees; and evacuation start behavior, which can change based on the exchange of messages between agents (representing people urging others to evacuate).



**Figure 1:** How agents acquire Evacuation Route Information (ERI). In Step 1, agent (a) that does not have ERI shouts a request. In Step 2, agent (b) hears the request and shouts a response. In Step 3, agent (c), that also does not have ERI, gets information from another agent in the same cell. In Step (4), the agents update their path finding based on the ERI received. Note that the model implements “hearing” and “shouting” as the agents writing or reading messages in their respective cells.

### 3. PROPOSED MODELS

Following the ideas described in Section 2, we propose an evacuation simulation model that considers the mutual exchange of information among agents regarding evacuation routes and the location of shelters. This model could be used to test plans regarding the number of search and rescue personnel, and the deployment of Disaster Wireless Broadcast Systems (WBS). It could also be used to study and understand how information is disseminated considering the changing conditions of a tsunami-afflicted area.

Our model is based on the simulator proposed by Muraki and Kanoh (2007). This model represents evacuees as agents, and the roads and pathways as cells on a grid. Buildings in this model are abstracted as properties of the region lattice that divides the simulated area.

One agent in the simulation represents a group of one or more people, and one cell in the grid represents a section of road that can contain one or more agents and obstacles (debris from the natural disaster). At each time step, which represents one second in real world time, the agents move towards their evacuation destinations following their path finding rules.

Using Muraki’s model as a base, we add the ability of the agents to exchange evacuation route information, and the ability of tsunami damage to affect the available evacuation routes in the simulation. These additions are summarized in the following list:

- Addition of *Evacuation Leader* (EL) and *Wireless Broadcast System* (WBS) agents.
- Each agent can add information it has about the environment to the limit of its voice.
- Each agent can request and acquire information about disaster shelters from the environment.
- The evacuee agent’s path finding rule is influenced by the information about disaster shelters.
- Each evacuee agent has an “intent to evacuate” attribute, which determines when it actually starts the evacuation process. Intent to evacuate is modified by receiving information from other agents.
- Addition of “height” and “tsunami damage” properties to cells, which influence path finding.
- Addition of a mechanism of spreading tsunami damage to the simulated area.

The information exchange model used is described in Fig. 1. Specifically, agents place requests and offers for *Evacuation Route Information* (ERI) as a sound message in their current cell. The cell propagates this message to neighboring cells, based on the voice message sound intensity. Other agents can then pick up messages in their own cells, and use those messages to update their internal state. In our model, the ERI is assumed to contain information about the location and availability of evacuation shelters. This information is qualified by its newness and source, so that evacuees prefer newer ERIs, and those that come from official sources (EL and WBS) rather than those that come from other evacuees.

**Table 1:** Attributes of the Agents

Attribute	Description	Agent types
Resident	<b>Flag:</b> This agent lives in the area	Evacuees
Familiar	<b>Flag:</b> Agent knows designated shelter	Evacuees
Weak	<b>Flag:</b> Agent includes elderly or children	Evacuees
Number	<b>Integer:</b> People in this group	Evacuees, EL
Car	<b>Flag:</b> Agent is moving by car	Evacuees, EL
Asound	<b>Number:</b> Sound broadcast intensity	All agents
Interval	<b>Number:</b> Time steps for ERI request	Evacuees
Current cell	<b>Pointer:</b> Agent’s current cell	All agents
Moving Speed	<b>Number:</b> Agent’s current speed	All agents
Has ERI	<b>Flag:</b> Agent received ERI information	Evacuees
Current ERI	<b>Pointer:</b> Time and source of ERI	All agents
Sasking	<b>Flag:</b> Agent is currently requesting ERI	Evacuees
Sproviding	<b>Flag:</b> Agent is currently providing ERI	All agents
Intention	<b>State:</b> Condition for evacuation start	Evacuees
Evacuation Start	<b>Time:</b> Time stamp for evacuation start	Evacuees

### 3.1 Agent types

The proposed model defines three types of agents: Evacuees, Leaders, and Wireless Broadcast Systems.

- **Evacuee:** The evacuee agent represents one or more people evacuating towards their destination. The agent destination depends on their internal state (Section 3.4). This state includes whether they are on foot or in cars, whether the group includes “weak walkers” (such as elderly or children), whether the group is a resident or commuter, and whether it is familiar with local evacuation

information.

- **Evacuation Leader (EL):** The EL agent represents a staff member from the municipal rescue efforts. During the evacuation, it will look for evacuee agents to disseminate evacuation shelter information. It is equipped with a loudspeaker and a radio, so it always has up-to-date ERI data.
- **Wireless Broadcast System (WBS):** The WBS agent represents a system of fixed radio broadcast poles that exists in most municipalities in Japan. During an evacuation, it will broadcast ERI over a large area at regular intervals.

The agents are defined by the attributes listed in Table 1. These attributes define the agent’s ability to move, transmit information to other agents, and its decision-making process regarding path finding and starting the evacuation. Some of these attributes are common to all agents, while others are specific to evacuee agents. While the exact behavior of the agent depends on its type (Evacuee, EL or WBS), the general behavior of an agent is described by Algorithm 1. In this algorithm,  $t$  is a time stamp for simulation iterations, which begins at zero, and where each iteration corresponds to one real world second.

---

**Algorithm 1** Agent update algorithm

---

**Require:** Current simulation time  $t$

- 1: **if**  $t\%15 == 0$  **then**
  - 2:     Request/Provide ERI . Sec. 3.2
  - 3: **end if**
  - 4: **if**  $t \geq$  Evacuation Start **then**
  - 5:     **if** (Car is TRUE **and**  $t\%2 == 0$ ) **or** (Car is FALSE **and**  $t\%15 == 0$ ) **then**
  - 6:         Test for evacuation start and completion . Sec. 3.3
  - 7:         Update Agent’s Location and destination . Sec. 3.4
  - 8:     **end if**
  - 9: **end if**
- 

### 3.2 Agent ERI exchange behavior

Following the rules in Algorithm 1, every 15 simulation steps an agent tries to provide/receive ERI information from the environment. While the transmission of this data across distances is handled by the cell model (see Section 3.5), the transfer of data to and from agents is handled by the agent model. Figure 1 gives an overview of this process.

Evacuee agents first try to acquire information from the cell (EL and WBS agents are assumed to always have the newest information). This process takes the following steps:

- Agent pools the local data from the cell ( $Info_{local}$ ) with probability  $p_{local}$ , if available. This corresponds to agents in the same cell sharing information.
- Agent pools regional data from the cell ( $Info_{prop}$ ), if available. This corresponds to agents overhearing information.
- Agent compares any information that it currently possesses with the local and regional data, and keeps the newest one.
- If the agent has no information, it sets its own  $S_{asking}$  flag to true, indicating to the cell model that the agent may send out an information request.

