Development of an Integrated Simulator for Tsunami Inundation and Agent Based Evacuation

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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 study, we will present a new developed evacuation model integrated with the numerical simulation of tsunami and the casualty estimation evaluation (Chapter 3). It is a tool to support decisions for disaster management and disaster prevention education.

The model was developed in NetLogo, a multi-agent programming language and modeling environment for simulating complex phenomena. Geographic Information Systems (GIS) data are used as spatial input information for the road and the shelter locations. A new approach of Tsunami Departure Curves (TDC) is proposed for the start time of evacuation simulation. TDC is a novel combination of Stated Preference Surveys and the Estimated Arrival Time of tsunami scenario. The formulation of two boundaries of evacuation decision distribution on time, and the stochastic simulation of scenarios in-between, yields to an average evacuation scenario for analysis of evacuation feasibility.

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. The bottleneck identification, shelter demand and casualty estimation are some of the applications of the simulator. The model is called *TUNAMI-EVAC1* an acronym for **T**ohoku **U**niversity **N**umerical **A**nalysis **M**odel for **I**nvestigation of **Evac**uation No. **1**.

To validate and test the model (Chapter 4) a case study 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% (S.D.=3.0%) of population evacuated, including a total average of 498 agents evacuating to a multistory 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 (Chapter 5). The model allows the observation of 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.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

In the last fifty years, physics of tsunami and technologies of forecasting, modeling, warning systems and defense structures against this phenomenon have improved considerably around the world. For instance, after the 9.5 Mw of 1960 Chilean earthquake on May 22^{nd}, the largest magnitude recorded so far in our earthquake history, 142 casualties were found 17,500 km away from the source, in Japan. Tsunami warning was issued after waves have already arrived two hours before in other locations. After this event the Pacific Tsunami Warning Center (PTWC) and the International Tsunami Information Center (ITIC) were established to act as the tsunami warning system for the Pacific Ocean (Imamura, 2009). Fifty years later, on February 27^{th} 2010, following the north edge of the above mentioned earthquake rupture a new megathrust earthquake occurred offshore Chile with magnitude 8.8 Mw. However, this time the PTWC and the Japan Meteorological Agency (JMA) issued the warning of tsunami and through advance modeling techniques they followed the event forecasting arrival times and tsunami heights for Japan coast with much more time in advance. In 2010, Japan reported no casualties in their coasts, despite the damages to fishery ports and local coast towns. Therefore, Tsunami Early Warning System, Risk Communication and Evacuation of people have proven an effective way of saving lives in coastal areas from the threat of tsunami across the ocean.

However, the lines above refer exclusively to the far-field tsunami scenario, when the available time of forecasting, dissemination of information and evacuation decision is sufficiently enough for cross-checking estimations, searching warning confirmation and carefully decide next actions. A far more complicated situation would be the one of a near-field tsunami; where in the previous examples becomes the point of view of Chilean population. For such scenarios, large number of casualties has been recorded. Even Japan, one of the most recognized nations for tsunami mitigation and tsunami awareness could not reduced to zero the number of casualties in the last 2011 Great East Japan Earthquake Tsunami. The surprising magnitude of the earthquake (9.0 Mw) (USGS, 2011) and extensive inundation of tsunami far exceeded expectations and designed countermeasures in several towns. As a lesson, residents learned that hardware components of tsunami mitigation, such as seawalls, coastal forests and others; might reduce tsunami impact but not always assure a full protection of the urban area. However, one of the key factors for surviving a tsunami was the evacuation procedure.

It is well-known that authorities in low-lying coastal areas under high risk of tsunami-attack promote the immediate evacuation after a strong ground motion or a warnings issued. In tsunami-prone areas with short times available for evacuation, finding safety in high ground is an important issue and especially difficult in plain areas. Development of effective warning systems and evacuation strategies are of primary importance in mitigation measures for tsunami (Clerveaux et al., 2008; Hayakawa and Imamura, 2002). For this, simulations can play a decisive role in the analysis of risk, helping to prevent dangerous situations in huge crowds and improving the overall evacuation performance (Meister, 2007) as a contribution to the disaster management.

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Finally, the reality described above, and the lack of tools for the assessment of feasibility of evacuation with optimal evacuation strategies, is the main motivation for this research on the human behavior, the evacuation simulation and further more the integration with the well-known technique of tsunami simulation.

1.2 Objectives

To develop an Integrated Simulator for Tsunami Inundation and Agent Based Evacuation.
Specific objectives are:

- To manage inputs based on GIS data to smooth the pre-process of simulation and application in multiple areas.
- To clarify the use of questionnaires to model the human behavior in evacuation.
- To explore and propose alternatives for the estimation and simulation of start time decision of evacuation.
- To integrate the characteristics of tsunami inundation from the TUNAMI model to estimate casualties.
- To propose multiple applications for the tsunami evacuation feasibility assessment.

1.3 Outline of the study

Figure 1.1 shows the outline of the research for the available three years of study. The 1st year consisted on the extensive review of the literature to comprehend the state-of-the-art in the tsunami evacuation modeling and the human behavior during large scale evacuations (see Chapter 2.1). Also, the second half of this year expected a proposal for a model to estimate the start time decision of evacuation in tsunami based on the questionnaire data available and parameters from the numerical simulation of tsunami (see Chapter 3.2.1). The 2nd year of study aimed on finding an adequate representation of the Goal, Mean and Route decision from evacuees; at the same time, the application of traffic simulation and pedestrian dynamics that characterizes the movement of agents in the simulated world (see Chapter 3.2.2 and Chapter 3.2.3). The output of this step is a traditional Evacuation model with just the agent movement but no hazard features interacting with the units of simulation. Finally, in the 3rd year, the Tsunami Inundation Model (TUNAMI) is used for the casualty condition of evacuees on movement (see Chapter 3.2.4). The integration of features such as the arrival time, inundation depth and flow velocity enhance the evacuation model result and in general the interpretation of the real phenomenon. The output of this stage and

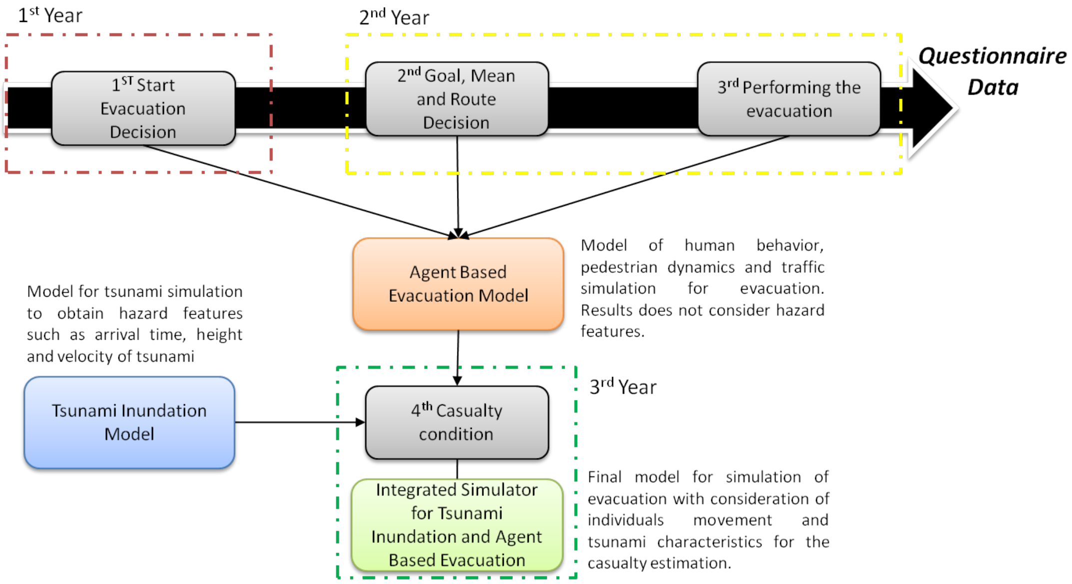


Figure 1.1: Outline of the study - 1st Year: Explore the Start Time Decision of Evacuation; 2nd Year: Build the Evacuation Model; 3rd Year: Integrate Evacuation Model with Tsunami Model.

the whole thesis is the Integrated Simulator for Tsunami Inundation and Agent Based Evacuation which in this document will be called *TUNAMI-EVAC1* an acronym for **T**ohoku **U**niversity **N**umerical **A**nalysis **M**odel for **I**nvestigation of **Evac**uation No. **1**.

Although the outline of the study was conducted as described before, for the sake of a better understanding for the reader, the order of ideas exposed in this document is focused on the description of the latest version of the TUNAMI-EVAC1 model and its features. Therefore Chapter 3, as the main body of the thesis, describes an overview of the model, the logic and theory behind its processes, assumptions related to the conceptualization of the problem, the graphic user interface (GUI) developed and the limitations of the model. Next, as required for every new model, however particularly difficult for the case of Agent Based Models (Ormerod and Rosewell, 2009), a sort of validation is conducted in Chapter 4. Additionally, in order to guide the user and demonstrate the applicability of the TUNAMI-EVAC1, Chapter 5 deals with several examples of application of the present model. Finally, conclusions and future works related to the topic of interest are presented in Chapter 6.
As further reference, six appendices are included:

- Appendix A: TUNAMI-EVAC1: User Manual

A user manual with the details to run the model and create new models. It complements the information in this study with a practical description of the steps to follow.

- Appendix B: TUNAMI-EVAC1: Source Code
  The original source code including some comments from the author for better understanding.

- Appendix C: Questionnaire template
  A template of pre-tsunami and post-tsunami questionnaire recommended in order to assure enough inputs required by the model.

- Appendix D: Questionnaire results in La Punta 2010 and 2011
  Results of questionnaires applied in La Punta, Peru.

- Appendix E: Risk Perception Approach for the Start Time Evacuation Decision
  A psychological and mathematical framework model of individual decision of start time of evacuation. This approach is not used in this model, however it presents a novel perspective of the detailed simulation of individual decision for evacuation worth to be study in the future.

- Appendix F: An improvement of the Steiner (2009)'s A* algorithm in NetLogo in order to increase the time efficiency of the method for computing the path finding in NetLogo.

1.4 Contributions

The main contributions from this study are:

- A new approach of start time evacuation decision is proposed based on departure time curves and the stochastic analysis of simulations.

- The model itself is a new tool with an easy-to-use and easy-to-understand principles due to the graphical user interface (GUI) available and the small number of parameters needed.

- Multiple applications are possible due to the availability of NetLogo (Wilensky, 1999) in the web and the already wide use of GIS tools by local stakeholders that provide spatial input data.

- The required questionnaire to obtain parameters for simulation has been reduced as much as possible in order to facilitate the process of survey.
- Although its simplicity, the model allows for a great exploration of individual aspects and emergent behavior in the complex of evacuation due to the agent based method applied. Some applications are presented in Chapter 5

The model was developed as universal as possible and based on abstract algorithms, therefore its application to other areas populated is possible with some minor efforts.

Chapter 2

Background and Literature Review

2.1 Evacuation Simulation models

This section is a brief review of the state-of-the-art in evacuation modeling, especially on the tsunami evacuation field, describing the recent techniques and approaches used in several other studies. Additionally, a review of some aspects of human behavior in evacuation.

Evacuation simulation is a method to determine evacuation times for areas, buildings, or vessels. A level of description for models was provided by Gershenfeld (1999) shown in Table 2.1:

Table 2.1: Classification of Models

Bold text shows a description of the model to develop in this study.

specific	-	**general**
phenomenological	-	first principles
discrete	-	**continuous**
numeric	-	analytic
stochastic	-	deterministic
quantitative	-	**qualitative**
macroscopic	-	**microscopic**

There is a large number of evacuation models in the literature. Models such as the ones related to building evacuation due to fire events (Friedman, 1992; Gwynne et al., 1999a,b; Kuligowski and Peacock, 2005; Santos and Aguirre, 2004; Watts, 1987; Zheng et al., 2009); evacuation from ships (Park, 2004) and aircrafts (Amos and Wood, 2004); also models to simulate traffic and regional evacuation in case of hurricanes, nuclear accidents and flood (Cova and Church, 1997; Dawson et al., 2011; Kumar et al., 1996; Lindell and Prater, 2007). These, and others (Fujioka et al., 2002; Lämmel, 2011; Naser and Birst, 2010; Oda, 2007; Post et al., 2009; Watanabe and Kondo, 2009), were consulted to comprehend the state-of-the-art in the field of pedestrian dynamics and traffic simulation. As a result, it was observed that there is an increasing interest in the microscopic and individual simulation of complex events. Also, there is a need for realistic and effective tools to simulate the human behavior and the several phenomena and risks that threatens the human safety.

With models of evacuation simulation is possible to analyze alternatives for safer routes, destinations, evacuee response and other possible future decisions for the disaster mitigation in an area (Kietpawpan, 2008; Southworth, 1991). Emergency evacuation models may be classified at first on: (i) large-scale scenarios, e.g. hurricanes, nuclear power plants, tsunami, etc. and (ii) small-scale evacuation of buildings or vessels due to bomb threat, fire, etc. Traditionally, large-scale scenarios were modeled following the macroscopic approach with vehicular evacuation. In macroscopic models the flow or group of individuals on move is the smallest unit to simulate. In recent years, researchers are focusing on the microscopic simulation of individuals. Here, an agent or individual is the smallest unit to simulate. Although it is the individual the main element during the develop stage, the final attention lies on the overall emergent behavior of agents interaction. This is possible due to the fast development of computing capacity in memory process, graphic rendering and data storing. Here, TUNAMI-EVAC1 will be developed as a model for large-scale scenarios, however considering the microscopic level through the agent based simulation approach.

2.2 Tsunami Evacuation Models

Tsunami hydrodynamic models have significantly contributed to the scientific and engineering investigation of tsunamis. However, understanding social science and risk management is necessary for complete modeling of the problem. Evacuation is most likely 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. Table 2.2 shows a comparison of previous tsunami evacuation models and simulators with respect to some features of simulation. It is intended to depict the integration of several features of previous models and other new features developed for the TUNAMI-EVAC1.

Table 2.2: Comparison of some features present in recent Tsunami Evacuation Models

Features	Description	A	B	C	D	E	F	G	H	I	J
Interface	None	O	O	O	O	O		O			
	GUI						O		O	O	O
Space	Network	O	O	O	O	O	O		O	O	
	Grid							O			O
Extension	GIS		O				O		O		O
	Tsunami								O	O	O
Level of simulation	Crowd							O			
	Group					O				O	
	Individual	O	O	O	O		O		O		O
Agent type	Pedestrian	O	O	O	O	O	O	O	O	O	O
	Vehicle	O			O					O	O
Start Time of Evacuation behavior	User input		O	O	O		O	O	O		O
	SP/RP survey*	O				O				O	O
	TDC**										O
Route and Pathfinding	None (pre-set)					O			O	O	
	Potential field							O			
	Self-selecting	O	O	O	O		O				O
Speed	Fix		O	O	O	O	O				
	Variable	O						O	O	O	O

*Stated Preference (SP) or Revealed Preference (RP) survey.
**Tsunami Departure Curves.

A:(Imamura et al., 2001)
B:(Fujioka et al., 2002)
C:(Ohhata et al., 2005)
D:(Suzuki and Imamura, 2005)
E:(Saito and Kagami, 2005)
F:(Nozawa et al., 2006)
G:(Kato et al., 2009)
H:(Lämmel, 2011)
I:(Goto et al., 2012)
J:(Mas et al., 2012d) - This Study

A brief review of the most recent tsunami evacuation models is as follows:

- Goto et al. (2012).- The model uses multi agent systems moving on a road network map and following predefined rules. Some assumptions in this model are: (i) agents follow the shortest paths through a linked network. Short in terms of distance for pedestrians and time for vehicles. (ii) fast evacuees pass slower ones when space is available. (iii) vehicle speed depends on the road width. In this model, the unit agent of model is the family (4 persons). Three kind of agents are shown; the family by walk, the family by car, half a family by motorcycle. Tsunami casualties are counted when inundation depth exceeds 1.00 m on the actual location of an agent. In this case, there is a limitation on the representation of individual behavior and outcomes for each evacuee.

- Lämmel (2011).- In this model, Multi-Agent Transport Simulation (MATSim) is used as the toolbox for the implementation of a large-scale agent based simulation. The purpose of this model is to find the best evacuation condition that benefits all agents. The set of repetitions and iterative learning framework lead to the Nash equilibrium as the best approximation of a desired evacuation. some of the findings in this study are, (i) the shortest path solution is not suitable for the evacuation planning because it does not consider congestion effects and underestimates travel times. (ii) the Nash equilibrium considers these congestion effects, however does not take into account the time-dependent aspect of the hazard.

- Watanabe and Kondo (2009).- The authors present a tsunami evacuation model based on the multi agent system approach. Each evacuee is an agent with characteristics of age, speed, fatigue level and consciousness of disaster mitigation. The interaction of these data with the environment describes the evacuation behavior. The model only considers agents as pedestrians, there is no vehicle simulation for traffic condition. Also the start time of evacuation is strictly based on questionnaire data. There is no use of departure time on minutes scale but on situations that triggered the protective action.

- Other tsunami related models.- Clerveaux et al. (2008) developed a static tsunami evacuation model using GIS tools in order to investigate and assess risk and evacuation planning in a multilingual society. On the other hand, Fujioka et al. (2002) aims at the understanding of human behavior and their interaction effects in a tsunami disaster by means of multi agent simulation.

Among these models there are several differences related to the representation of the unit of simulation (the agent) and its characteristics like start time of evacuation decision, route choice, mean of mobilization, shelter selection, rules of avoiding obstacles. While some of them does not consider the vehicle agent in the simulation, underestimating possible crowding and bottleneck conditions, others use a simplistic method of casualty estimation by stopping the simulation at the estimated tsunami arrival time and categorizing all remained agents on move as possible casualties. In this study, a casualty is understood as the individual trapped in tsunami with very few chances to survive to the inundation depth and flow velocity. Therefore, the integration of a more realistic condition of probability of becoming casualty, related to the characteristics of tsunami, will be presented here.

2.3 Agent based modeling

Models are used to gain understanding and insights about some aspects of the real world. In several cases, the cost of developing and experimenting with models is comparatively small to the cost of experimenting in the real world (Sanchez, 2006). For instance, in the case of tsunami evacuation drills, it is required that the society or community involve should stop its daily activities and move along the streets to safe areas. Sometimes the evacuation lasts for long distances and time, creating unpleasant feelings in residents and tourists. Moreover, the level of participation is rarely near the 100% of population. Therefore, it is difficult to repeat the exercise very often (Kietpawpan, 2008). However, local stakeholders and authorities need to test the feasibility of their evacuation plans and the possible flaws related to it. For that reason, modeling techniques help on the understanding of systems which are difficult to observe in the real world. As a principle in modeling, the model is only a simplification of the real system and it answers a specific set of questions. Only a replica of the original system may answer any unanticipated question (Sanchez, 2006).
Agent-based modeling and simulation (ABMS) is a relatively new technique to model systems comprised of autonomous and interacting agents (Macal and North, 2007). Each agent individually assesses its situation and makes decisions on the basis of a set of rules. Various behaviors can be given to the agent for the individual decision-making process or the interaction with the environment and other agents. The main benefit of ABMS is that it captures the emergent phenomena from the bottom up by modeling the agents interactions and behaviors. For the case of interest in this study - the evacuation process -, in several events it was observed that the crowd

movement followed certain patterns called self-organization. These patterns of self-organization emerged from the individual intention of evacuees related to the state of the environment or their communication with others (Meister, 2007). Based on this, ABMS models are suitable for the evacuation simulation considering aspects of human behavior. Although pedestrians, and in general drivers too, usually try to walk or drive minimizing detours or taking the optimal path to his target, there are fluctuations on the human behavior. Therefore, simulations results are always to some extent uncertain. However, if the simulated crowd is large enough and the simulation run is repeated several times (Monte Carlo simulation), then the uncertainty about the individual behaviors is averaged out at the macroscopic level of description (Meister, 2007).

2.4 Human behavior in evacuation

Evacuation is a way of coping with the emergency and the key to a successful evacuation is the fact of being able to move all people at risk to safer areas in the time available (Charknol and Tanaboriboon, 2006; Quarantelli et al., 1980). Early Warning Systems (EWS) have been developed to contribute on promoting the fast evacuation when a tsunami happens. However, after great improvements on the EWS technology for tsunamis, some people still decide not to evacuate from an area threatened by a dangerous situation such as a tsunami (Imamura, 2009; Katada et al., 2005; Lachman et al., 1961; Saito, 1990; Tanaka et al., 2006). Therefore, it is important to look not only into the technology available and ways to improve it, but the people involved and their behavior and decisions. Warning is only one element, not necessarily the most important in evacuation behavior (Quarantelli et al., 1980).
When we look into the individual, we may found that the human behavior is the most complex and difficult aspect of the evacuation process to simulate (Gwynne et al., 1999a). Human behavior includes complex problem solving (Gagne, 2005) and individual characteristics with both aspects difficult to capture in mathematical equations (Pan et al., 2007). In several model attempts, human behavior in evacuation is observed and a simplification of these individual and emergent behavior has been considered to explain a piece of the whole phenomenon. For example, herding effects generally occur if the view is limited, e.g. by smoke, in the night, etc., or if the people do not have local knowledge, e.g. they do not know where the next emergency exits or shelters are. Under such circumstances people often rely on others, hoping that they know better (Meister, 2007). Another example is the phenomenon of lane formation

which can be observed when uniform walking direction emerge instead of being equally distributed over the sidewalk/corridor. This way, the number of encounters, braking and avoidance maneuvers between opposing pedestrians in counterflow are minimized. The resulting pattern balances both directions and may be considered as an optimal self-organization phenomenon (Meister, 2007).

Human behavior in tsunami evacuation has been studied through questionnaires on risk perception of natural hazards (Bird, 2009; Charknol and Tanaboriboon, 2006; Gierlach et al., 2010) or post tsunami surveys addressing the respondent behavior in the event (Gaillard et al., 2008; Iemura et al., 2006; Katada et al., 2005; Lachman et al., 1961; Mas et al., 2011b; Saito, 1990; Shishido and Imamura, 2008; Spence and Palmer, 2009). In this study, human behavior will be studied through the analysis of several questionnaires found in the literature and conducted by the author. Such behavior and findings are included in the components of the TUNAMI-EVAC1 model.

2.5 Summary

This chapter provided a brief review on previous tsunami evacuation models found in recent literature (Table 2.2). Also we discussed the agent based simulation approach and the necessity to integrate human behavior in the evacuation simulation.Models can be classified and describe from several points of view, however in this study, a numerical and stochastic microscopic model on a continuous space will be developed. Several components similar to previous models are to be kept, however new features of GIS input, GUI, Tsunami inundation for casualty estimation and a new method to simulate the start time of evacuation from tsunami will be developed and introduced in this study. A recent technique of agent based modeling will be used for the exploration of residents behavior in an emergent process of evacuation. In the next chapter a detailed insight of the TUNAMI-EVAC1 model will be presented.

Chapter 3

Proposal of Tsunami Evacuation Model (TUNAMI-EVAC1)

3.1 Model Overview

In this section, as an overview of the model, the required Input Data and its formats, the platform for data processing and the description of the available outputs at this version of the model are described. The theory behind the process of simulation will be describe in the next section (see Chapter 3.2). As an overview, Fig. 3.1 shows a scheme of the model. It consists on the input data provided by the spatial data in GIS format, the human data related to evacuees' preferences obtained from questionnaire results, the component of Hazard provided by the TUNAMI inundation model output, and a set of agent behavior rules loaded into a platform of agent-based simulation. The chosen platform in this study is the NetLogo modeling environment (Wilensky, 1999). The outputs of casualty estimation, evacuation times, bottlenecks, shelter demand, etc. are obtained through report files, snapshots or video of the simulation process. The model has been named *TUNAMI-EVAC1* an acronym for **T**ohoku **U**niversity **N**umerical **A**nalysis **M**odel for **I**nvestigation of **Evac**uation No. **1**. A screen snapshot of the model interface is shown in Fig. 3.2

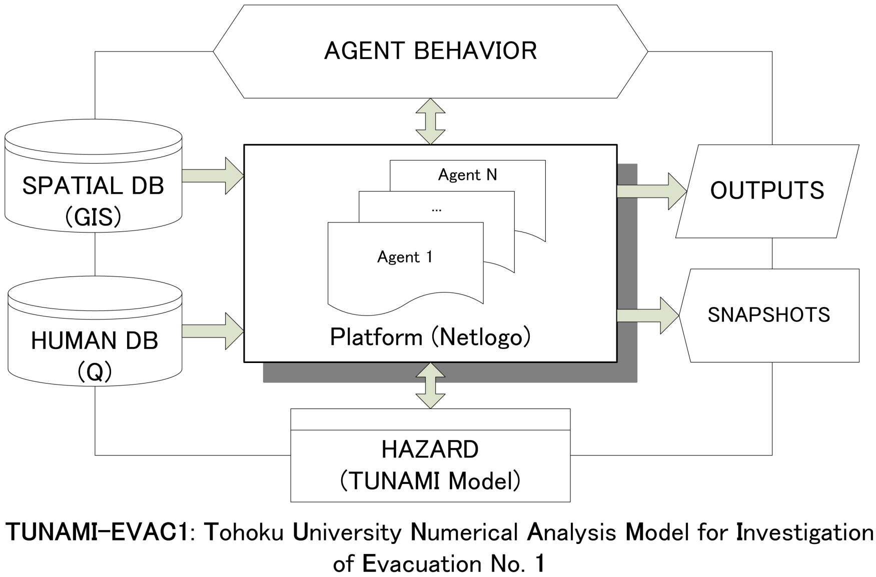


Figure 3.1: Model Framework - Inputs, libraries and hazard characteristics are use in the NetLogo Platform to obtain the screen and report outputs.

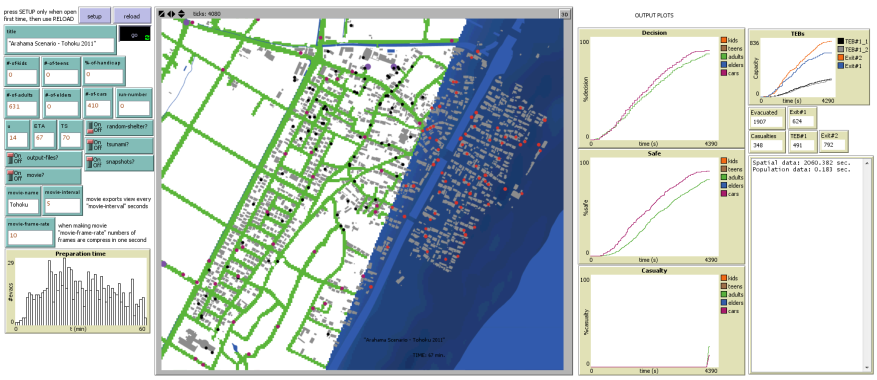


Figure 3.2: Model Interface - GUI of TUNAMI-EVAC1 with scenario variables and parameter inputs on the left, update screen on the center and real-time outputs on the right side.

3.1.1 Input Data

Spatial Input Data

Traditionally, the process to prepare the input data in evacuation modeling requires an extensive work on building networks (Goto et al., 2012), creating floor plans or potential topography (Meguro and Oda, 2005). However, nowadays the wide use of Geographic Information Systems (GIS) available in many municipalities can be exploited. The platform for simulation is called NetLogo, a programmable modeling environment for simulating natural and social phenomena. An extensive introduction to this platform will be discussed in the next subsection (see Chapter 3.1.2). As part of NetLogo capabilities, a GIS Extension is available to load vector GIS data and raster GIS data into the model. Through this mean, the time for preparation of simulation is reduced to its minimum. Also it gives to the model a potential universality of application in a short time. The required GIS data is as follows:

- Land.shp: The area of land where agents and urban elements are positioned. Polygon shapefile. (required)
- Streets.shp: The street, principal and secondary roads. Polygon shapefile. (required)
- Urban.shp: The urban and housing of the study area. Polygon shapefile. Only used for visual effects. (optional)
- Sea.shp: The ocean, lakes, channel or other area that includes water within the study area. Polygon shapefile. Only used for visual effects.(optional)
- Exits.shp: Location of possible exit points for evacuation. Generally outside the inundation area or at the edge of the simulation extent. Point shapefile. (required)
- TEB.shp: The location and capacity of Tsunami Evacuation Buildings (TEB) in the area. Point shapefile. (required)

It is convenient that all data is projected on the same projection format (i.e. WGS84), however it is also possible to initially load a desired projection, then new files will be reprojected into the loaded projection. Shapefiles data are used specifically for the attributes of each patch or grid in the environment. Note that the superposition of patches or grids overwrites the attribute of the last data over the previous one.

Agent Input Data

Parameters such as initial location, start time of evacuation decision, mean preference, shelter preference and heuristic for route selection are obtained through questionnaire survey results or model scenario decision. For example, the modeler may decide to start the evacuation using a day or night population spatial distribution in a point dataset of GIS. Another option available in the model is the random allocation of a certain number of population. A summary of the available conditions for setting the scenario and the parameters of simulation is shown in Table 3.1.

Table 3.1: Input variables and parameters

Scenario conditions	Parameters
With or without Tsunami	Number of Agents
With or without Output	Percentage of handicap
Only Horizontal Evacuation	Total simulation time
Only Vertical Evacuation	Slow evacuation parameter
Horizontal and Vertical Evacuation	Fast evacuation parameter

3.1.2 Data process

We provided agents with the minimum necessary capabilities to process information and execute their evacuation through a simple behavior divided on layers. A brief introduction to the agent architecture and each layer is as follows:

- Layer 0: Evacuation decision. The timing to start the evacuation is assigned randomly to each agent based on the Tsunami Departure Curves (see Chapter 3.2.1).

- Layer 1: Shelter decision. There are two possible options for scenario exploration; first, the nearest shelter is selected by the agent based on a direct euclidean distance measure and second, any of the shelters can be selected randomly. Traditionally nearest shelter condition has been applied, however in many cases preferences are not for the nearest sheltering place (see Chapter 3.2.2).

- Layer 2: Route decision and Path finding. The method used for finding a route (not necessary the shortest) is the A* (A star) algorithm on grid space. This is the most popular graph search algorithm also used in the video game industry (Anguelov, 2011) (see Chapter 3.2.3).

- Layer 3: Speed adjustment. The speed variation is assumed as a one-tail Normal Distribution of evacuee density in the agent field of view, with a maximum value of 1.33m/s for pedestrians and 30km/h (8.33m/s) for cars (Meister, 2007; Suzuki and Imamura, 2005) (see Chapter 3.2.4).

3.1.3 Output Data

TUNAMI-EVAC1 model can show the output as the simulation is in progress. The visual environment obtained from the GIS spatial data with the agent movement is updated at each step or ticks in NetLogo. Also it displays graphs of the process of decision of evacuation of the whole population, the traditional evacuation time curves showing the percentage of population who has reached the targeted shelter. As an additional feature, the process of sheltering at each Tsunami Evacuation Building and crossing each Exit point is plotted on graphs.
Graphic outputs are also supported by numeric monitors showing the exact value of number of evacuated people and casualties estimated. Other complementary output formats are: snapshots in image and movie format, reports of casualties, evacuated agents, shelters, and a summary report of each agent condition related to the start point, the decided shelter, the distance of route selected and the final condition of safety (see Appendix B).

3.2 Model Logic

In order to fully explain the features and theory proposed in the model, we will use the previously mentioned agent architecture of layers to navigate through the whole features and new approaches proposed in this study and model.