As a result of this process, the agent may obtain an up-to-date ERI, which will be used to define the agent’s path finding (see Section 3.4) and also when the agent begins evacuating (see Section 3.3). After the agent has acquired information, it will determine whether it is broadcasting its own information. This is controlled by the  $S_{providing}$  flag, which is turned on according to the following conditions:

- **Evacuee agent:** will set  $S_{\text{providing}}$  to true if it hears an information request (represented by cell’s attribute  $S_{\text{asked}}$ ).
- **EL agent:** will set  $S_{\text{providing}}$  to true if any cell within 50m of its location contains at least one evacuee agent.
- **WBS agent:** will set  $S_{\text{providing}}$  to true at fixed intervals, according to the simulation parameters.

### 3.3 Agent evacuation start behavior

Before moving, an evacuee agent will test whether it should begin the evacuation process, and then test whether it has completed the evacuation process.

The test for beginning the evacuation process has two different patterns: “Start by time distribution” and “Start by intention”. These two patterns were designed following the patterns observed in earthquake and tsunami evacuations, respectively.

In the first pattern, the evacuation start time for each agent is fixed, following the distribution defined in the scenario parameters. This reflects the situation of an earthquake evacuation where after the earthquake is finished, each evacuee will start to move according to their own conditions.

In the second pattern, the evacuation start time is controlled by the agents *Intention* attribute. The value of this attribute is one of “evacuate immediately”, “evacuate tentatively” and “do not evacuate”, and each value determines a range of possible start times. The distribution of intention values, and the evacuation start time associated with each value are determined by the scenario parameters.

An agent’s intention attribute can be modified when the agent receives information from other agents. In other words, nearby evacuees or EL may call this agent to start evacuation, or the WBS may cause the agent to begin evacuating. In the model, whenever an agent that has not begun evacuating receives information from other agents, it may change the value of its Intention attribute, following the probabilities listed in Table 2.

To test whether the evacuation is complete, an agent checks whether its current cell corresponds to its intended evacuation shelter. If it does, it checks whether the evacuation shelter is full. If the evacuation shelter is not full, the agent will enter the “evacuation complete” state, which stops any further state changes, and also stops the sending or receiving of voice messages. If the evacuation shelter is full, the agent will update its ERI, and change its destination to the nearest non-full evacuation center.

**Table 2:** Probability of change in the intention attribute of an agent when it receives an ERI from other agents. Data based on the 2012 survey from the Japanese Cabinet Office (Cabinet Office, 2012)

Source of ERI	Change on Intention value		
	Ev. Immediately	Ev. Tentatively	No Change
WBS (only first time)	0.4	0.4	0.3
Evacuation Leader	1	0	0
Evacuee (first time)	0.4	0.45	0.15
Evacuee (after first)	0.1	0	0.9

**Table 3:** Movement and Path Finding Patterns for Evacuee Agents

Scenario	Agent			Cell	Pattern	
	ERI	Resident	Familiar	Cell <i>follow</i>	Destination	Path finding
Earthquake	Yes	Yes	Yes	–	Shelter	Dijkstra
			No	–		RTA*
		No	–			–
	No	–		Yes	Cell <i>follow</i>	–
		–		No	Random	–
Tsunami	Yes	–			Shelter or High Place (Closest)	Dijkstra
	No	–			High Place	

### 3.4 Agent movement and path finding

An agent’s movement is divided into two steps: calculating the agent’s destination, and then calculating the agent speed. WBS agents are static and do not move. Evacuee and EL agents use the same rule for calculating agent speed, but different rules for path finding.

#### (1) Destination and Path finding

Evacuation Leaders try to find and guide evacuees. Therefore, they will alternate between two states: the agent will move for 5 to 30 minutes, and then stay in place between 0 and 20 minutes. While it is moving, the agent will keep going in the same direction, until it reaches an intersection, when it will choose a new direction at random. In the case of tsunami scenarios, directions that lead to higher elevation have a higher weight in this selection, and this weight increases as the simulation progresses.

Evacuee agents’ path finding will depend on whether they possess ERI, how familiar they are with the area, and whether it is a tsunami or earthquake evacuation scenario. These cases are summarized in Table 3.

If the agent has no information about evacuation shelters at all, it will follow other agents in the same cell, or move randomly. If the scenario is a tsunami evacuation, it will move towards a higher place following the Dijkstra algorithm. Agents moving randomly will have a higher weight towards map areas with high building density, to simulate the observed tendency of evacuees to move to places that are familiar to them (Kashiwabara et al., 1998).

Resident agents will move towards an evacuation shelter, while non-resident agents can move to an evacuation shelter, or to the outer borders of the map (during the tsunami scenario, the “map border” option is not available).

Finally, agents familiar with the region will use the Dijkstra algorithm to choose their path to the destination, while agents without familiarity will use the Real Time A-star (RTA\*) algorithm.

#### (2) Movement Speed

After the EL or Evacuee agent chooses its destination, and consequently which cell it wants to move to next, the simulation calculates the agent speed, and whether the agent successfully changes cells in this simulation step.

The agent speed is decided based on: The average crowd density (Fruin, 1987) between the cell the agent is in, and the cell it wants to move to, the number of people represented by the agent, whether the agent is in a car, whether it includes “weak walkers”, and whether the agent has ERI. If the agent is in a car, the speed calculation also takes into account whether there are obstacles (road damage) in the cell. Given these attributes, the agent’s speed is calculated using Algorithms 2 and 3, resulting in a final speed between 0 and 1.43 m/s for pedestrian agents, and 0 to 40 km/h for driving agents.

Once the speed of an agent is found, the simulation calculates how many cells the agent can move to within 15 (for pedestrians) or 2 (for drivers) simulation steps, and updates the agent’s current cell

accordingly.

---

**Algorithm 2** Walk speed algorithm

---

**Require:** Cell Density  $cd$ , Agent attributes Weak, Has ERI, Number

```
1: speed = max(1.433 - 0.417 * cd, 0)
2: if Weak then
3:     speed = min(speed, 0.94)
4: end if
5: if  $cd > 0.67$  then
6:     if not Has ERI then
7:         speed = speed*0.75
8:     end if
9:     if Number > 1 then
10:        speed = speed*(0.95 - 0.025*Number)
11:    end if
12: end if
```

---

---

**Algorithm 3** Car speed algorithm

---

**Require:** Cell Obstacle  $co$

```
1: speed = 40000 / 3600
2: if First time agent is moving then
3:     speed = 30000 / 3600
4: end if
5: if Current cell is a curve or Evacuation Shelter then
6:     speed = 10000 / 3600
7: end if
8: if Current cell has an obstacle then
9:     speed = 5000 / 3600
10: end if
```

---

### 3.5 Environment

The simulation environment is organized into a regional grid and the local cells. The regional grid contains large-scale information about the simulated environment, such as height, type and density of buildings. It is also used to calculate the spread of tsunami damage across the map. The local cells represent small stretches of connected roads. In the simulation, agents only move within the local cells.

For the generation of regional and cell data, our model uses the map database and regional file data from the Car Navigation Research S Standard format, Version 2.2 (Navigation System Research Group, 1997). The list of configuration parameters for regional and local data is summarized in Table 6.