3.2.1 Layer 0: Evacuation Decision

Human Behavior with respect to the start time of evacuation

Recently, more emphasis has been put on social science in tsunami mitigation. In tsunami-prone areas with short time available for evacuation, the immediate response is an important issue. Development of effective warning systems and evacuation strategies are of primary importance in mitigation measures for tsunami (Clerveaux et al., 2008; Hayakawa and Imamura, 2002). However, after great improvements on the tsunami early warning system technology in the past decades, and implementations of mitigation programs in coastal communities around the world, some people still do not evacuate

from an area threatened by tsunami (Imamura, 2009; Katada et al., 2005; Lachman et al., 1961; Saito, 1990; Tanaka et al., 2006).
Little research has been done on the human response to tsunami and still relatively few studies have provided concrete evidence on when, where, and in total how many people will choose to evacuate. One approach would be simulations of evacuations as experiments that could guide the development of more effective educational and mitigation programs and the exploration of human behaviors (Bernard et al., 2006; Johnston et al., 2005; Shuto, 2009; Sorensen and Mileti, 1988). Thus, researches have to address the intersection between mathematical modeling and empirical research (Lindell and Prater, 2007).
There are many reasons why people did not react appropriate to the ground shaking or the information of tsunami threat. For instance some of them were reported after the September 12^{th}, 2007 Bengkulu Earthquake in Padang, Indonesia (Letz and Spahn, 2009), the May 9^{th}, 2010 earthquake affecting Meulaboh, Indonesia (Nurdin et al., 2011) and in some reports of the March 11^{th}, 2011 tsunami in Japan (Dengler, 2011).

- Warning messages were not clear and did not give direct order or guidance of the necessity for evacuation. An ambiguous or not clear message without any direct order allows people to hesitate and wonder if the threat is worth of leaving ongoing activities, abandon properties and perform a possible unnecessary effort. Authorities are afraid of compelling evacuation to avoid future complains and mistrusts in the system in case of low tsunami height, inundation or damages at the moment. Then, the message is generally given as a recommendation instead of an order or using the wording "potential tsunami" which leads residents to doubt on their next action or to wait for further confirmation.

- High uncertainty of information such as areas at risk. For residents very near to the coastline the risk is clear and easy to understand, however as the distance from the shoreline increases, residents' risk perception might decrease and create a false sense of security due to past events where no damages were experienced. If there is no clear information of the possible area of inundation, the normalcy bias of the event results on a late decision of evacuation.

- Reliability on natural warnings. Residents near the coast and fisherman in general rely on their knowledge of the sea. This was the triggering condition in several areas in the 2010 Chile earthquake and tsunami (Marín et al., 2010). Thus, in most cases they will not evacuate unless a receding tide is observed. However this is a dangerous behavior; because not in all cases receding waves appear first.

Further reasons can be found through questionnaire surveys and interviews to survivors and witnesses. In this study, however, we are not interested on the reasons for a non evacuation or a delayed evacuation, but the expected or resulting behavior of evacuation decision obtained through questionnaires.

Evacuation Models and the start time of evacuation

Start time of evacuation is an important item in evacuation simulation (Suzuki and Imamura, 2005) since it is expected that human damage will decrease depending on the early evacuation (Sugimoto et al., 2003). Efforts of simulating the evacuation of humans from tsunami have considered this factor in so many approaches that all these models may result on different casualty estimation and congestion points. Three main approaches can be described from the efforts on developing the start time of tsunami evacuation modeling.

First, an "all together" evacuation based on scenarios of 0min, 5min, etc. starting time for the whole population under study (Fujioka et al., 2002; Meguro and Oda, 2005; Ohhata et al., 2005; Post et al., 2009; Sugimoto et al., 2003; Suzuki and Imamura, 2005). Such instantaneous group behavior has never been recorded in past events. In general, individuals from a large population at risk never start their evacuation at the same time, due to individuality and complex of human behavior. Based on general observations we know that people do not leave an area simultaneously (Sorensen, 1991; Southworth, 1991) as several models assumed. Outcomes under this assumption may mislead the evaluation of evacuation feasibility and casualty estimation (see Chapter 4).

A second approach is similar to the previous one, however the fixed values are assigned to groups or areas and directly based on questionnaires (Imamura et al., 2001; Saito and Kagami, 2005). Basically, this is a special case of the first approach, where a whole population is divided in small groups and the average of starting time is obtained through questionnaire surveys conducted in the area. Although, this may lead to better approximations in the evacuation process of a large population, the use of one questionnaire result may not explain the complexity and uncertainty of human behavior or spatial initial condition of population.

The third approach is a more sophisticated approach with introduction of psychological parameters obtained through questionnaires and treated in the individual scale considering aspects of rationality (Mas et al., 2011a; Sato et al., 2008) (see Appendix E), however for these cases, the definition of parameters and values for the simulation are of difficult assessment in large populations.

In this study, we will introduce a fourth approach modified from the emergency, urban and traffic planning fields, where departure times are sketched under derivations of sigmoid curves.

Stated Preference and Revealed Preference surveys

Tsunami evacuation models often utilize data provided by questionnaire surveys in order to establish an average start time of evacuation or an estimated distribution of evacuation decision. The need of these data is common to researchers and stakeholders, however, conducting surveys and updating survey data is usually faced by budget and time constraints, limiting the decision for new mitigation actions.

According to Naser and 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 tools pretend to obtain an idea of the human behavior during the emergency; however the use of one questionnaire result may not explain the complexity and uncertainty of human behavior or the spatial initial condition of population. There is a frequent variation of the level of awareness and risk perception of individuals, due to recent experiences, public information or education. As a result, previous estimations of evacuation times on past SP surveys may decrease or in the opposite case, where events have been forgotten, there might be an increase on estimated times (Tatano, 1999).

As an example, for the case of SP surveys, two questionnaires were conducted in La Punta district (see Appendix D), a peninsula area threatened by tsunami in Peru (Fig.3.3-left). This community has a high awareness of tsunami despite the lack of experience of near-field tsunami events in the last decades. Risk information and education by the local authorities had played an important role. The questionnaires addressed the estimated preparation times for a future near-field tsunami. Stated answers in Sept. 2010 (n=128) after the tsunami warning of the Chile earthquake (h=1.00m.) were compared to new estimations (n=110) in a second survey one year later (Sept. 2011), after the 2011 Japan earthquake warning (h=1.63m.).

As a result, a faster evacuation is expected by residents (Fig.3.3-right). Then, in the case of SP surveys, it is possible that the timing of the survey with respect to the recent events experienced have an influence on the stated preferences in surveys. Therefore, the direct use of SP survey results as estimation for future evacuation modeling might result inaccurate when warning events or educational programs have been experienced.

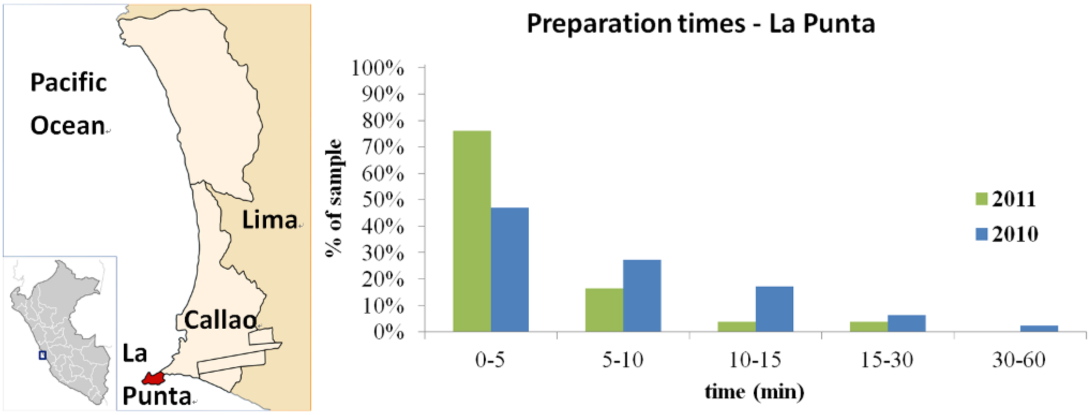


Figure 3.3: State Preference (SP) surveys - Left: La Punta district near the capital Lima of Peru. Right: Preparation times of a sample in La Punta in questionnaires conducted in 2010 and 2011.

On the other hand, in the case of RP surveys, a future event might be different as the one surveyed, therefore faster or slower decisions can be observed. As an example, two questionnaire surveys (RP surveys) were conducted in Padang, Indonesia by Hoppe (2007); Hoppe and Marhadiko (2009), in two events Fig.3.4:

- The Bengkulu Earthquake on September 12^{th}, 2007 (8.5 Mw - 410km SSE of Padang). 78% of interviewed residents (n=200) did not evacuate at that time, out of this people, a 70% had received warning of "potential tsunami". The rest of respondents (n=29) did evacuate and by the time of arrival of tsunami, 45min after the earthquake, 79% of them had already started to evacuate. According to USGS report, peak ground acceleration in Padang was about 11.0%g (Intensity VI). Also, tsunami records show a wave height of h=0.90m.

- The West Sumatra Earthquake on September 30^{th}, 2009 (7.6 Mw - 60km WNW of Padang). 51% of interviewed residents (n=200) did not evacuate despite the strong ground motion with a higher peak ground acceleration of 28.6%g (Intensity VII). In this event, no tsunami warning was issued due to the low estimated height of tsunami (h=0.27m) which arrived 15min after the earthquake. 83% of the total of residents who evacuated (n=98), had started their evacuation in the first 15min.

Comparison of these two experiences in the same community show that RP surveys cannot be directly used as estimations for future events with different characteristics. For instance, both earthquakes occurred around the same time of a Wednesday in the afternoon, then, activities and level of alert of population can be consider of similar condition. However, higher intensity was felt in 2009 as well as a larger number of effective evacuees was observed. Therefore, it is reasonable to think on a possible correlation between intensity felt and fast reaction for evacuation.

In the case of tsunami information; although no information was received in 2009, the reaction of evacuees was faster than in 2007 where tsunami warning was issued. Apparently tsunami warning information did not influence on Padang residents' reaction compared to the ground motion intensity.

Tsunami height was higher in 2007 but evacuation rates were lower. Then, information of tsunami heights affects the reaction in a positive or negative way? Or maybe no influence is exerted. Several questions arised just from the comparison of two experiences with different evacuee behavior and these answers remained as future investigations.

In any case, what we intended to prove here is that SP and RP surveys are not applicable from one event to another due to a change of behavior and expectations on time. Then, which start time behavior should be input on evacuation models for future assessment of evacuation feasibility?. In that sense, we will propose a new method to model departure times of evacuees.

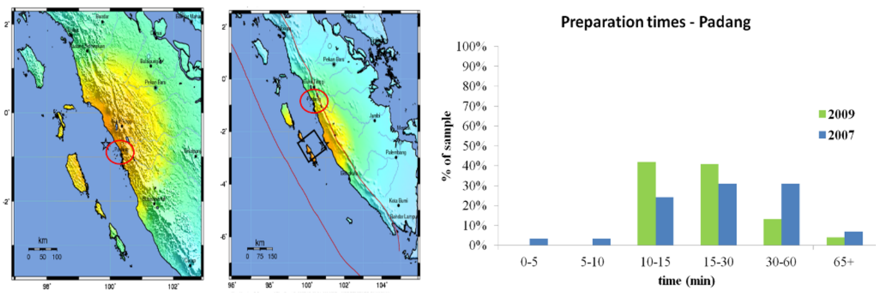


Figure 3.4: Revealed Preference (RP) surveys - Location of the 2007 and 2009 events in Indonesia. The circle shows the area where questionnaires were conducted. The graph shows preparation times stated in surveys.

Developing Tsunami Departure Curves

According to Southworth (1991), four approaches are commonly used for the approximation of departure curves:

- Based upon past empirical evidence for similar types of evacuation (i.e. RP surveys)

- Based upon surveys of the stated intentions of potential evacuees (i.e. SP surveys).

- Based upon simulation of the diffusion of emergency warning system messages and the subsequent spread of information within the community at risk.

- Based upon planner judgment and conceptualizations of human response to an emergency.

For the first two approaches mentioned, we have introduced before the limitations on using either only RP surveys or SP surveys due to the variability of behavior on time. In the case of the third approach the diffusion of warning messages does not mean the actual time of decision of taking an action, as we have discussed previously and also Padang case has explained. It is not necessary the warning message the one that triggers the reaction on evacuees. For the fourth approach much concern has been expressed on the reliability of planner judgments and the model for human response conceptualization. Therefore, the four approaches hold limitations for an adequate human behavior representation. Thus, a new approach is needed.

As part of the fourth approach described before, Tweedie et al. (1986) used a methodology based on probabilistic departure time curves for estimating times required for the partial or total evacuation of an area at risk. The departure curve was based upon the Rayleigh probability distribution function (Eq. 3.1):

$$F_t = 1 - e^{\frac{-t^2}{T}} \tag{3.1}$$

where F_t is the percentage of the population mobilized by time t and T is a parameter the analyst can adjust to control both the slope of the traffic loading curve and the maximum time at which all evacuees are assumed to have mobilized. Then, the shape of the curve and the value of T are determined using local stakeholders' expertise. Tweedie's model lacks of any criteria to link the population behavior with the hazard characteristic. Building over this idea, the parameter T is of great influence on the model, such parameter must be decided carefully. Looking at the theoretical Rayleigh distribution (Eq. 3.2), the parameter T is a modified value of the parameter σ, which can be also related to the mean of the distribution (Eq. 3.3). Finally, the Rayleigh distribution can be expressed as in (Eq. 3.4).

$$D(t) = 1 - e^{\frac{-t^2}{2\sigma^2}} \tag{3.2}$$

$$\mu = \sigma\sqrt{\frac{\pi}{2}} \tag{3.3}$$

$$D(t) = 1 - e^{-\frac{\pi t^2}{4\mu^2}} \tag{3.4}$$

When the sample is obtained through questionnaire surveys, either SP or RP surveys, the value of μ can be calculated to find the best fit of distribution to the sample data. Here Rayleigh curves (Eq.3.4) as well as the Logistic curves (Eq.3.5) were tested for the goodness of fit (GOF) with the questionnaire data available. Table 3.2 shows the results based on the GOF analysis for both distributions. Kolmogorov-Smirnov statistic (D) (Eq.3.6) value is shown for each case. As a result either Logistic curves and Rayleigh curves fitted the data without rejecting the null hypothesis (H_0: the data follow the specified distribution).
Although sometimes Logistic curves had better D values, the parameters of location (μ) for both distributions were similar. However on the RP survey case, Rayleigh distribution location parameter shows slightly better correlation (Pearson's r) (Eq.3.7) with the arrival time of tsunami (Rayleigh $r = 0.736$ and Logistic $r = 0.732$). Finally, in order to facilitate the estimation of a suitable distribution for a future scenario, when RP survey would not be available - this makes difficult the estimation of the scale parameter for logistic curves σ -, the Rayleigh distribution with one parameter closely related to the arrival time of tsunami of the future scenario - obtained through the numerical simulation - was adopted.

$$P(t) = \frac{1}{1 + e^{\frac{\mu - t}{\sigma}}} \tag{3.5}$$

$$D = max_{1 \leq i \leq n}\left(F(x_i) - \frac{i-1}{n}, \frac{i}{n} - F(x_i)\right) \tag{3.6}$$

$$Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{3.7}$$

Finally, Table 3.3 shows a number of available questionnaire data for several areas in Japan and examples in other countries. The date of event, date of survey and the number of respondents are shown. The arrival time of tsunami is taken as the scenario of tsunami related to the SP survey or the recorded tsunami related to the area in the day of the event for RP surveys.

Data of a survey conducted in La Punta district in September 2011 will be used as an example to illustrate the calculation of the mean of distribution. The question

Table 3.2: Goodness of fit (GOF) analysis for Rayleigh and Logistic distributions

No.	Name	Rayleigh		Logistic			Evaluation*	ETA(min)	$\mu(R)$	$\mu(L)$
		σ	K-S	σ	μ	K-S				
1	Arahama Village	7.181	0.243	2.892	9.000	0.257	R	45.0	9.0	9.0
2	Tohoku area	19.231	0.337	9.558	20.954	0.261	L	45.0	24.1	21.0
3	Japan except Tohoku	17.016	0.301	7.035	21.326	0.308	R	30.0	21.3	21.3
4	Tohoku area	18.643	0.268	7.741	23.365	0.268	L	45.0	23.4	23.4
5	Tohoku area	18.726	0.303	8.949	20.925	0.239	L	45.0	23.5	20.9
6	Sophia Univ. (Tokyo)	20.558	0.233	9.194	25.766	0.254	R	30.0	25.8	25.8
7	Tokyo Inst. Of Tech.	15.427	0.339	6.028	19.335	0.354	R	30.0	19.3	19.3
8	Tohoku area	14.641	0.325	7.454	18.350	0.344	R	45.0	18.3	18.4
9	Tohoku area	15.319	0.320	8.151	19.200	0.268	L	60.0	19.2	19.2
10	Ito City (Shizuoka)	12.586	0.390	8.266	15.774	0.328	L	20.0	15.8	15.8
11	Tokushima Prefecture	17.657	0.239	8.210	22.130	0.229	L	30.0	22.1	22.1
12	Miyagi prefecture	17.374	0.287	8.953	21.775	0.229	L	45.0	21.8	21.8
13	Tokai area	20.334	0.230	9.490	25.485	0.245	R	25.0	25.5	25.5
14	Matsushima town	14.304	0.215	5.759	17.298	0.262	R	45.0	17.9	17.3
15	Phuket village	20.494	0.388	18.778	25.685	0.292	L	90.0	25.7	25.7
16	La Punta 2010	8.809	0.320	5.775	11.040	0.287	L	20.0	11.0	11.0
17	La Punta 2011	6.004	0.337	2.684	7.525	0.349	R	20.0	7.5	7.5
1	Sanriku area	22.523	0.201	7.646	28.675	0.244	R	25.0	28.2	28.7
2	Nonamae town	5.130	0.378	1.246	6.430	0.473	R	5.0	6.4	6.4
3	Inaho town	12.315	0.552	11.061	15.435	0.453	L	5.0	15.4	15.4
4	Yamasedomari town	18.399	0.506	12.347	23.060	0.385	L	10.0	23.1	23.1
5	Tamaura town	5.167	0.374	1.646	6.670	0.467	R	10.0	6.5	6.7
6	Hotokezawa town	6.982	0.524	6.574	8.750	0.403	L	10.0	8.7	8.8
7	Okushiri division 1	16.237	0.413	10.866	20.350	0.307	L	12.5	20.3	20.4
8	Okushiri division 2	14.893	0.443	11.023	18.665	0.360	L	12.5	18.7	18.7
9	Okushiri division 3	18.098	0.416	12.445	22.682	0.347	L	12.5	22.7	22.7
10	Okushiri division 4	10.494	0.425	7.895	13.152	0.389	L	12.5	13.1	13.2
11	Okushiri division 5	9.822	0.358	6.819	12.310	0.346	L	12.5	12.3	12.3
12	Iachi town	10.584	0.470	8.929	13.265	0.420	L	10.0	13.3	13.3
13	Bushigawa town	5.833	0.308	1.749	7.310	0.404	R	10.0	7.3	7.3
14	Akaishi town	7.121	0.388	5.267	8.925	0.328	L	10.0	8.9	8.9
15	Onkouta town	12.140	0.462	9.795	15.215	0.380	L	10.0	15.2	15.2
16	Matsue town	10.807	0.523	9.931	13.545	0.459	L	7.5	13.5	13.5
17	Hatsumatsumae town	8.921	0.569	8.790	11.181	0.438	L	7.5	11.2	11.2
18	Tomisato town	9.359	0.479	8.267	11.730	0.466	L	7.5	11.7	11.7
19	Aonae division 1	5.450	0.344	1.505	6.830	0.438	R	7.5	6.8	6.8
20	Aonae division 2	5.318	0.357	1.500	6.665	0.456	R	7.5	6.7	6.7
21	Aonae division 3	6.391	0.372	3.233	8.010	0.353	L	7.5	8.0	8.0
22	Aonae division 4	5.831	0.521	5.109	7.308	0.439	L	7.5	7.3	7.3
23	Aonae division 5	6.694	0.669	7.140	8.390	0.529	L	5.0	8.4	8.4
24	Aonae division 6	12.723	0.356	8.643	15.946	0.287	L	5.0	15.9	15.9
25	Aonae division 7	9.970	0.382	5.454	12.495	0.298	L	5.0	12.5	12.5
26	Aonae town	6.427	0.428	4.369	8.055	0.357	L	5.0	8.1	8.1
27	Okushiri Island	7.485	0.251	3.482	9.381	0.297	R	5.0	9.4	9.4
28	Taisei - Setana town	10.771	0.287	5.420	13.500	0.339	R	12.5	13.5	13.5
29	Shimamaki town	5.852	0.225	1.687	7.334	0.260	R	5.0	7.3	7.3
30	Hokkaido area	11.948	0.308	6.793	14.975	0.278	L	16.0	15.0	15.0
31	Padang city	25.617	0.220	10.332	32.106	0.246	R	45.0	32.1	32.1
32	Padang city	21.613	0.214	7.420	27.442	0.261	R	15.0	27.1	27.4
33	Kamaishi city	13.845	0.370	7.119	17.353	0.337	L	35.0	17.3	17.4
34	Natori city	26.837	0.232	10.652	33.635	0.281	R	65.0	33.6	33.6
35	Sendai	18.237	0.209	8.580	22.857	0.256	R	67.0	22.9	22.9
36	Natori city	22.900	0.282	12.294	28.701	0.242	L	65.0	28.7	28.7
37	Minami Sanriku	12.915	0.380	8.874	16.186	0.239	L	47.0	16.2	16.2
38	Onagawa	13.124	0.238	7.389	16.449	0.241	R	41.0	16.4	16.4
39	Ishinomaki	19.536	0.291	11.720	24.485	0.257	L	62.0	24.5	24.5
40	Tagajo	16.768	0.265	9.750	21.015	0.007	L	68.0	21.0	21.0
41	Watari	23.462	0.295	12.475	29.405	0.254	L	69.0	29.4	29.4
42	Yamamoto	29.053	0.281	11.976	34.875	0.291	R	68.0	36.4	34.9
43	Tohoku area (survivors)	26.628	0.401	21.602	33.373	0.305	L	30.0	33.4	33.4
44	Tohoku area (casualties)	62.218	0.356	28.271	71.503	0.359	R	30.0	78.0	71.5
*R: Rayleigh; L: Logistic								CORREL (r)	0.736	0.732

Table 3.3: Mean value of Rayleigh distributions for SP and RP surveys and expected or recorded Arrival Time of tsunami

No.	Type	Country	Area	Event	Survey	Sample	Arrival time (min)	μ (min)	Correl. (r)	NRMSE	Ref.	Height (m)
1	SP	Japan	Arahama village	-	Jul. 2000	1,073	45	9.0	0.964	13.5%	(Suzuki and Imamura, 2005)	-
2	SP	Japan	Tohoku area	-	Jul. 2000	391	45	24.1	0.929	21.5%	(Hayakawa, 2003)	-
3	SP	Japan	Japan except Tohoku	-	Apr. 2001	30	30	21.3	0.981	12.4%	(Hayakawa, 2003)	-
4	SP	Japan	Tohoku area	-	Jun. 2001	76	45	23.4	0.973	13.1%	(Hayakawa, 2003)	-
5	SP	Japan	Tohoku area	-	Jul. 2001	227	45	23.5	0.947	19.4%	(Hayakawa, 2003)	-
6	SP	Japan	Sophia Univ. (Tokyo)	-	Jun. 2002	90	30	25.8	0.971	13.5%	(Hayakawa, 2003)	-
7	SP	Japan	Tokyo Inst. of Tech.	-	Jun. 2002	29	30	19.3	0.977	13.0%	(Hayakawa, 2003)	-
8	SP	Japan	Tohoku area	-	Jun. 2002	15	45	18.3	0.934	17.6%	(Hayakawa, 2003)	-
9	SP	Japan	Tohoku area	-	Jul. 2002	125	60	19.2	0.959	16.4%	(Hayakawa, 2003)	-
10	SP	Japan	Ito City (Shizuoka)	-	Aug. 2002	53	20	15.8	0.923	19.9%	(Hayakawa, 2003)	-
11	SP	Japan	Tokushima Prefecture	-	Sept. 2002	198	30	22.1	0.971	13.8%	(Hayakawa, 2003)	-
12	SP	Japan	Miyagi Prefecture	-	Oct. 2002	1,460	45	21.8	0.964	15.6%	(Hayakawa, 2003)	-
13	SP	Japan	Tokai area	-	Oct. 2002	226	25	25.5	0.971	14.0%	(Hayakawa, 2003)	-
14	SP	Japan	Matsushima town	-	Jun. 2009	750	45	17.9	0.982	8.5%	(Shishido, 2010)	-
15	SP	Thailand	Phuket village	-	Mar. 2009	46	90	25.7	0.918	20.6%	(Suppasri, 2010)	-
16	SP	Peru	La Punta district	-	Sept. 2010	128	20	11.0	0.939	18.0%	This study	-
17	SP	Peru	La Punta district	-	Sept. 2011	127	20	7.5	0.956	14.5%	This study	-
1	RP	Japan	Sanriku area	02.11.1989	Oct. 1989	1,778	25	28.2	0.976	11.3%	(Saito, 1990)	0.56
2	RP	Japan	Nonamae town	12.07.1993	Oct. 1993	7	5	6.4	0.946	14.9%	(Tokyo Metropolitan University, 1994)	8.70
3	RP	Japan	Inaho town	12.07.1993	Oct. 1993	12	5	15.4	0.752	33.3%	(Tokyo Metropolitan University, 1994)	8.70
4	RP	Japan	Yamasedomari town	12.07.1993	Oct. 1993	70	10	23.1	0.840	27.6%	(Tokyo Metropolitan University, 1994)	3.00
5	RP	Japan	Tamaura town	12.07.1993	Oct. 1993	15	10	6.5	0.940	15.2%	(Tokyo Metropolitan University, 1994)	6.60
6	RP	Japan	Hotokezawa town	12.07.1993	Oct. 1993	20	10	8.7	0.849	24.8%	(Tokyo Metropolitan University, 1994)	3.50
7	RP	Japan	Okushiri division 1	12.07.1993	Oct. 1993	70	13	20.3	0.892	24.3%	(Tokyo Metropolitan University, 1994)	3.50
8	RP	Japan	Okushiri division 2	12.07.1993	Oct. 1993	45	13	18.7	0.856	26.9%	(Tokyo Metropolitan University, 1994)	3.50
9	RP	Japan	Okushiri division 3	12.07.1993	Oct. 1993	43	13	22.7	0.858	27.0%	(Tokyo Metropolitan University, 1994)	3.50
10	RP	Japan	Okushiri division 4	12.07.1993	Oct. 1993	43	13	13.1	0.890	23.3%	(Tokyo Metropolitan University, 1994)	3.70
11	RP	Japan	Okushiri division 5	12.07.1993	Oct. 1993	63	13	12.3	0.921	20.2%	(Tokyo Metropolitan University, 1994)	3.70
12	RP	Japan	Iachi town	12.07.1993	Oct. 1993	106	10	13.3	0.852	26.5%	(Tokyo Metropolitan University, 1994)	3.70
13	RP	Japan	Bushigawa town	12.07.1993	Oct. 1993	13	10	7.3	0.956	14.1%	(Tokyo Metropolitan University, 1994)	3.00
14	RP	Japan	Akaishi town	12.07.1993	Oct. 1993	33	10	8.9	0.919	19.1%	(Tokyo Metropolitan University, 1994)	3.00
15	RP	Japan	Onkouta town	12.07.1993	Oct. 1993	24	10	15.2	0.845	27.4%	(Tokyo Metropolitan University, 1994)	4.10
16	RP	Japan	Matsue town	12.07.1993	Oct. 1993	31	8	13.5	0.786	30.9%	(Tokyo Metropolitan University, 1994)	5.50
17	RP	Japan	Hatsumatsumae town	12.07.1993	Oct. 1993	21	8	11.2	0.785	30.2%	(Tokyo Metropolitan University, 1994)	15.90
18	RP	Japan	Tomisato town	12.07.1993	Oct. 1993	35	8	11.7	0.849	26.3%	(Tokyo Metropolitan University, 1994)	10.00
19	RP	Japan	Aonae division 1	12.07.1993	Oct. 1993	60	8	6.8	0.951	14.5%	(Tokyo Metropolitan University, 1994)	5.00
20	RP	Japan	Aonae division 2	12.07.1993	Oct. 1993	54	8	6.7	0.943	15.3%	(Tokyo Metropolitan University, 1994)	5.00
21	RP	Japan	Aonae division 3	12.07.1993	Oct. 1993	54	8	8	0.927	17.7%	(Tokyo Metropolitan University, 1994)	5.00
22	RP	Japan	Aonae division 4	12.07.1993	Oct. 1993	35	8	7.3	0.864	22.8%	(Tokyo Metropolitan University, 1994)	5.00
23	RP	Japan	Aonae division 5	12.07.1993	Oct. 1993	34	5	8.4	0.769	29.6%	(Tokyo Metropolitan University, 1994)	12.40
24	RP	Japan	Aonae division 6	12.07.1993	Oct. 1993	37	5	15.9	0.911	22.4%	(Tokyo Metropolitan University, 1994)	11.00
25	RP	Japan	Aonae division 7	12.07.1993	Oct. 1993	18	5	12.5	0.927	19.6%	(Tokyo Metropolitan University, 1994)	11.00
26	RP	Japan	Aonae town	12.07.1993	Nov. 1993	264	5	8.1	0.906	19.8%	(Amakuni et al., 1994)	20.00
27	RP	Japan	Okushiri Island	12.07.1993	Jan. 1994	170	5	9.4	0.961	14.4%	(Tokyo University, 1994)	7.00
28	RP	Japan	Taisei - Setana town	12.07.1993	Jan. 1994	141	13	13.5	0.957	14.9%	(Tokyo University, 1994)	6.00
29	RP	Japan	Shimamaki town	12.07.1993	Jan. 1994	130	5	7.3	0.985	9.0%	(Tokyo University, 1994)	5.00
30	RP	Japan	Hokkaido area	26.09.2003	Mar. 2005	2,500	16	15.0	0.959	14.5%	(Hiroi, 2005)	1.30
31	RP	Indonesia	Padang city	12.09.2007	Oct. 2007	29	45	32.1	0.975	10.4%	(Hoppe, 2007)	0.90
32	RP	Indonesia	Padang city	30.09.2009	Nov. 2009	98	15	27.1	0.969	12.2%	(Hoppe and Marhadiko, 2009)	0.27
33	RP	Japan	Kamaishi city	11.03.2011	Apr. 2011	30	35	17.3	0.924	19.2%	(NPO CeMI, 2011)	20.17
34	RP	Japan	Natori city	11.03.2011	Apr. 2011	33	65	33.6	0.977	12.4%	(NPO CeMI, 2011)	9.71
35	RP	Japan	Sendai	11.03.2011	May. 2011	33	67	22.9	0.982	11.7%	(Survey Research Center Co., 2011)	9.69
36	RP	Japan	Natori city	11.03.2011	May. 2011	54	65	28.7	0.955	17.7%	(Survey Research Center Co., 2011)	9.71
37	RP	Japan	Minami Sanriku	11.03.2011	May. 2011	42	47	16.2	0.924	18.7%	(Survey Research Center Co., 2011)	13.38
38	RP	Japan	Onagawa	11.03.2011	May. 2011	52	41	16.4	0.969	13.3%	(Survey Research Center Co., 2011)	20.15
39	RP	Japan	Ishinomaki	11.03.2011	May. 2011	86	62	24.5	0.940	19.4%	(Survey Research Center Co., 2011)	8.51
40	RP	Japan	Tagajo	11.03.2011	May. 2011	35	68	21.0	0.965	15.5%	(Survey Research Center Co., 2011)	3.88
41	RP	Japan	Watari	11.03.2011	May. 2011	51	69	29.4	0.955	17.9%	(Survey Research Center Co., 2011)	8.65
42	RP	Japan	Yamamoto	11.03.2011	May. 2011	40	68	36.4	0.985	13.7%	(Survey Research Center Co., 2011)	8.43
43	RP	Japan	Tohoku area (survivors)	11.03.2011	Sept. 2011	2,673	30	33.4	0.882	26.2%	(Weathernews, 2011)	10.00
44	RP	Japan	Tohoku area (casualties)	11.03.2011	Sept. 2011	860	30	78.0	0.944	20.5%	(Weathernews, 2011)	10.00

Data for 1993 Hokkaido Nansei-Oki Earthquake also compiled from Hayakawa (2001); Todd (1993) and PMEL `http://nctr.pmel.noaa.gov/okushiri_devastation.html`

posted in the tsunami survey was: "In the case of a near-field tsunami, how many minutes would you take to decide and prepare yourself for evacuation? (From the end of the earthquake to the beginning of your evacuation to a safe place)". The alternatives were: 0 min, 1-5 min, 6-10 min, 11-15 min, 16-20 min, 21-25 min, 26-30 min, more than 30 min. A total of 127 sheets were validated with results in Table 3.4:

Table 3.4: Departure times based on SP survey in La Punta on Sept. 2011

Time (min)	0	5	10	15	20	25	30	30+
No. Resp.	7	73	31	12	1	2	1	0
Freq. (%)	5.5%	57.5%	24.4%	9.4%	0.8%	1.6%	0.8%	0.0%
Acc. (%)	5.5%	63.0%	87.4%	96.9%	97.6%	99.2%	100.0%	100.0%

With the theoretical Rayleigh distribution (Eq. 3.4), we looked for the best-fit value of μ that gives the highest correlation (Correl. (r)) and the lowest normalized root mean square error (NRMSE) for the comparison of accumulated rate data of the questionnaire and the cumulative distribution of Rayleigh. Results are shown in Table 3.5.