#### 3.5.1 Regional Grids

The simulated area is divided into an  $x \times y$  lattice, where  $x$  and  $y$  are arbitrary integers. For each region in the lattice, we define its population, building type and inundation levels as input parameters in the model. The population parameters (number of inhabitants, proportion of residents, weak walkers, vehicle users, etc.) are used to define the initial setup of the evacuee agents. In the simulations discussed in this study, we obtain this data from the local census (See Section 4 for details).

The building type parameter is used to determine the presence of debris (damaged buildings) obstructing the cells. Following the model of Muraki and Kanoh (2007), each region in the lattice has a

*building type* value. At the start of the simulation, each cell in the region has a chance of having obstructions depending on the building type of the region (see Table 4). These obstructions reduce the effective area of the cell.

**Table 4:** Regional Building Types and Chance of Obstruction in Cells

Building type	Regional grid meaning	Chance of obstruction at each cell
0	No buildings	No obstructions
1	Low buildings, Low density	10% chance
2	Low buildings, High density	50% chance
3	High buildings, Low density	1% chance
4	High buildings, High density	5% chance

**Table 5:** Cell attributes

Attribute name	Attribute meaning
Coordinates	X and Y location of the cell in the regional map
Area	Surface area of this cell available for pedestrians and vehicles
Neighbor	List of connecting cells
MapBorder	Is true if this cell borders the map
Shelter	True if a shelter is adjacent to this cell
Inundation Level	Index for the time when this cell is considered inundated
Population	Sum of the people of all agents currently in this cell
Density	Population / Area, in $m^2$
Cellfollow	Neighbor cell to which more than half the agents are moving
Sasked	True if an information request has propagated to this cell
Plocal	Probability of obtaining ERI indicated in $Info_{local}$
$Info_{prop}$	ERI that was propagated by a broadcasting agent
$Info_{local}$	ERI that is most common in this cell
Shelter Available	True if an adjacent shelter can receive more evacuees

In addition to Muraki’s model of building damage, we also include tsunami damage in the simulation. Each region is assigned a height, and an *inundation level*, and the simulation as a whole has a *global inundation value*. The global inundation value begins at zero and increases at pre-determined intervals. Cells in regions with an inundation level equal to or less than the global inundation value are considered inundated and inaccessible. To calculate the speed at which the regions and cells become inundated, we used recorded evacuation and disaster data (Ishinomaki Municipal Government, 2014).

### 3.5.2 Local Cells

A cell in our model represents a 20-meter road region that can be traversed by cars or pedestrians. In this sense, highways and roads exclusive to cars are not represented. Also, buildings are represented at the region level, not the cell level.

All cells have information regarding which other cells are adjacent. They may also contain an adjacent evacuation shelter (which has a maximum number of people and vehicles that it can handle before becoming full). Also, cells may be flagged as “border” cells, and be eligible as evacuation shelters for agents representing commuters who live outside the area defined in the scenario. Other attributes of a

cell, such as the number of people currently in it, and whether any ERI can be heard from this cell, are listed in Table 5. Every 30 simulation steps the cell attributes are updated according to the following steps: Receive ERI requests and offers from agents; Propagate sound messages across cells; Update cell attributes.

- **Receive ERI requests and offers:** An evacuee agent will generate an ERI request if its  $S_{\text{asking}}$  attribute is true, and if the crowd density of this cell is less than  $0.05/m^2$ . After the request,  $S_{\text{asking}}$  is set to false. An agent will generate an ERI offer if the attribute  $S_{\text{asked}}$  of this cell is true (i.e., a request can be heard). Also, EL and WBS agents will generate ERI offers following the rules described in Section 3.2.

- **Propagate sound messages:** Each cell will try to propagate the messages generated in the previous step to other nearby cells. The probability  $p_{ij}^m$  of a message  $m$  at cell  $i$  to be transmitted to cell  $j$  is given by Equation 1, which is truncated to the (0,1) range. This formula assumes a point sound source, with no acoustic reflection or diffraction. It is based on experimental results on word intelligibility in crowds (Kondo et al., 2007) and average noise intensities at crowded downtown locations (Japanese Ministry of the Environment, 1998, Mitsuoka, 2005).

**Table 6:** Initial Scenario Configuration Parameters

Scope	Parameter
General	Simulation starting time
	Tsunami arrival time
	Inundation level increase interval
Evacuee	Total number
	Proportion of residents
	Proportion of regional familiarity
	Proportion of weakened walkers
	Proportion of evacuation by vehicle
	Evacuation Starting Time
EL agent	Total number
	Starting time of activity
WBS agent	Total number
	Placement
Cell	Placement of evacuation shelters
	Shelter vacancy limit
Region	Population density
	Building type
	Height level

$$p_{ij}^m = \begin{cases} 0 & (a_{ij}^m \leq 45) \\ \frac{a_{ij}^m - 72 + 10}{20} & (c_j > 3.97) \\ \frac{a_{ij}^m - (55 + 17 \frac{c_j}{3.97}) + 10}{20} & (c \leq 3.97) \end{cases} \quad (1)$$

$$a_{ij}^m = A_{\text{sound}}^m - 20 \log_{10} d_{ij}$$

$$c_j : \text{crowd density of cell } j \text{ people}/m^2$$

$$d_{ij} : \text{Euclidian distance between cells } i, j \text{ (meters)}$$

$$A_{\text{sound}}^m : \text{voice capacity of agent } m \text{ in decibels (db)}$$

In this equation, the value of the  $A_{\text{sound}}$  parameter is set as 85 for the evacuee agent, 105 for the Evacuation Leader agent, and 115 for the WBS agent. These values make the assumption that the EL agent is equipped with a loudspeaker or loudspeaker vehicle. It is worth noting that in the current model,

buildings and obstructions do not affect sound transmission directly (however, obstacles affect it indirectly by increasing the crowd density of a cell).

- **Update attributes:** The cell updates its attributes according to the following rules:
  - If the cell receives one or more ERI requests, it sets  $S_{asked}$  to true.
  - If the cell receives one or more ERI offers, it sets the value of  $Info_{prop}$  to one of them, selected randomly. Otherwise, this value is set to *none*.
  - $P_{local}$  is set to the proportion of agents in the cell that possess ERI information.
  - If  $P_{local}$  is greater than 0,  $Info_{local}$  is set to the ERI of one of the local agents, selected randomly.
  - Population, Cell Density, Cell Follow and Shelter Available are updated according to the number and attributes of agents in the cell.
  - Inundation status is updated according to information from the region in which this cell is located.

**Table 7:** Details of the Agent Composition for the Two Simulated Regions

Model Attribute	Value	Data Source
Kobe city scenario		
Number of evacuees	43,998	National Census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010)
Number of agents	14,666	
Weak walkers	43%	National Census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010), people less than 15 or more than 65 years old.
Evacuees in car	20%	Post-evacuation survey (Kashiwabara et al., 1998)
Non-residents	20%	Assumption based on transit at 6:00 am
Familiar residents	54%	National Census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010), people who have lived in the same area for more than 5 years.
Ishinomaki city scenario		
Number of evacuees	104,271	National Census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010), and Disaster Prevention Plan (Ishinomaki Municipal Government, 2014)
Number of agents	34,757	
Weak walkers	43%	National Census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010), people less than 15 or more than 65 years old.
Evacuees in car	50%	Post-evacuation survey (Cabinet Office, 2012)
Non-residents	0%	Not considered for this simulation
Familiar residents	60%	Post-evacuation survey (Cabinet Office, 2012)

#### 4. MODEL EVALUATION

In this section, we present simulation experiments to observe the proposed model, and evaluate how it performs as a representation of a natural disaster evacuation.

In these experiments, we use hypothetical scenarios based on the observed initial conditions of the evacuations in Kobe city during the Great Hanshin-Awaji Earthquake, and in Ishinomaki city during the Great East Japan Earthquake and tsunami. These initial conditions are set based on demographic data from the national census and post-evacuation surveys (see Table 7).

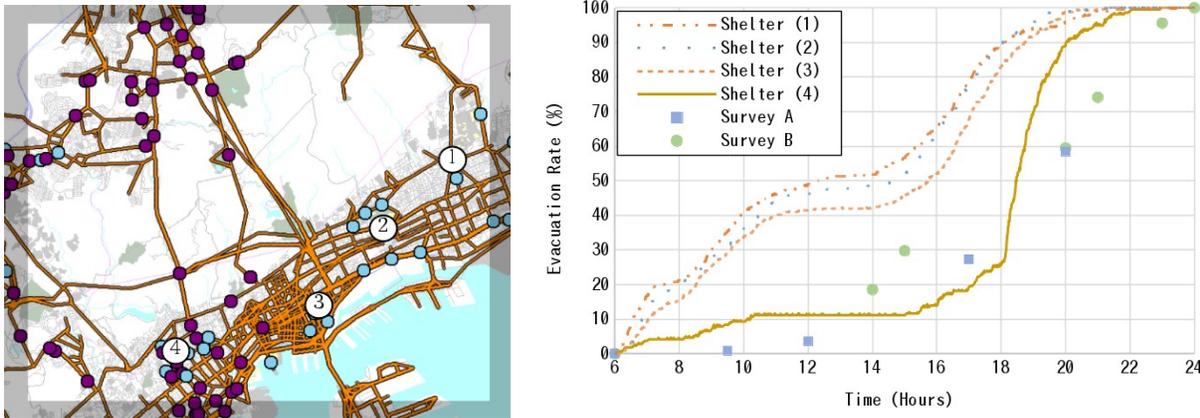
For each experiment, we change the voice information exchange parameters or the evacuation start behavior parameters, and observe how the change of these parameters affects the end state of the simulation. Namely, we observe the time to start the evacuation, the end time of the evacuation, and the number of completed evacuations. In the first two experiments, we compare these values to the observed values in the post-evacuation survey, to consider to what degree the simulated outcomes agree with the observed data from the real-world evacuation.

In the third experiment, we modify the hypothetical scenario based on the Great Hanshin-Awaji Earthquake evacuation, adding Evacuation Leaders and Wireless Broadcast System infrastructure, which were not deployed during the original disaster. The objective of this experiment is to demonstrate how the proposed model could be useful as a way to measure the effect of new disaster mitigation strategies, and to assist in the design and decision of new policies.

A summary of the experiments and their results is listed in Table 8. To understand the internal variance of the proposed model, for each experiment we repeat the simulated scenario 30 times. In the following sections we report the averaged results along with their standard deviation. We report statistical significance when relevant in the text, using Bonferoni corrections when comparing multiple quantities. These statistical significance tests are useful to observe the influence of the inherent variance of stochastic multi-agent systems, but do not necessarily take into account uncertainties related to the limitations of the simulated model (which are discussed in Section 5.1).

**Table 8:** Summary of the Experiments and Results

Experiment	Controlled parameters	Results summary
<b>Experiment I, Section 4.1: Kobe City – Analysis of route information exchange</b>		
Case 1-1	No route information exchanged	Case 1-3 shows a higher evacuation rate, closer to the expected value. Case 1-2 shows higher variance, while 1-3 seems to reduce the randomness of the model (Table 9)
Case 1-2	ERI exchanged in the same cell	
Case 1-3	ERI exchanged across cells	
<b>Experiment II, Section 4.2: Ishinomaki City – Analysis of evacuation start behavior</b>		
Case 2-1	Evacuation-start: 0-10, 5-15 min	Case 2-3 shows the best agreement with the observed data, in terms of evacuation start time, and total evacuation time (Figures 4 and 5)
Case 2-2	Evacuation-start: 5-15, 10-20 min	
Case 2-3	Evacuation-start: 10-15, 15-25 min	
<b>Experiment III, Section 4.3: Kobe City – Introduction of EL and WBS</b>		
Case 1-3	No communication agents	The introduction of WBS agents showed a reduction in average evacuation time. The contribution from EL agents was unclear (Table 11)
Case 3-1	EL agents only	
Case 3-2	WBS agents only	
Case 3-3	Both agents	



**Figure 2:** Left: Area for the hypothetical scenario in Kobe City. Blue circles indicate designated shelters, purple circles volunteer shelters. Right: Evacuation Rate over time for four shelters in the simulation Case 1-3, and two post-disaster survey results.

#### 4.1 Validation experiment I: Kobe City

For this experiment, we use a 11 km×9 km area around the district of Kobe City, as illustrated in Fig. 2. We use data based on the post-disaster report (Kashiwabara et al., 1998) to determine the location and quantity of evacuation shelters, the number of evacuees, and their starting evacuation times. Other regional parameters of the simulation were set based on the Japanese national census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010), and the city plan drawing of Kobe city (Kobe City Planning Division).

Data from the municipal government states that there were 28 “designated” evacuation shelters. Additionally, there were reports of “voluntary” shelters formed by the evacuees (Kashiwabara et al., 1998). Because there is no exact data about the voluntary shelters, we simulate them by adding 60 shelters at random residential areas in addition to the 28 designated shelters.

Following the post-disaster report, our simulation includes 44000 evacuees during the period between 6:00 and 24:00 on January 17th, 1995. We define evacuation starting times for the evacuee agents according to the following rule:

- 25% of the agents begin evacuating immediately following the earthquake. Evacuation start time is drawn from a normal distribution ( $\mu = 6:30, \sigma = 0:10$ ).
- 25% of the agents begin evacuation a few hours after the earthquake. Evacuation start time is drawn from a normal distribution ( $\mu = 9:00, \sigma = 1:00$ ).
- 50% of the agents begin evacuation late in the afternoon. Evacuation start time is drawn from a normal distribution ( $\mu = 16:30, \sigma = 2:30$ ).