Table 3.5: Correlation, NRMSE and the optimum μ value for the Rayleigh distribution and the departure times based on the survey. La Punta 2011.

Time (min)	0	5	10	15	20	25	30	30+
Acc. (%)	5.5%	63.0%	87.4%	96.9%	97.6%	99.2%	100.0%	100.0%
D(t)	0.0%	29.5%	75.2%	95.7%	99.6%	100.0%	100.0%	100.0%
Correl. (r) = 0.956			NRMSE = 14.5%			$\mu = 7.5$		

The same process was conducted to all the available questionnaire data with departure time information. Fig. 3.5 shows the comparison between the values of the mean of the distribution based on the questionnaire answers (μ) with the value of the Estimated Tsunami Arrival time (ETA) or Recorded Tsunami Arrival time (RTA) for SP and RP surveys respectively.

It appears that SP survey results estimate fast evacuations with respect to the ETA (Fig. 3.5-left). Respondents in general expect from themselves a rapid reaction in case of a tsunami. However, the RP surveys revealed that the mean of the distribution of evacuation decision is relatively close to the RTA (Fig. 3.5-right). Sorensen (1991) affirmed that people appear to adjust the rapidity of their evacuation behavior in accordance with the severity and timing of the impending threat. Findings of this study using questionnaires of human behavior in evacuation from tsunami, confirms that most of the people adjust their behavior to the timing of the arrival of tsunami.

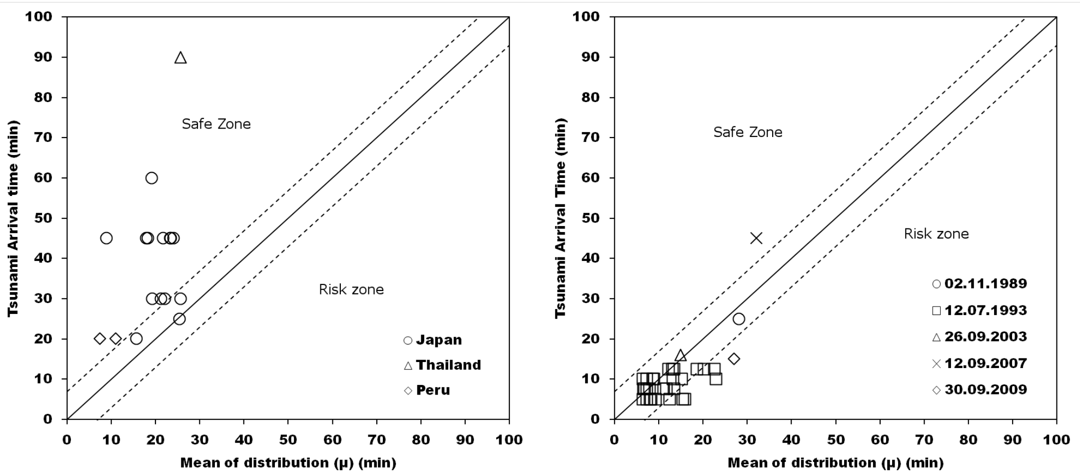


Figure 3.5: Survey Results vs Tsunami Arrival Time - Left: Comparison of SP survey mean values of Rayleigh distribution with the estimated tsunami arrival time. Right: Comparison of RP survey mean values of Rayleigh distribution with the recorded tsunami arrival time.

Based on these results, a new approach for the use of the Rayleigh distribution in the case of tsunami evacuation can be formalized. As observed, values of mean of Rayleigh distributions calculated using questionnaire answers in RP surveys agrees with the tsunami arrival time. Therefore the traditionally assumed parameter (μ) in the departure curves (Eq. 3.4) can be reasonably estimated as the tsunami arrival time of previous historical events. If such previous events are not in the record, or if the earthquake scenario is different to the past recorded event, the numerical simulation of tsunami can provide the arrival time of tsunami or in this case the parameter μ. Additionally, SP survey results cannot be neglected since some respondents might be holding a similar reaction to the stated in the questionnaire. To support this idea, notice the rapid evacuation on 12.09.2007 in Fig. 3.5-right that falls in a Safe Zone for evacuation. Despite most of the events show evacuation behaviors adjusted to the timing of the event, we have to be aware that other factors influence on evacuation decision and might accelerate the overall reaction of a population. For example, a high strong ground motion intensity, a fast, clear and well-follow warning issue, a good training and awareness, etc. Further on this observation is the behavior on the recent March 11^{th}, 2011 Japan earthquake. Fig. 3.6 shows the result of questionnaires of evacuation in several areas asked to survivors and families of casualties. It is clear that in all of the areas a fast reaction compared to the arrival of tsunami was performed by survivors, while the only point in the Risk Zone is the result of evacuation behavior of casualties; this behavior was obtained through interviews to families and friends of the victims (Weathernews, 2011).

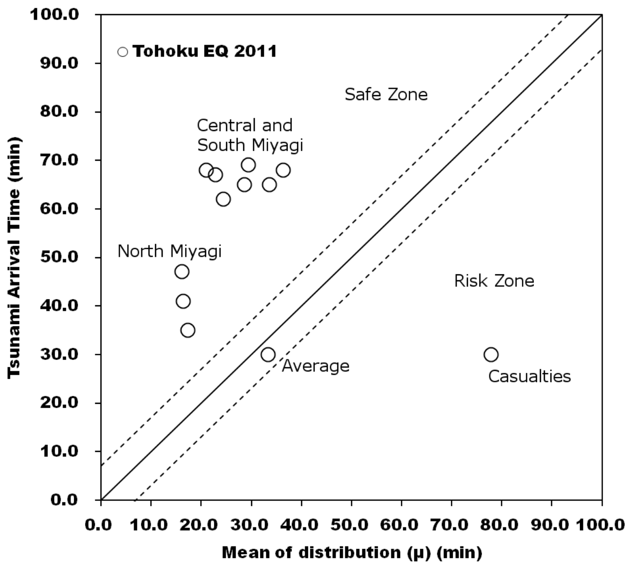


Figure 3.6: 2011 Great East Japan Earthquake - Evacuation behavior on March 11^{th}, 2011 Japan Earthquake. A fast evacuation in all areas was performed by survivors (points in the Safe Zone), while victims present a slow evacuation decision (point in the Risk Zone).

In summary, we have to accept that human behavior varies from individual to individual and the uncertainty of a rapid or slow reaction should be considered if possible. Therefore, the use of Eq. 3.4 in a unique simulation might be leading to one of the possible scenarios of evacuation decision.
Thus, we propose that a suitable approach will be of a stochastic simulation of several possible behaviors of departure curves, however bounded by SP surveys and RP surveys, or if the latter is not available, then (Eq. 3.4) with μ estimated by the numerical simulation of the tsunami. In order to illustrate this approach and the use of the proposed departure curve for tsunami evacuation, a case study of evacuation was conducted for the 2011 Great East Japan Earthquake Tsunami in the village of Arahama in the Sendai Plain area as a validation of the method and the model (see Chapter 4).

3.2.2 Layer 1: Shelter and Mean decision

Shelter decision

In small urban systems or rural evacuations, looking for the nearest shelter may be a good assumption in modeling, especially for hazards like tsunami with short time available for escaping (Southworth, 1991). However it has been reported also that sometimes people does not immediately evacuate to shelters, but target for a first destination like their own house or children's school or other intermediate goal prior to the shelter or exit of inundation area (Cabinet Office of Japan, 2011). It is a very difficult task to determine who will have such behavior or which one would be the first destination among a large number of population. To simplify the use of the model and following principles of protective action (immediate evacuation to shelters), the TUNAMI-EVAC1 model does not consider intermediate destinations. Either nearest shelters or exits are the first and unique destination for an agent, with a preference of shelters over exits for pedestrians and exits over shelters for cars. For further exploration on this matter we have also opened in the model the option of "random" selection of shelter, thus, not necessary the nearest may be selected. For the applications and other scenarios in this study, the "nearest" condition was used. Future upgrades to the model might consider intermediate goals during evacuation.

Mean of evacuation decision

The transportation used to escape from tsunami inundation is a crucial factor affecting the total time of the individual evacuation. For instance, in the 2011 Great East Japan Earthquake principal means of evacuation were vehicles and walking. It is said that more than half of surveyed people evacuated by car, and a third of them got caught in heavy traffic (Cox, 2011; Yun and Hamada, 2012). Traffic congestion due to massive car evacuation is one of the risks at the time of tsunami. This was observed also in the Chile tsunami in 2010 (Marín et al., 2010). The relation on foot and car evacuation varies according to the territory and available facilities for refuge. For example in a survey by the Guard Police Psychology Research Society (Yamamoto and Quarantelli, 1982) addressing a future hypothetical earthquake in Tokyo, a 75% of respondents prefered the "on foot" evacuation while 11% chose "by car", the rest 14% chose alternatives between bicycle, motorcycle or do not know. In constrast, from a survival sample in 2011 Great East Japan Earthquake results are clearly opposite (Table 3.6).

Consequently, it is apparently a good approximation to expect a majority of residents to evacuate "on foot" when the condition of distance to shelters is less

Table 3.6: Means of evacuation in three prefectures of Japan (Cabinet Office of Japan, 2011)

Prefecture	Mean	No.	%	Avrg. Dist.(m)
Iwate	on foot	128	52	350
	by car	118	48	1225
Miyagi	on foot	78	34	550
	by car	150	66	1550
Fukushima	on foot	12	17	675
	by car	59	83	5050
Total	on foot	218	40	450
	by car	327	60	2000

than half kilometer. On the other hand, evacuation "by car" may be performed to look for long distances over one kilometer possibly out of the expected inundation area. Although these conclusions seem to be rational, particularities of each location should be explored. For that reason, the use of questionnaire surveys to obtain people's preference of evacuation is taken as the default method in the TUNAMI-EVAC1 model. In the model either vehicle and on foot evacuation is possible to simulate, the number of evacuees with each of these preferences should be obtained from the result of a simple survey in the community posing the following or similar question: "In the case of a near-field tsunami, which mean of transportation would you use to evacuate?" and alternatives such as "on foot" and "by car". A questionnaire template needed can be found in Appendix C.

3.2.3 Layer 2: Route decision and Path finding

The shortest path for evacuation route has been widely used by previous tsunami evacuation models (Clerveaux, 2009; Goto et al., 2010; Uno and Kashiyama, 2008), however not all of evacuees take necessary the shortest path; sometimes they just take any path or a regularly known path. Thus, in the TUNAMI-EVAC1 model the path finding problem is solved using the A* (A star) algorithm for grid space (Hart and Nils, 1968; Steiner, 2009). A* algorithm still remains the most popular graph search algorithm and its use is ubiquitous in the video game industry (Anguelov, 2011).

The A* algorithm

The algorithm proposed by Hart and Nils (1968) was presented as an improvement to the point-to-point version of Dijkstra's algorithm (Dijkstra, 1959). The principle of this method can be explained as follows (Lester, 2005): Assuming the position of an agent in a grid space world separated from his target by a wall (Fig. 3.7-A). In the grid space there are walkable and unwalkable grids (the wall). The center of a grid is called a node, in NetLogo squares or grids are called patches. The search starts at the location of the agent by adding to an "open list" the adjacent walkable nodes, plus the node of the agent location. The center of these group of nodes - the node where the agent is located - is saved as the "parent node" for the eight neighbors around it. Then, the current parent node is erased from the "open list" and save into a "closed list", this means there is no need anymore for further exploration of this node (Fig. 3.7-B). The process is repeated with all nodes adjacent and so on (Fig. 3.7-C), until finding the target node (Fig. 3.7-D). The trick of the algorithm is to decide on the way which nodes are the bests to explore first. As a rule, the node with the lowest F cost is the best. the F cost is determined by the path scoring following Eq. 3.8

$$F = G + H \tag{3.8}$$

where:
G = the movement cost to move from the starting point to a given node, following the path generated to get there. The path generated is based on the parent-child relation going backwards.
H = the estimated movement cost to move from the given node to the final destination. This is referred as the heuristic. An heuristic is a sort of guess or spatial bias related to how far the agent thinks the target is from his actual point or a relative point. There are several kinds of heuristics that will be discussed later in this section.
Finally as observed in Fig. 3.7-D the path is generated by repeatedly going through the "open list" and "closed list" choosing the node with lowest F score. Nodes in the "open list" are also compared in the process to verify if the path is more convenient when changing the parent-child relation, this assures finding a better path, however not the shortest path if H is different than zero.