For this scenario, it was reported (Kobe City Fire Department, 1995) that Kobe municipality did not set up radio broadcast stations (WBS), and the loudspeaker cars of the fire brigade were being used for rescue activities. Therefore, we consider only the communication between evacuee agents. We simulate the evacuation using three different information sharing models:

- **Case 1-1:** Evacuees do not share information.
- **Case 1-2:** Evacuees share information with others in the same cell.
- **Case 1-3:** Evacuees share information with others in the same cell, and use voice to communicate with agents in nearby cells.

Case 1-1 is the same as the original Muraki Model that we use as the base for our proposed model. Cases 1-2 and 1-3 include the changes to the communication model described in this study. The results of these simulations are summarized in Table 9 and Fig. 2.

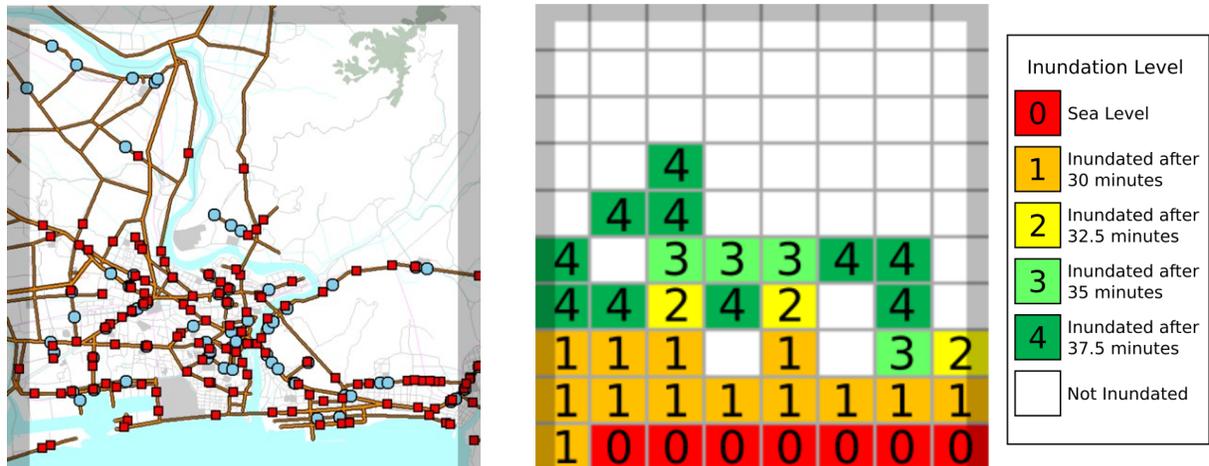
**Table 9:** Simulation results for the Kobe City validation experiment. An average of 30 simulations is reported, with its standard deviation in parentheses.

Case	Evacuation Ratio	Evacuation Time
1-1 (Muraki Model)	92.2 (0.28)	27.8 min. (0.41)
1-2 (Same cell communication)	93.9 (1.68)	28.4 min. (1.41)
1-3 (Voice communication)	95.5 (0.59)	27.3 min. (1.18)

The results of Table 9 show that as we add communication abilities to the evacuee agents, we get a higher evacuation ratio without an equivalent change in the average evacuation time. In this hypothetical scenario, since the initial number of evacuees was not available, we defined the initial number of agents to be the same as the number of evacuees who reached shelters according to the evacuation records. Therefore, our goal is to find a parameter set that brings the simulated evacuation rate to be as close to 100% as possible. In this sense, Case 1-3 seems to be the most appropriate parameter setting to make this hypothetical scenario closer to the observed data. By modeling the spread of information about evacuation routes, our model can represent the initial confusion from evacuees, followed by a more organized movement towards the shelters as the agents exchange information.

In Fig. 2 we see the graph of the rate of evacuation completion over time for Case 1-3. The lines represent the results of four simulated shelters (indicated by numbers in Fig. 2), while the points represent data from post-disaster surveys. It is interesting to note that we can infer the shelter density from these curves: Shelters 1, 2 and 3 are in areas with low shelter density, and they receive over 50% of their evacuees over the first 5 hours of the simulation. Shelter 4, on the other hand, is located in a region with multiple voluntary shelters. So, for the first 12 hours, it receives less than 30% of its capacity, and then quickly fills up as the other shelters around it become full. This indicates how the simulator could be used to find areas that have a lack or excess of evacuation shelters.

It is interesting to also consider the higher variance of Case 1-2. Figure 2 shows that the evacuation speed and completion ratio change with time. As more and more evacuees get off the streets and into shelters, the effectiveness of information exchange varies as well. At the beginning of the evacuation, there is a higher number of evacuees on the move, and information exchange occurs often. As the evacuation progresses and agents reach their destinations, the number of agents on the streets is reduced, and exchange of evacuation route information depends on whether two agents happen to be in the same cell. Using voice propagation in Case 1-3 makes it easier for agents to contact each other even if they are relatively far apart, and therefore makes it more likely that late agents will obtain some sort of evacuation route information, reducing the randomness of the model.



**Figure 3: Left:** Simulated area in Ishinomaki City. Circles indicate shelters, while squares indicate WBS positions.

**Right:** Inundation levels used in the simulation. Numbers indicate the order in which each zone becomes inundated.

#### 4.2 Validation experiment II: Ishinomaki City

For this experiment, we use a 11 km×10 km area around the high population zone of the former Ishinomaki district in Ishinomaki city, as shown in Fig. 3. This city was one of the most affected by the Great East Japan Earthquake and its ensuing tsunami. Using numbers derived from the disaster management operation based on Ishinomaki City (Ishinomaki Municipal Government, 2005), the evacuation scenario defines 68 evacuation shelters, 100 EL agents in cars, and 132 WBS agents. WBS agents repeat their broadcast every 5 minutes for the duration of the evacuation process. Other regional parameters are set following the 2010 national census (Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010).

The simulation generates agents for the people living or working in the area who were affected by inundation (inundation levels 1-4 in Fig. 3). In this figure, Area 0 represents the sea, Area 1 becomes inundated 30 minutes after the earthquake, and each subsequent area becomes inundated 2.5 minutes after that, until Area 4 at 37.5 minutes. These values were obtained from the municipal report on the disaster (Ishinomaki Municipal Government, 2014).

Note that while an earthquake evacuation scenario, such as that described in Section 4.1, happens over a period of 18 hours, a tsunami evacuation scenario is much shorter, in this case, under 40 minutes. Therefore, the time when people begin evacuating is a critical issue in disaster mitigation for tsunami scenarios. Accordingly, in this hypothetical simulation we evaluate both the evacuation start time, and the evacuation time across the agents in the simulation.

A survey with the evacuees for the 2011 tsunami (Cabinet Office, 2012) identified the following behavior patterns of people regarding evacuation starting times:

- 20.5% of evacuees began evacuation *immediately* after the earthquake.
- 23.1% of evacuees began evacuation *tentatively* after the earthquake.
- 3.4% of evacuees began evacuation *immediately* after receiving information through radio broadcasts.
- 4.5% of evacuees began evacuation *tentatively* after receiving information through radio broadcasts.
- 48.5% of evacuees began evacuation after noticing the approaching tsunami.

In our model, these four patterns are represented through the “evacuation start” behavior in

evacuee agents, described in Section 3.3. In this experiment, we want to see to what degree this model is able to reproduce the observed evacuation start patterns.

To this end, we focus on three parameter settings for the simulation. For each case we change the delays associated with the “evacuate immediately” and “evacuate tentatively” behaviors according to Table 10. Note that, in addition to the initial evacuation start behavior, the model also allows agents to begin evacuating earlier when they receive messages from other agents, as described in Table 2.

The simulation of each case is repeated 30 times. In Table 10 we can compare the evacuation ratio between each case and the historical record. We see that Case 2-2 reaches a very close mean to the record, but also has quite a large variance.

**Table 10:** Simulation results for the evacuation start behavior validation experiment. Results in the right column are the average of 30 simulations, with standard deviation in parentheses. Values in the middle two columns are the range of simulation start times for the two behaviors included in the model.

Case	Time to start Evacuation		Result Evacuation ratio
	“Immediately”	“Tentatively”	
Historical record	–	–	79.4
Case 2-1	0-10 min	5-15 min	82.0 (0.48)
Case 2-2	5-15 min	10-20 min	79.6 (4.19)
Case 2-3	10-15 min	15-25 min	75.4 (0.30)

**Table 11:** Variation in simulation results according to the introduction of disaster preparedness policies. Values in parentheses are the standard deviation of the results.

Policy introduced	Evacuation completion ratio (%)	Average evacuation time (min)
Case 1-3 (No policy)	95.5 (0.59)	27.3 (1.18)
Case 3-1 (EL agents)	95.7 (0.22)	27.7 (0.9)
Case 3-2 (WBS agents)	95.8 (0.19)	25.1 (0.38)
Case 3-3 (Both)	95.8 (0.20)	25.1 (0.31)

To better understand these results, Figs. 4 and 5 offer a breakdown of the start evacuation time and the total evacuation time, respectively, across the evacuee population. In these images, we can see that the breakdown of Case 2-3 is closer to the survey record than that of Case 2-2. One way to explain this discrepancy is to consider that the historical record on the evacuation ratio includes people who did not evacuate because their home was already in a secure location, while the evacuation ratio of the hypothetical scenario considers only agents that both began evacuating at some point and then successfully completed their evacuation. Taking these “non-evacuees” into account when interpreting Table 10 leads us to believe that Case 2-3 provides the best reproduction of the available survey data.

We also note that while both Cases 2-2 and 2-3 do not include behaviors for agents to begin evacuation before the 10-minute mark, 40% of the agents begin their evacuation between 0 and 10 minutes. This reflects agents that began evacuation initially by receiving information from either EL or WBS agents, and eventually a cascading situation from other evacuee agents calling each other. As these proportions approximate the survey data, it indicates that the proposed sound propagation model is a good approximation of evacuees calling each other out during a natural disaster.

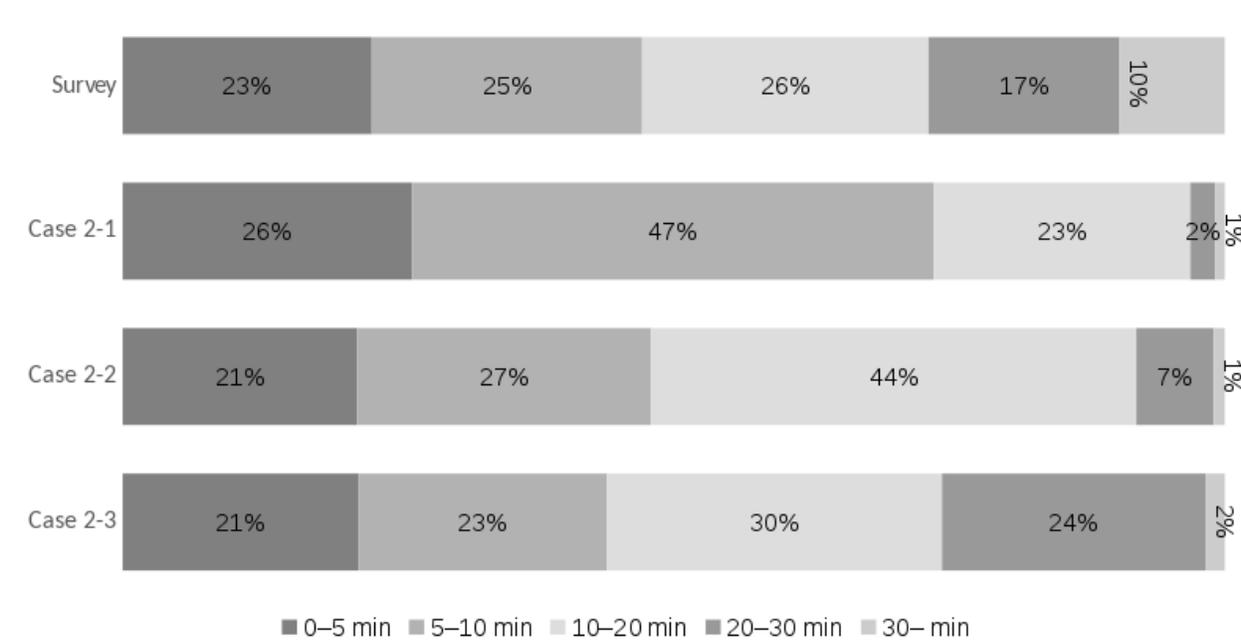
#### 4.3 Planning experiment: Kobe City

In this third experiment we want to demonstrate how the proposed model could be useful in the planning of disaster mitigation policies. To this end, we repeat the Kobe City Earthquake experiment, but add to it three scenarios that do not correspond to the historical evacuation effort. Namely:

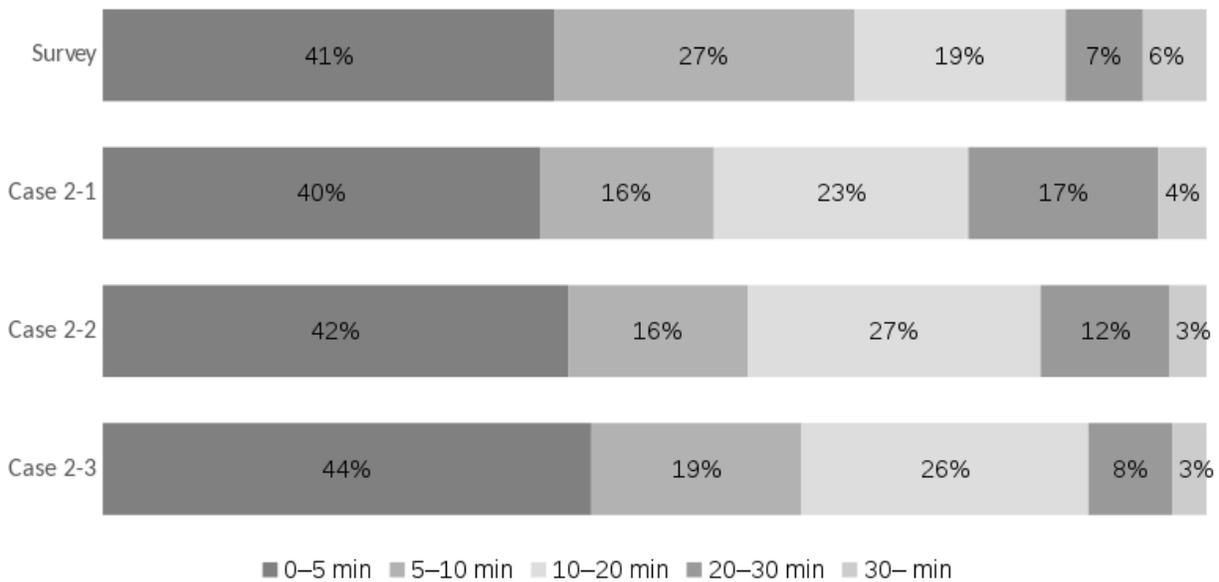
- Case 3-1 Addition of Evacuation Leaders;
- Case 3-2 Addition of Wireless Broadcast Systems;
- Case 3-3 Addition of both EL and WBS agents.