Heuristics

The heuristic is an estimation of the minimum cost from any node to the goal. An heuristic can be used to control A*s behavior. For example if H is zero, then only

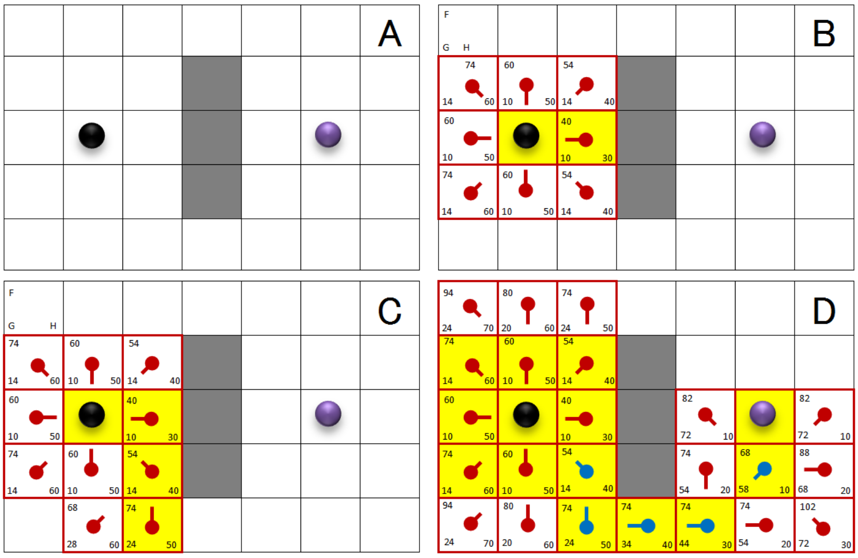


Figure 3.7: A* algorithm - A)An agent in the left separated by a wall from his goal on the right side; B)Exploration of adjacent nodes and calculation of G, H and F values; C)Yellow squares show explored nodes; D)The path found is shown by blue bots showing the direction of its parent-child relation

G is calculated at each step and A* turns into a Dijkstra's algorithm, which finds always the shortest path. However, if H is given always a correct estimation of the distance to the goal, the algorithm turns very fast in the exploration time of nodes, but it cannot assure to find the shortest path. In the real world, pedestrians tend to prefer to minimize their distance effort, then the shortest path appears to be adequate. However, not only distance preference influences the route decision; also familiarity or risk avoiding, traffic avoiding and other conditions. Thus, not always is the shortest path the suitable behavior for pedestrian dynamics. In TUNAMI-EVAC1 we are using heuristics for the path finding. A initial algorithm for A* in NetLogo by Steiner (2009) was based on the creation of new agents as bots and other breeds of a*nodes, however the process of calculation was found to be too demanding in a real application for the TUNAMI-EVAC1. The main reason was the creation of these new agents in a large space where already pedestrian and vehicle agents where created. In total, the addition of pedestrians, vehicles, bots and a*nodes resulted in the run out of memory of computer. Steiner (2009) is a good stand alone application to understand the use of heuristics, however was not possible to be integrated in the final model. For this reason, the author modified the initial idea of creating new agents through the simple use of lists and grid variables. A faster algorithm in NetLogo is proposed by this study. Details of the source code can be found in the Appendix F. For TUNAMI-EVAC1 the five heuristics included in the original model of Steiner (2009) are also considered as alternatives for exploration of scenarios of route decision and related different computation times.

- *Euclidean distance*
  A straight line distance estimation between start-point and target-point. This estimation is one of the numerically shortest approximations, thus shortest paths will be obtained, however the process will take longer to run. The Euclidean equation is widely known as Eq. 3.9.

$$\sqrt{(Y_b - Y)^2 + (X_b - X)^2} \tag{3.9}$$

  where:
  (X, Y) is the coordinate of the current node in evaluation.
  (X_b, Y_b) is the coordinate of target point.

- *Manhattan distance*
  This is the standard heuristic for a square grid, however not necessary to be the best. The estimation is based on the positive difference of X coordinates plus the difference of Y coordinates of start and target points. It is calculated through Eq. 3.10.

$$|(Y_b - Y)| + |(X_b - X)| \tag{3.10}$$

  where:
  (X, Y) is the coordinate of the current node in evaluation.
  (X_b, Y_b) is the coordinate of target point.

- *Diagonal distance*
  When the diagonal movement is allowed this estimation computes the number of possible steps along a diagonal and the Manhattan distance, then, it combines the two weighting the diagonal steps with a D_2 cost. See Eq. 3.11.

$h_{diagonal} = min(|(Y_b - Y)|, |(X_b - X)|)$
$h_{straight} = |(Y_b - Y)| + |(X_b - X)|$

then,

$$D_2 * h_{diagonal} + D * (h_{straight} - 2 * h_{diagonal}) \tag{3.11}$$

where:
(X, Y) is the coordinate of the current node in evaluation.
(X_b, Y_b) is the coordinate of target point.
D_2 is $\sqrt{2}$
D is 1

- *Tie breakers*
  A tie breaker is a nudge on the scale of H. Scaling H upwards is always convenient for the expansion of nodes near the goal instead of the start point. For TUNAMI-EVAC1 to assure the upward scaling of H value the scaling parameter is calculated according to Eq. 3.12.

$$H_{scale} = (1 + 2/(worldwidth) + (worldheight)) \tag{3.12}$$

3.2.4 Layer 3: Speed adjusting - Agent movement

A large number of agents move around streets in the model, either pedestrians or cars, therefore collision avoidance should be taken into account. In the model, agents move in a continuous grid space according to their actual speed. Notice that an agent not necessary ”jumps” from grid to grid strictly at the center of grid (integer coordinates), but he may step on borders or in between (real coordinates). In order to move and according to the spatial accuracy or grid size, a certain number of agents are allowed in an area. Assuming a $1m^2$ personal area for each pedestrian, it is expected that for example 25 pedestrians can fit in a 5m x 5m grid. However, due to the dynamic movement of agents and the consideration of personal space between individuals, the total area of the grid is not used as the theoretical condition would suggest. For that reason, we used the predictive collision avoidance proposed by Karamouzas et al. (2009) and test the movement of pedestrians through a corridor (Helbing, 1991) (Fig. 3.8). In this corridor with 1m x 1m grid size, we count the number of agents passing through a 5m x 5m area at each time step, the results show that the maximum capacity of the grid is a 70% of its total area. Finally, we established a congestion condition when there is more than the round number of a 70% used of the grid space for pedestrians and in a similar approach a 7% for cars. In summary, for a 5m x 5m cell size, a maximum of 18 pedestrians are allowed and define as the limit crowd condition, therefore, other agents with the intention of crossing to an already crowded space will wait until available space appears. For the case of cars, in the same 5m x 5m cell size, a maximum of two cars are allowed.

For the speed variation condition, the walking speeds in pedestrian crowds with densities smaller than 0.2 $persons/m^2$ are Gaussian distributed with a mean value of 1.33 m/s and a standard deviation (S.D.) of about 0.26 m/s (Meister, 2007). Thus, the speed varies as a one-tail Normal Distribution of density in the agent field of view of a 60 degrees cone with 5m distance for pedestrians and 10m for cars (Fig. 3.9 and Fig. 3.10).

3.2.5 Casualty estimation

For the casualty model we used the experimental results of Takahashi et al. (1992) which consist on flow depth (cm), flow velocity (cm/s) and casualty condition of binomial explanation - safe or fall (Fig. 3.11). 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 the flow features such as depth and velocity that tsunami may also present. A binomial logistic regression was performed to obtain the casualty probability as a function of flow characteristics. Results are shown in Fig. 3.12 and Eq. 3.13.

$$f(z) = \frac{1}{1 + e^{15.48 - z}} \tag{3.13}$$

Where:

$z = \beta_0 + \beta_1 * h + \beta_2 * u$

$\beta_0 = -12.37; \beta_1 = 22.036; \beta_2 = 11.517$

$h =$tsunami inundation depth

$u =$tsunami velocity

The experimental data are limited to depth and velocity intervals of $h \in [0.28, 0.85](m)$ and $u \in [0.50, 2.00](m/s)$. Values for tsunami features above these ranges cannot be probabilistically calculated with the developed binomial function. Therefore, the model applies the binomial function to estimate casualties when the tsunami conditions are in ranges 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

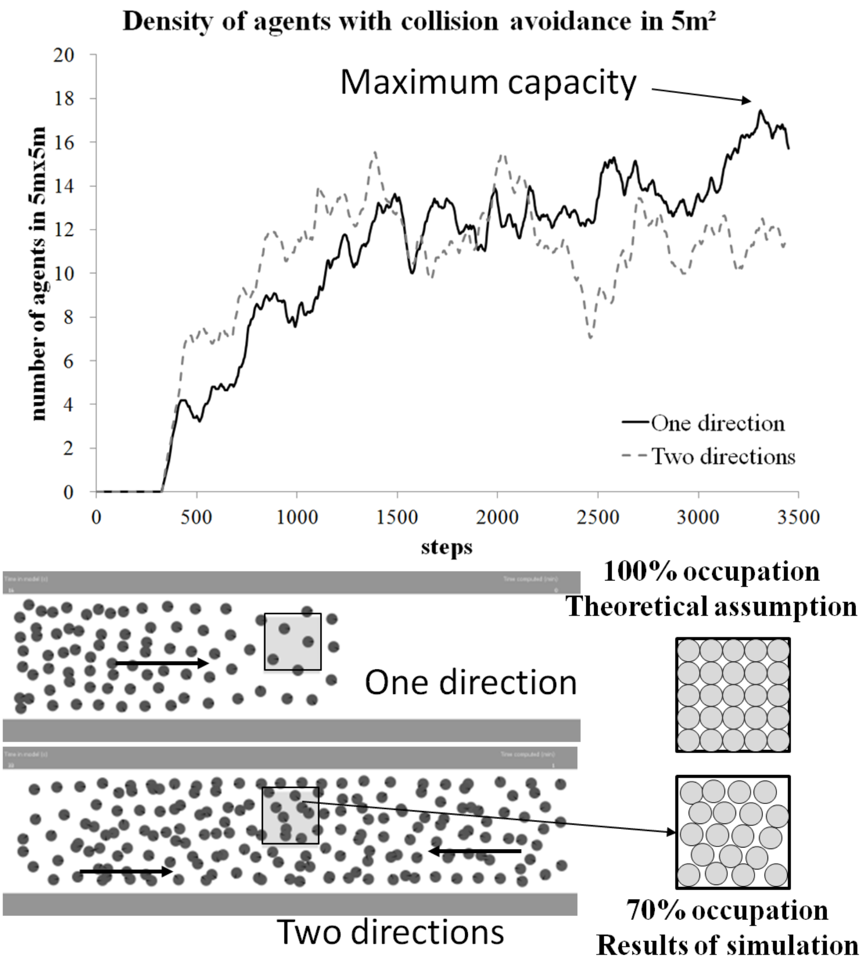


Figure 3.8: Density test - The corridor test (Helbing, 1991) using Predictive Collision Avoidance method Karamouzas et al. (2009) to find the maximum capacity of agents in a certain area as a congestion parameter for bottleneck calculation. In the dynamic condition of agents, only a 70% of the total area is used for movement with collision avoidance.

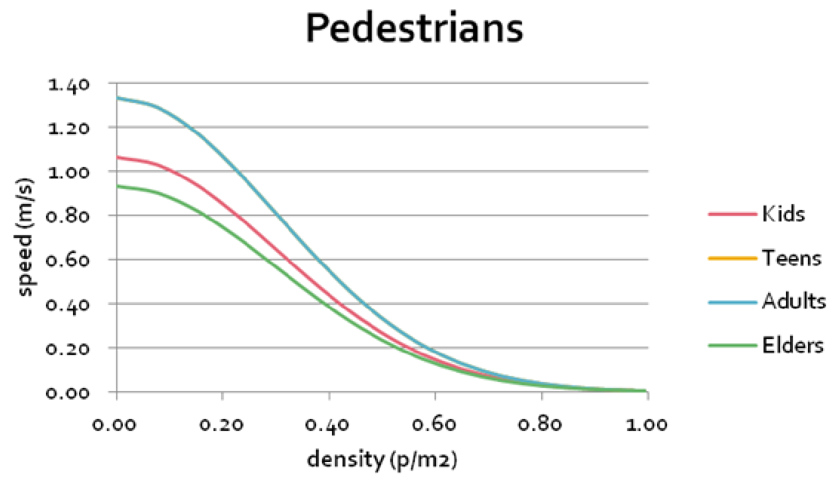


Figure 3.9: Pedestrian speed variation - The speed variation of pedestrian agents according to the density of cars and pedestrians inside the field of view

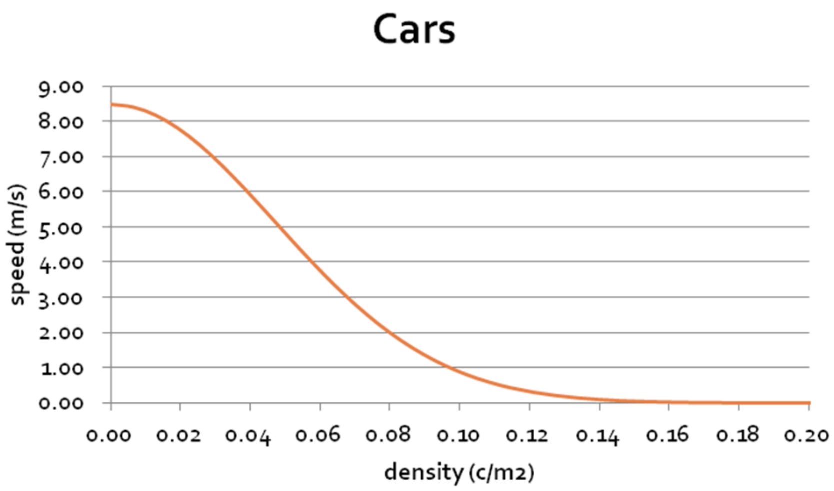


Figure 3.10: Vehicle speed variation - The speed variation of car agents according to the density of cars inside the field of view

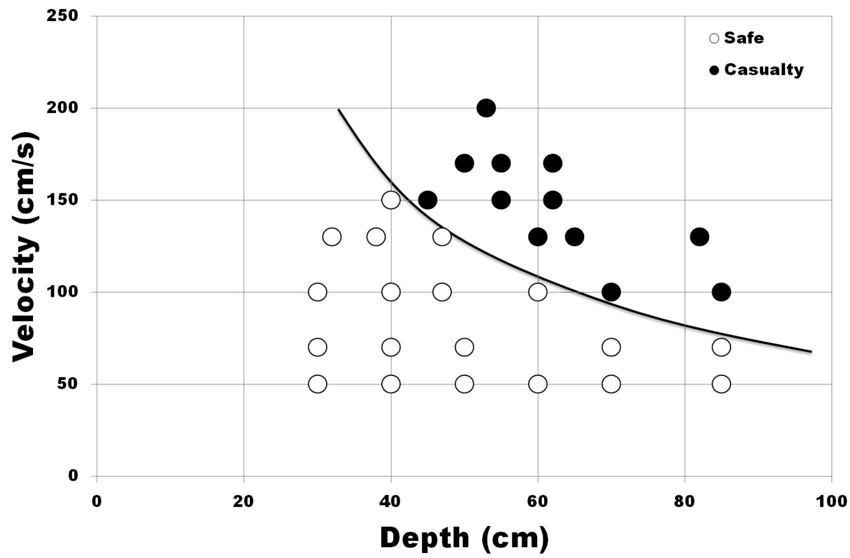


Figure 3.11: Casualty Experiment - Results of Takahashi et al. (1992) experiment

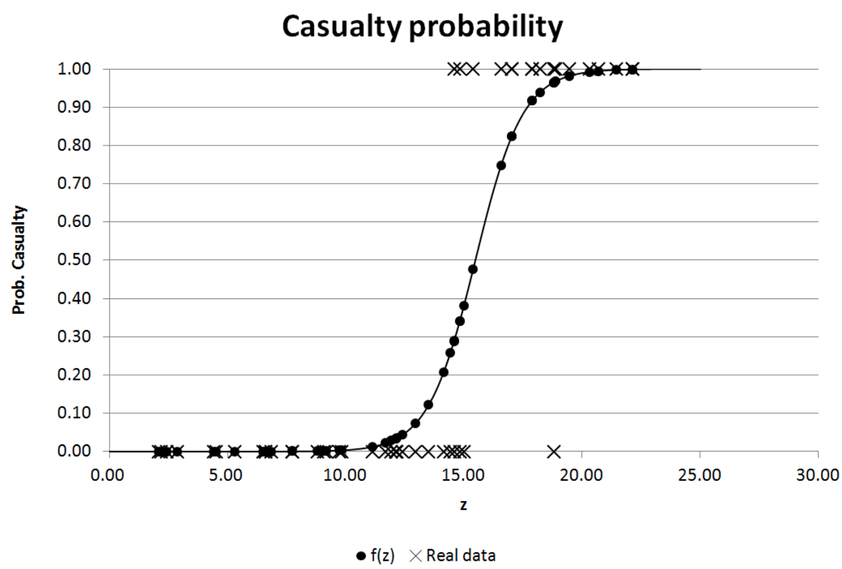


Figure 3.12: Casualty Estimation - Binomial Logistic Regression derived from the experimental data of Takahashi et al. (1992)

cases, passengers caught by a tsunami do not survive because they drown in the car or succumb due to debris impacts. Based on Yasuda and Hiraishi (2004) a value of 0.50 m of inundation depth is considered enough for a driver lose control of the vehicle and in many cases the car begins to float. Thus, when a car is trapped by a tsunami inundation depth greater than 0.50 m is considered as a casualty with all its passengers (four by default).