It was reported (Kobe City Fire Department, 1995) that during the Great Hanshin-Awaji Earthquake, Kobe municipality did not have emergency wireless broadcast setup, and that the fire brigade focused mainly on rescue activities, so they did not act as evacuation organizers. Therefore, in these experiments we consider the addition of each of these two systems. We are interested in observing the effect of these changes in the evacuation ratio and the average evacuation time.

For Cases 3-1 and 3-3 we add two EL agents for every evacuation center, for a total of 172 agents. These agents are deployed 4 hours after the start of the simulation, to coincide with the time that the regular rescue operations took place. For Cases 3-2 and 3-3, we deployed one WBS agent for every evacuation center, for a total of 88 agents, which broadcast Evacuation Route Information every 5 minutes after the earthquake.



**Figure 4:** Time to start evacuating across the population in the Ishinomaki City hypothetical simulation



**Figure 5:** Evacuation time across the population in the Ishinomaki City hypothetical simulation

The results of this experiment are listed in Table 11. In this table, we compare the three proposed scenarios with Scenario 1-3 of the first experiment (Section 4.1). None of the three proposed cases show a difference in terms of the evacuation ratio from the original setup without the deployment of communication systems. However, we observe that Cases 3-2 and 3-3, which add WBS agents to the scenario, show a small reduction in the average evacuation time. The statistical analysis confirms that this reduction is caused by the change in simulation parameters (with confidence above 95%).

Because of the limitations of the model, it is difficult to extract exact prediction information. For example, in real life the Evacuation Leaders could decide to change their strategy dynamically according to what they observe during the evacuation. However, we can infer from the results that even in such a simple simulation of human behavior, a system that provides information to the evacuees made their evacuation efforts more effective. Regarding the Evacuation Leaders, a more complex agent might have been able to show a positive effect on the evacuation too.

In any case, this result shows that the distribution of information to evacuees is most critical during the initial moments of evacuation (before they are able to eventually organize themselves). This observation reflects the complaints and observations made after the earthquake, as discussed in Section 2.1.

With the proposed simulation model, a governmental body could use this result to justify an investment in communication systems such as damage mitigation measures, and even perform further investigations into the most effective areas for adding such a system.

## 5. CONCLUSION

Because of the difficulty of predicting earthquakes, currently the best policy for mitigating damage from these natural disasters is to maintain preparedness of the population and infrastructure. To this end, simulation models of evacuations are an important tool for the planning and development of effective damage mitigation policies.

In this context, we proposed a multi-agent simulation model for the simulation of an earthquake or

tsunami evacuation. Considering the importance of the exchange of information between evacuees and evacuation personnel during a natural disaster, our Multi-Agent System uses a communication model where: a) The agents exchange information by sending messages to each other over voice; b) These messages influence the agent's behavior regarding path finding and start-evacuation behavior; c) We use Kondo et al.'s voice intelligibility model to determine the spread of information in crowded streets. With these characteristics, we reproduce behaviors that have been observed during actual evacuations, such as agents that do not begin their evacuation until someone else urges them to do so.

The proposed system is an extension of an existing earthquake simulator, introducing the concepts of message exchange described above, as well as the simulation of time-dependent tsunami damage. To evaluate the validity of our extended model, we performed experiments on three hypothetical scenarios, based on the starting conditions observed in Kobe City during the Great Hanshin-Awaji Earthquake in 1995, and in Ishinomaki City during the Great East Japan Earthquake in 2011, and varying message exchange parameters. We observed the initial and final states of the evacuation simulation, and compared them with observed data to validate the proposed model. Additionally, we studied the use of the proposed model as an analysis tool, by considering the use of Evacuation Leaders and Wireless Broadcast Systems in the Kobe hypothetical scenario.

These results show that the proposed information exchange model, and the accompanying model for changing agents' evacuation-start behavior, are important components of a large-scale, multi-agent evacuation simulation model. Therefore, we recommend the addition of the model described in this study to such simulators, and its further study.

### **5.1 Model limitations and future work**

Multi-agent simulation models involve uncertainty based on the decisions of what to represent, and what to abstract in the model. Adding the representation of abstracted effects to the model may reduce these uncertainties if the effects can be represented effectively, but will also increase the complexity of the model.

For the model presented in this study, we highlight three abstracted effects that we believe could effectively improve the precision of the model, and will be considered in future work. These are not the only abstractions contained in this model.

First, the current model uses a proprietary car navigation map that, while it is very accurate for Japanese cities, is difficult to modify or use with arbitrary maps. This limits the current model to streets that are passable by cars, and prevents behavior such as evacuees crossing parks or pedestrian roads. One way to fix this limitation would be to change the simulation model to use data from the OpenStreetMaps foundation.

Second, our current agent model represents only a very small set of human agent strategies. For example, it was observed during the evacuations that some evacuees employed a multi-stage evacuation, first going to a temporary nearby safe location, and then moving to the proper evacuation shelter. Also, the evacuation leader behavior is largely random, while rescue efforts in the real world are much more organized, which may explain the lack of effects observed in experiment Cases 3-1 and 3-3. Consequently, we intend to add more complex agent behavior in future versions of our model.

Finally, in the current model, buildings and obstructions do not have direct effects on the voice intelligibility, and the model for the sound wave propagation is fixed. It would be interesting to further investigate the sound propagation physics model by adding the effect of buildings and visibility to message transmission, and also the effect of sound wave speed on the simulation.

## **REFERENCES**

Beck Z., Teacy L., Rogers A., and Jennings, N. R., Online planning for collaborative search and rescue by heterogeneous robot teams. In *Proceedings of the 2016 International Conference on Autonomous Agents and Multi-Agent Systems*, pp. 1024–1033, 2016.

- Borve, S., Crowd dynamics modelling – a literature study. Technical report, Norwegian Defense Establishment, 2014.
- Bosse T., Gerritsen C., and Treur J., Agent-based simulation of episodic criminal behavior. *Multiagent and Grid Systems*, 9(4): 315–334, 2013.
- Boukas E., Kostavelis I., Gasteratos A., and Sirakoulis G. C., Robot guided crowd evacuation. *IEEE Transactions on Automation Science and Engineering*, 12(2), April 2015.
- Cabinet Office. Information collection regarding the lessons learned in the Great Hanshin Earthquake. online: [http://www.bousai.go.jp/kyoiku/kyokun/hanshin awaji/data/index.html](http://www.bousai.go.jp/kyoiku/kyokun/hanshin_awaji/data/index.html), 1999. (Accessed November 2015, in Japanese).
- Cabinet Office. Survey on earthquake and tsunami evacuation during the Great East Japan Earthquake. online: <http://www.bousai.go.jp/jishin/tsunami/hinan/index.html>, 2012. (Accessed November 2015, in Japanese).
- Cafaro A., Glas N., and Pelachaud C., The effects of interrupting behavior on interpersonal attitude and engagement in dyadic interactions. In *Proceedings of the 2016 International Conference on Autonomous Agents and Multi-Agent Systems*, pp. 911–920, 2016.
- Clerveaux V., Katada T., and Kuwasawa K., Tsunami scenario simulator: A tool for ensuring effective disaster management and coastal evacuation in a multilanguage society. *Science of Tsunami Hazards*, 27(3): 48–72, 2008.
- Eck A. and Soh L., To ask, sense, or share: Ad hoc information gathering. In *Proceedings of the 2015 International Conference on Autonomous Agents and Multi-Agent Systems*, pp. 367–376, 2015.
- Foundation for the Center of Fire Fighting Science, General data for regional disaster prevention: Basic data for the Great Hanshin Earthquake. Technical report, 1997. In Japanese.
- Fruin J. J., *Pedestrian Planning and Design*. Elevator World, 1987.
- Genter K. and Stone P., Adding influencing agents to a flock. In *Proceedings of the 2016 International Conference on Autonomous Agents and Multi-Agent Systems*, pp. 615–623, 2016.
- Inoue H., Tsunami alert using imperative form: Examples of expressions used in the disaster prevention administrative radio system in the Great East Japan Earthquake and the subsequent attempt to introduce them (one year after the Great East Japan Earthquake). *The NHK Monthly Report on Broadcast Research*, 62(3): 22–31, 2012. In Japanese.
- Ishinomaki Municipal Government, Ishinomaki-shi disaster management administration, radio station management operation regulations. Instruction No. 82, April 2005. In Japanese.
- Ishinomaki Municipal Government, Ishinomaki city disaster prevention plan. Public Edition, Revised December, 2014. In Japanese.
- Japanese Ministry of the Environment, Regarding environmental standards concerning noise, announcement on September 30, 1998 64. Announcement Number 64, September 30, 1998. In Japanese.
- Kashiwabara S., Ueno A., and Morita T., A study on evacuation centers in the Great Hanshin-Awaji Earthquake. Technical report, Osaka University Press, 1998. In Japanese.
- Kobe City Fire Department, Snow magazine. Kobe City Dangerous Goods Safety Association, March 1995. In Japanese.
- Kobe City Planning Division, Kobe city application area search. <http://www.city.kobe.lg.jp/business/plan/search/>. (Accessed July 2014). In Japanese.
- Kondo K., Izumi Y., Fujimori M., Kaga R., and Nakagawa K., Study of alternative Japanese speech intelligibility testing method. *Journal of the Acoustical Society of Japan*, 63(4): 196–205, 2007. In Japanese.
- Mas E., Suppasri A., Imamura F., and Koshimura S., Agent-based simulation of the 2011 Great East Japan Earthquake/Tsunami evacuation: An integrated model of tsunami intention and evacuation. *Journal of Natural Disaster Science*, 34(1): 41–57, 2012.
- Melo A., Belchior M., and Furtado V., Analyzing police patrol routes by simulating the physical reorganization of agents. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, pp. 99–114, 2005.

- Mitsuoka N., An indication of the noise in urban areas. Technical report, Tokyo Metropolitan Institute of Environmental Science and Technology, 2005. Pp. 209–214, In Japanese.
- Morishita T., Frank I., Kubo T., Kawarabayashi T., Shimora H., Nakanishi T., Tadokoro S., Tanaka-Ishii K., and Matsubara H., Simulating inter-agent communication in disaster relief scenarios – an initial implementation of rescue-mike. In *41st Annual SICE Conference*, p. 865, 2002.
- Muraki K. and Kanoh H., A multi-agent model for large area disaster evacuation simulation considering local characteristics. *Journal of the Japanese Association for Artificial Intelligence*, 22(4): 416–424, 2007. In Japanese.
- Navigation System Research Group, *Navigation Research Software Development Guide, Standard S (Version 2.2)*, 1997. In Japanese.
- Noda I., Shinoda K., and Ohta M., Communication in multi-agent simulation. In *41st Annual SICE Conference*, p. 875, 2002.
- Oki T. and Osaragi T., Wide-area evacuation difficulty in densely built wooden residential areas. In *International Conference on Information Systems for Crisis Management*, 2016.
- Pynadath D. V., Rosoff H., and John R. S., Semi-automated construction of decision-theoretic models of human behavior. In *Proceedings of the 2016 International Conference on Autonomous Agents and Multi-Agent Systems*, pp. 891–899, 2016.
- Ren C., Yang C., and Jin S., *Agent-Based Modeling and Simulation on Emergency Evacuation*, pp. 1451–1461. Springer Berlin Heidelberg, Berlin, Heidelberg, 2009. ISBN 978-3-642-02469-6.
- Shinoda K., Noda I., and Ohta M., Behavior design of civilian agent for rescue simulation. In *Proceedings of the 2002 International Conference on Autonomous Agents and Multi-Agent Systems*, 2002.
- Singh V. K., Modanwal N., and Basak S., MAS coordination strategies and their application in the disaster management domain. In *IEEE Intelligent Agent and Multi-Agent Systems*, 2011.
- Sirakoulis G. C., *Cellular Automata for Crowd Dynamics*, pp. 58–69. Springer International Publishing, Cham, 2014. ISBN 978-3-319-08846-4.
- Statistics Bureau of the Ministry of Internal Affairs and Communications, 2010 Japanese census, 2010.
- Stone P. and Veloso M., Multiagent systems: A survey from a machine learning perspective. *Autonomous Robots*, 8(3): 345–383, Jun 2000. ISSN 1573-7527. doi: 10.1023/A:1008942012299. URL <https://doi.org/10.1023/A:1008942012299>.
- Wolshon B., Zhang Z., Parr S., Mitchell B., and Pardue J., Agent-based modeling for evacuation traffic analysis in megaregion road networks. *Procedia Computer Science*, 52: 908–913, 2015.
- Yamashita T., Matsushima H., and Noda I., Exhaustive analysis with a pedestrian simulation environment for assistant of evacuation planning. *Transportation Research Procedia* 2, pp. 264–272, 2014.