3.3 Model Default parameters

There are values built in the model which should be taken into consideration by the user. The default parameters are based on the author's criterion of best values, however those can be modified by the user.

- Handicap speed: maximum walking speed of handicap agents are set to the 50% of the maximum speed of their respective agent type.
- Car's passengers: the number of passengers in every vehicle is set as four (4).
- Heuristic: the default used heuristic is the "euclidean distance with tie breaker". All agents apply the same heuristic. There are other four options available in the model.
- Field of View: the field of view is a cone shape area of 60° with 5 m. radius for pedestrians and 10 m. for cars.

3.4 Graphical User Interface

As it was presented before in Fig. 3.2, the model shows a Graphical User Interface (GUI) to facilitate the exploration of scenarios and the immediate observation of outcomes (Fig. 3.13). GUI allows users to interact with the model through images, helping on the post process of outputs. Also it accelerates the analysis and discussion of scenario outcomes and emergent behavior observed. Some of the important features of GUI in TUNAMI-EVAC1 are presented here, for further details on the use and manipulation of GUI see the model User Manual (Appendix A or the NetLogo User Manual).

3.4.1 Buttons and Controls

Three types of controls are used in the model (Table 3.7). BUTTONS (SETUP and GO), to load the spatial and population data into the view screen with initial variable

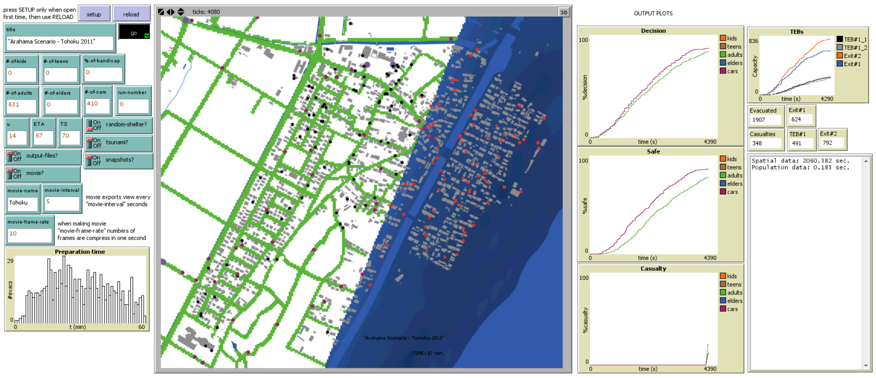
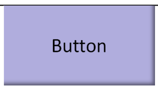
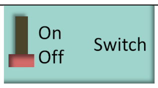
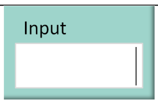


Figure 3.13: Model Screen snapshot - GUI of TUNAMI-EVAC1 with scenario variables and parameter inputs on the left, view screen on the center and graphs and monitors on the right side.

and parameter values; and to start the simulation. SWITCHES are used for scenario conditions and output options. The INPUT control receives the title, file name, number of agents, parameters for the Tsunami Departure Curves and computation times. A summary of the button and control panel can be found in Fig. 3.14.

Table 3.7: Buttons and Controls available in NetLogo

Icon/Name	Description
 Button	A button is either once or forever. When you click on a once button, it executes its instructions once (SETUP button). The forever button executes the instructions over and over, until you click on the button again to stop the action (GO button).
 On Off Switch	Switches are a visual representation for a true/false global variable. You may set the variable to either on (true) or off (false) by flipping the switch.
 Input	Input Boxes are global variables that contain strings or numbers.

Extracted and modified from http://ccl.northwestern.edu/netlogo/docs/

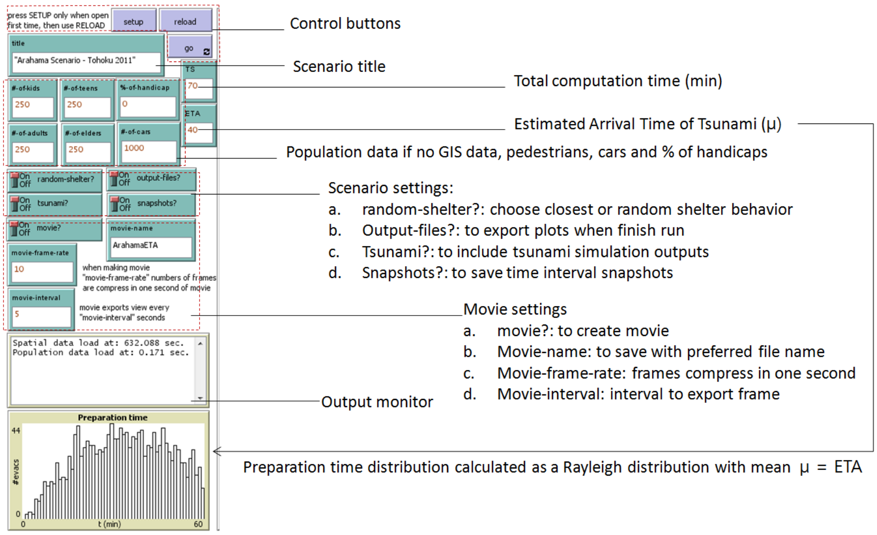


Figure 3.14: Buttons and Controls - The left side of the interface shows the Control Panel for parameter and variable setting.

3.4.2 View screen

The View Screen is a 2-dimensional visual representation of the NetLogo world of agents (turtles) and grids (patches). The initial appearance is colored black, because no agents have been loaded and patches are of black color by default. An example snapshot of the View Screen when the data has been loaded for a model in La Punta, Peru is shown in Fig. 3.15. It is possible to load image backgrounds such as satellite images like the one shown in the same figure. The View Screen is used to follow the simulation condition at each step. It allows the user to monitor and observe the emergent behavior.
In case of large scale simulations on small graphic memory computers it is convenient for the user to run the simulation in the background (without updates on the view screen). The View Screen can be deactivated by dragging the upper slide of update speed to the right or simply setting the "view updates" box unchecked. Finally snapshots during the simulation can be created or/and a final animated movie of the whole scenario.

3.4.3 Graphs and Monitors

To the right of the view screen, plots and monitors can be observed (Fig. 3.16). Output plots show the population decision on time (DECISION), the percentage of evacuees into shelters (SAFE), the percentage of casualties on time (CASUALTY) and a special plot of all Tsunami Evacuation Buildings (TEBs). Monitors are boxes that show also on-real time of the simulation, the update number of reporter commands like

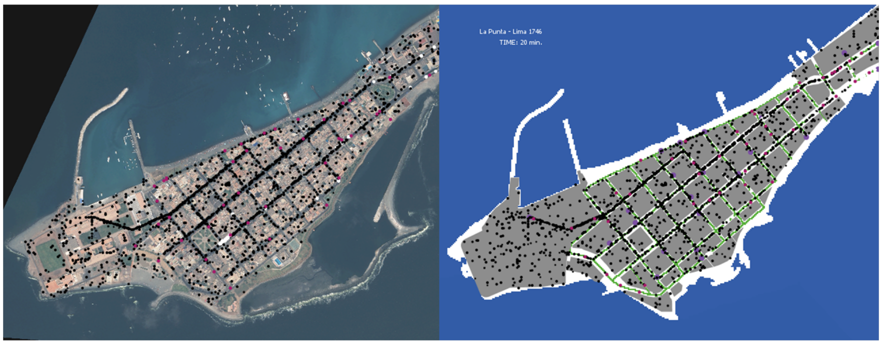


Figure 3.15: The View Screen - Left: With Satellite Image background. Right: Without Satellite Image Background.

the number of evacuated agents, casualty agents, agents at certain exit or TEB and the total time of data loading and computation.

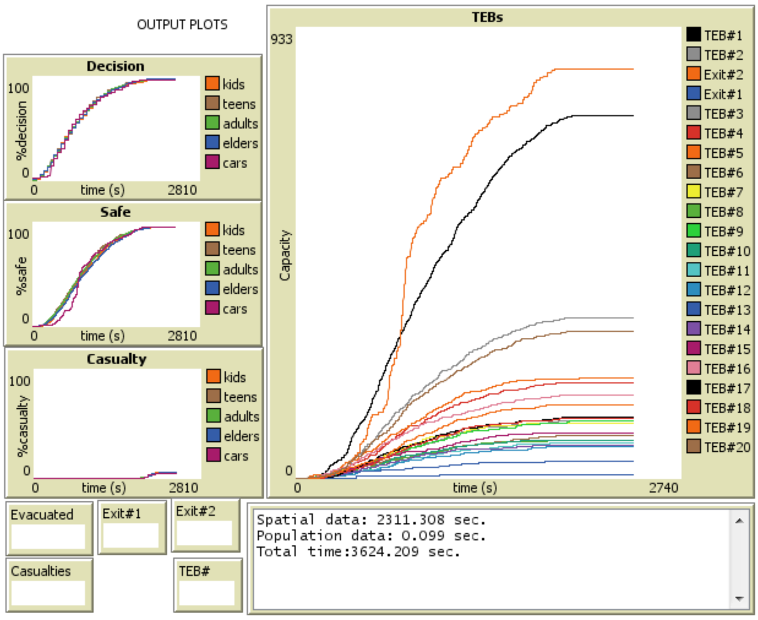


Figure 3.16: Graphs and monitors - A snapshot of the Output Plot panel with Monitors to follow the process of simulation

3.5 Model Limitations

Due to the recent development of this tool, the TUNAMI-EVAC1 model is bounded by certain limitations of hardware, software, coding and philosophy. The main limitations can be summarized as:

- Tsunami Departure Curves is a method to evaluate different possible behaviors in the population; it does not characterize individuals' triggering factors for evacuation. Therefore, the model will not show what factors contribute on the individual evacuation decision, but the consequences of different behavior for evacuation.
- Tsunami information in order to explore behavioral changes during the evacuation is not considered. Thus, cancellation of evacuation cannot be assess in the model.
- In the case of traffic simulation, there is a lack of driving direction for vehicles. In other words, all streets are possible to be driven in two directions. Traffic direction is not considered. Thus, non-rational behavior such as going back into the risk area cannot be modeled. This feature will be added in the future.
- There is no route changing behavior considered. Therefore, bottleneck avoiding behavior cannot be observe in the model.
- The casualty estimation condition is a probabilistic and statistical model based on experimental data for an specific body of an average adult type. Therefore, the casualty criteria of Eq. 3.10 overestimates the stability condition of children, women or elder. It is expected that instability on children will occur at lower depths and velocities compared to the adult body type. Thus, results should be taken carefully.
- The multiagent system approach demands a big memory consumption, especially for computer graphic memory and RAM access memory. It has been observed that simulations for large scenarios in area and population demand considerable periods of time. From a different point of view, it is more a hardware disadvantage than a model built-in limitation. A possible solution is the partition of large areas into smaller and reasonable sizes for separate computation. For instance, an example can be found in Imamura et al. (2012) where the TUNAMI-EVAC1 model was applied for a preliminary evaluation of the evacuation procedure in Padang, Indonesia. For this case, a total of 2000 km^2 area was simulated with a total of 125,160 residents in a 5m x 5m grid scale. Thus, 800,503 grids and 125,160 residents sum up a total of 925,663 agents (turtles and patches are considered agents in NetLogo, both can perform actions and hold variables). Here, scenarios were modeled at average of 1 day computation with a 2GB RAM memory and

2.66GHz processor computer. In the case of the Arahama case study (Chapter 4), the model developed in NetLogo works at average 500MB of RAM usage in an Intel Core 2 Quad CPU (2.66GHz). Although the installed memory is 4.00 GB (32-bit OS) there are some limits inherent to the Java VM preventing NetLogo not to exceed the 512MB of RAM usage (sometimes 1.0 GB). Then the OutOfMemoryError appears when a big space with variables in patches is used or a big number of agents is created. For instance, in the case of the model for Arahama, the model of 60,720 (264 x 230) patches which represent a 5m resolution area (1.32km x 1.15km) has 6 variables for patches and 10 for agents. An example of resulting run time with variation of the number of agents is shown in Table 3.8 and Fig. 3.17. In conclusion, bigger areas with huge amounts of population will be time consuming and at some point might run out of memory.

Table 3.8: Experiment of Arahama model with variable number of agents involved.

No. Agents	Time (min)
100	3.4
500	24.5
1000	43.7
5000	218.6
10000	386.3

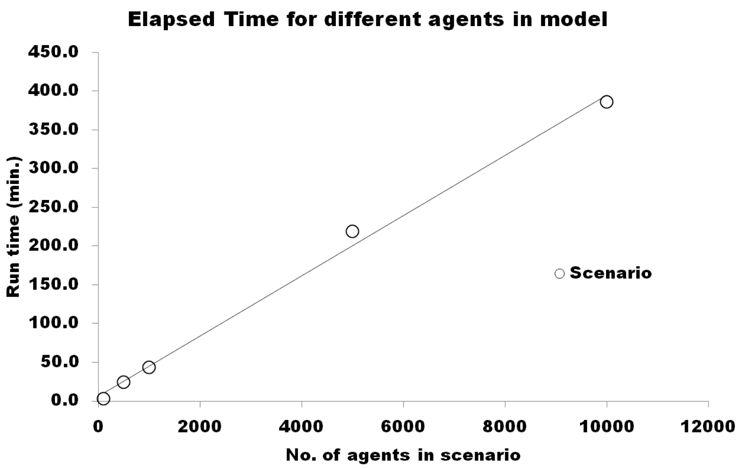


Figure 3.17: Elapsed time of simulations - Elapsed time for different number of agents involved in scenario simulation. Times are for one repetition.

- NetLogo is a powerful environment for multiagent system, however its limitation for parallelization for multiple processor running gives the model the same limitation. Also the Java Virtual Memory (JVM) is commonly bounded by a maximum capacity memory, generally 1GB, for fast simulation it is recommendable to increase this value in the register, however some times JVM cannot go over 2GB, then the high specification of new computers become meaningless if the JVM cannot be increased and use in its full potential. A future solution for this limitation is the migration of NetLogo coding to the more sophisticated software RePast that has a NetLogo translator and advance options for parallel running.

- In the case of A* algorithm for grid spaces. The search method prioritizes grids next to "walls", then resulting paths are in general close to the lateral edges of streets. The total width of street is not been used. Due to this limitation in the algorithm, the model uses the density criteria for crowd evaluation.

- Finally, in the case of pedestrians, even though the topographic data can be loaded into the model. In the present version the cost or fatigue of walking in slopes is not considered in the model of speed variation. Therefore, the application of the model is suitable for plain areas, and results should be taken carefully for hillside areas.

3.6 Summary

TUNAMI-EVAC1 has been introduced as a new tool for the disaster management and the disaster prevention education. The model uses GIS data, Questionnaire answers and Tsunami Inundation modeling results as input for the integration to a pedestrian and vehicle simulation of evacuation. The agent behavior follows the process of start time decision based on a new approach proposed and called Tsunami Departure Curve (TDC). TDC takes the results of a stated preference survey and the estimation of tsunami arrival time as the parameters to define boundary conditions of behavior of population. The stochastic simulation of these possible behaviors and the dynamics of the simulation lead to the emergent behavior of population during the evacuation. The model Graphic User Interface contributes to the future use by non experts and local stakeholders as an educational tool for lay persons.

Chapter 4

Model Validation at targeted area

As a validation and evaluation of the degree of accuracy of the model we conducted a simulated scenario related to the 2011 Great East Japan Earthquake in the Arahama village of Sendai plain in Miyagi prefecture (Mas et al., 2012d). After the 2011 Great East Japan Earthquake Tsunami of magnitude 9.0 Mw most of the structural countermeasures were destroyed, however nearly 90% of the estimated population at risk survived due to a fast evacuation to high-ground or inland. In this section, we will use the TUNAMI-EVAC1 to validate the TDC method and the model casualty estimations.

4.1 The 2011 Great Japan Earthquake and Tsunami

4.1.1 Overall damages

Before the 2011 event, the expected occurrence of the Miyagi-oki earthquake was one of the most concern seismic gaps in Japan. The calculated probability of an earthquake with 7.5-8.0 Mw in Miyagi Prefecture was estimated on 99% within 30 years. That was the highest probability of earthquake in Japan. At 14:46 on 11th March 2011, the massive earthquake recorded in Japan occurred at N38.1, E142.9 with the magnitude of 9.0 at 24 km depth (Japan Meteorological Agency (JMA), 2011) followed by many aftershocks and a devastating tsunami. The earthquake was ranked as the fourth in the world, after the 1960 Chile (M9.5), 2004 Sumatra (M9.3) and 1964 Alaska (M9.2). The earthquake had a long duration (about three minutes) and the largest slip of approximately 30 m (USGS, 2011). The maximum recorded earthquake intensity was 7 (Japan Meteorological Agency (JMA), 2011). Earthquake early warning system was issued 8 seconds after detection of the first P-wave. Tsunami warning was issued 3 minutes after the earthquake. At Miyagi Prefecture, it was estimated at first 6m tsunami height; after 24min a second bulletin was issued increasing the estimation to over 10m height tsunami (Japan Meteorological Agency (JMA), 2011). Around 67 minutes after the earthquake, tsunami arrived to the coast of Arahama village. The tsunami caused 19,212 dead and missing and more than 50,000 damaged houses and buildings (National Police Agency (NPA), 2012; Suppasri et al., 2012).

4.1.2 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 the cities of Kamaishi and Natori (NPO CeMI, 2011) 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 et al., 2011) and clocks observed in the field confirming the arrival time of waves (Muhari et al., 2012), 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.

4.2 Tsunami Modeling

4.2.1 Tsunami source model

An instantaneous displacement of the sea surface identical to the vertical sea floor displacement is assumed in the model of tsunami source. Ten sub fault segments based on the Tohoku University Source model version 1.1 (Imamura et al., 2011) were used as initial surface deformation (Fig. 4.1). The parameters are shown in Table 4.1.

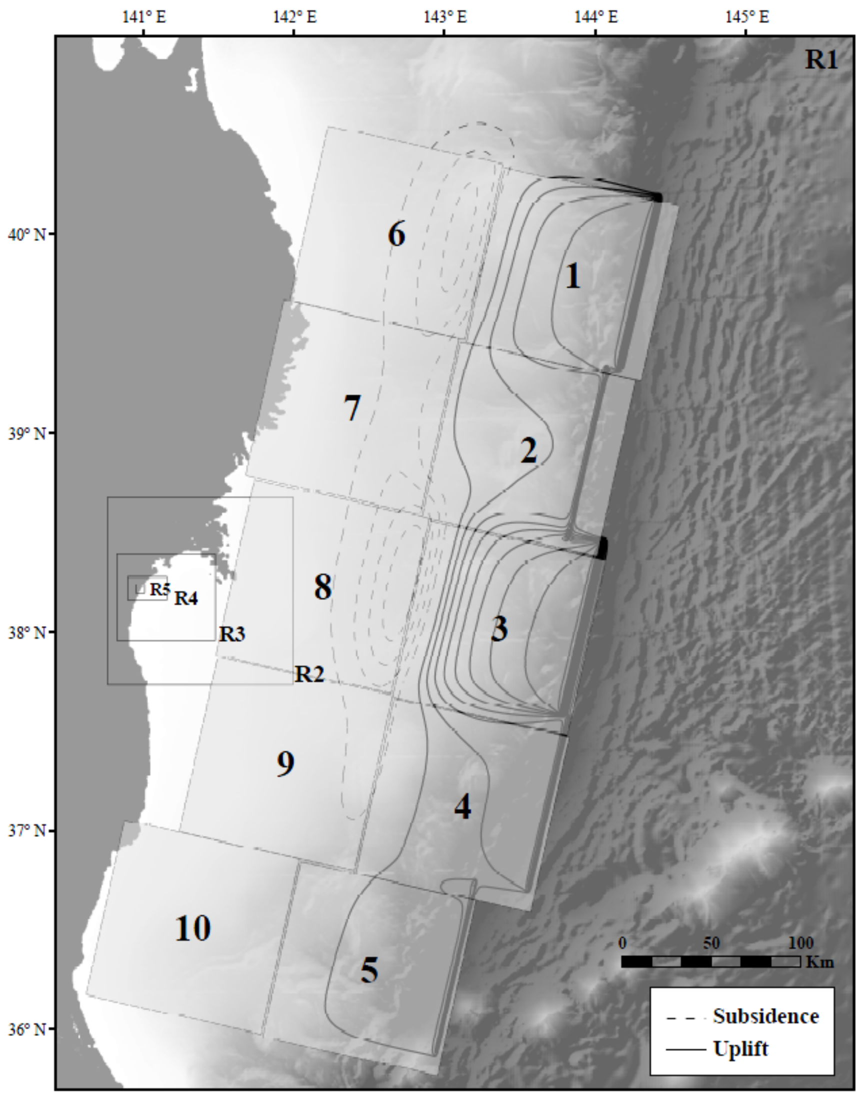


Figure 4.1: Tohoku University source model version 1.1 - Tsunami source model and Nested Grid setting

Table 4.1: Dimension of the subfaults 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

4.2.2 Numerical model setup

The source model presented above was use for the numerical simulation of tsunami into Arahama village in the Sendai plain of the Miyagi Prefecture. The Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI model) was used as the tool of tsunami modeling (Imamura, 1995). A set of non-linear shallow water equations (Eq. 4.1 to Eq. 4.3) are discretized by the Staggered Leap-frog finite difference scheme, with bottom friction in the form of Manning's formula constant in the whole domain.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{4.1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) = -gD\frac{\partial \eta}{\partial x} - \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} \tag{4.2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) = -gD\frac{\partial \eta}{\partial y} - \frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} \tag{4.3}$$

Where,

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

M and N are the discharge flux of x and y direction respectively, ν is the water level and h is the water depth above the mean sea level. Bathymetric and topographic data was obtained from the Central Public Disaster Prevention Council of Japan public database. Grid sizes vary from 405 m, 135 m, 45 m, 15 m and 5 m in five regions of nested grid system shown in Fig. 4.1.

4.3 Evacuation Modeling

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 in order 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 population spatial distribution. Tsunami characteristics are introduced as raster files at each tsunami numerical step time of simulation. Input parameters of scenario, model view and outputs are observed during the simulation on real time. Outputs are exported into file reports.

In order to deal with the complex and variability on time of human behavior and preference of evacuation time, a set of distributions of departing time might be use to convolve all the possible behaviors in the population. However, how to decide the most suitable distribution parameters?. Following the state of the art of departure times in large scale events such as hurricane or nuclear accidents evacuation, previous researchers found that sigmoid curves agreed on the population load rate into the evacuation network (Lindell and Prater, 2007; Southworth, 1991; Tweedie et al., 1986). Here, we used several Revelaed Preference (RP) and Stated Preference (SP) surveys of tsunami evacuation and compared them with the theoretical Rayleigh distribution which is similar to the shape proposed by Tweedie et al. (1986) for traffic simulation. For details see Chapter 3. Table 3.2 shows the results of correlations and values of mean of distribution (Eq. 3.3) compared to the reported or estimated tsunami arrival times in RP or SP surveys respectively.

From Fig. 3.5-left and Fig. 3.5-right it is observed that there is a higher correlation between the recorded arrival time of tsunami and the preparation time in RP surveys than the estimated arrival time through numerical simulation and preparation time related to the tsunami in SP surveys. This means that an SP survey might be revealing from respondents what it is considered a "correct" answer, a fast evacuation. However on RP surveys it is possible that at least half of the population at risk waited to the last moment to start their evacuation, close to a time of confirmation of tsunami arrival. This apparently irrational behavior of some people not evacuating until the last minute was observed in previous events and confirmed by the several videos available on the web. Based on Fig. 3.5, one might be tempted to rely on the distributions of previous revealed preference surveys as an input in the evacuation model. However, due to individualities on behavior we cannot neglect the stated preference surveys since some individuals might follow according to their expectations. Therefore, a better approach will be a bounded behavior between these two results.

It is the case of many areas on desire of evaluating their tsunami risk, that recent events have not occurred, and then RP surveys might be not available. In this case, based on the results explained before, stakeholders may apply SP surveys and estimate the arrival time of tsunami through numerical simulations. The final boundary distributions of behavior are obtained from these two methods.

4.4 Arahama village

Arahama is a populated village of the Wakabayashi ward of Sendai city in the Miyagi Prefecture, Japan. It is located between the Natori and the Nanakita rivers, six kilometers south of Sendai Port. A total of 2,704 residents lived in this area; after the 2011 tsunami, Sendai city bureau reported a total of 2,421 residents (Sendai City Office, 2011). The discounted 283 might be the maximum number of casualties. Coincidently, after the earthquake local media reported that between 200 to 300 victims were found in the area. Tsunami arrived after one hour of the earthquake with maximum wave height of 10m. Tsunami inundated 5 km inland, around ten times of the expected Miyagi-oki tsunami (Fig. 4.2).

Arahama is provided with not so many high reinforced concrete buildings; however the only official tsunami evacuation building in the area is the Arahama Elementary School of four stories and accessible roof. It remained after the earthquake and tsunami, sheltering around 520 evacuees (National Governors Association (NGA), 2011). Figure 4.3 shows the synthetic waveform produced by numerical simulation of tsunami at 350m offshore and 7.5m depth in front of Arahama village. The estimated arrival time of the first peak of tsunami wave was 69.5min, from numerical simulation, it was confirmed by video footage and agreed with stopped clocks found in the area (Suppasri et al., 2012).

For instance, in the Arahama Elementary School, one clock found inside the one-story gymnasium stopped at 15:56, 70 min after the earthquake (Fig. 4.4a), similarly a second clock found in the surrounding residences also stopped at 15:56 (Fig. 4.4b).

Also, 2km south of the Elementary School, at the Arahama Adventure Park, an elevated area for children play ground, a third clock was found inside the information office, it stopped at 15:58 (Fig. 4.4c), here the tsunami height was of 2m while in other places around the area reached to 7 to 8 m. Apparently, the office was protected by the hill area which split the tsunami wave in two directions. Finally, a fourth example is the Higashi-Rokugo Elementary school, located 2km further inland. In this location the clock stopped at 16:03, 77min after the earthquake (Fig. 4.4d).

Figure 4.2: Arahama village - Left: Before tsunami taken on September 2009. Right: After tsunami taken April 17th 2011. (Kahoku Shimpo, 2012)

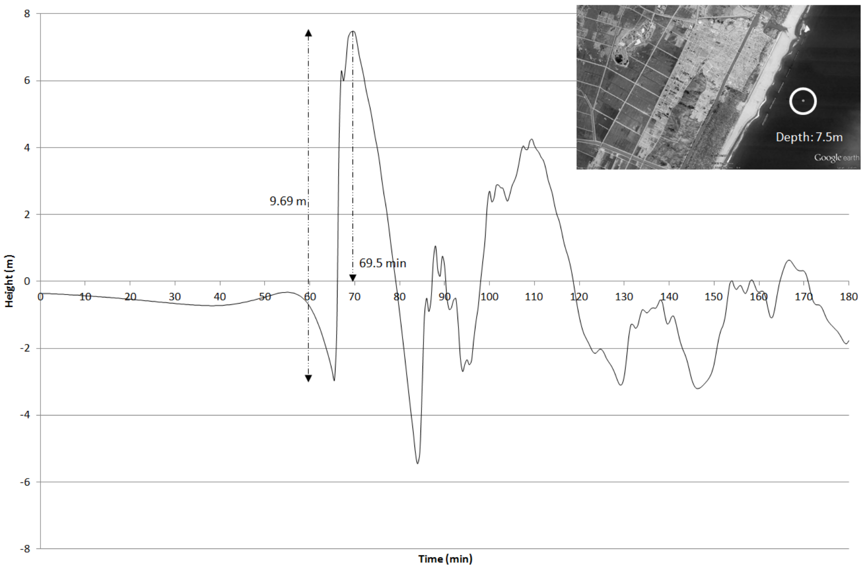


Figure 4.3: Waveform - A synthetic waveform of tsunami 350 m offshore of Arahama village at 7.5m depth. Arrival time: 69.5min; Height: 9.69m

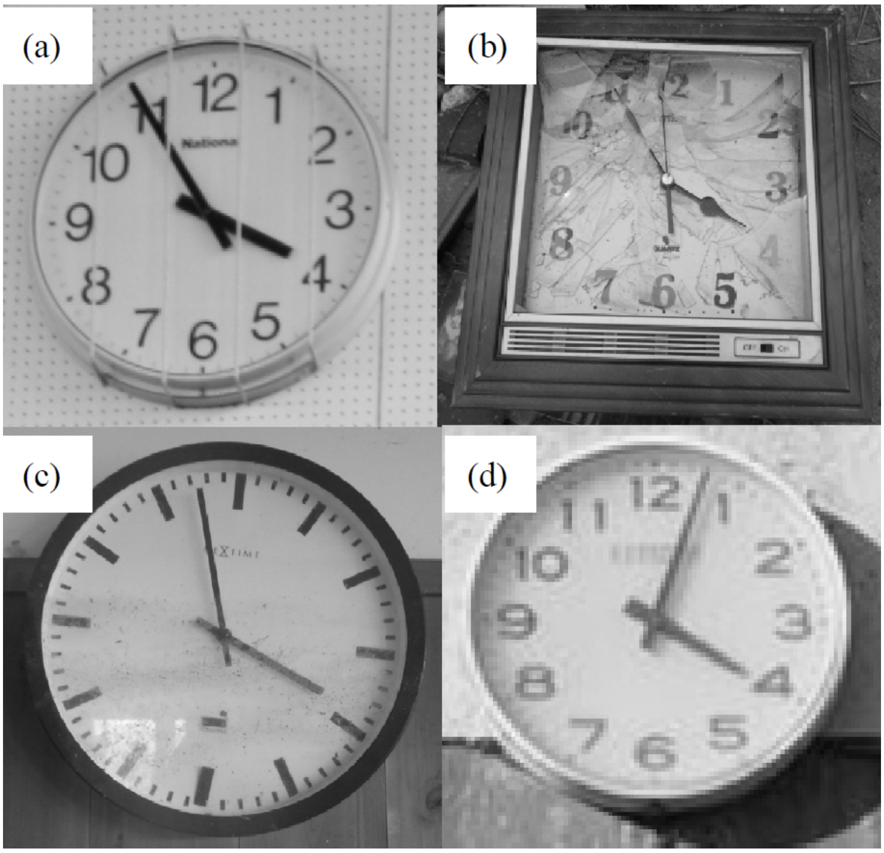


Figure 4.4: Stopped Clocks - Possible evidence of the tsunami arrival time in stopped clocks. Time agrees with video footage, witnesses' accounts and numerical simulation of tsunami. a) Arahama Elementary School Gymnasium (15:56); b) Arahama village (15:56); c) Adventure Park (15:58); d) Higashi-Rokugo Elementary School (16:03)

4.4.1 Spatial and Tsunami data

Local spatial data for the simulation was provided by the Geospatial Information Authority of Japan (GSI) on a shape format and converted for the model into a 5m x 5m grid raster. Tsunami data is taken from the output of calculations in the smallest domain shown previously (Fig. 4.1 and Fig. 4.2).

4.4.2 Population data

It is very difficult to determine the exact number of evacuees at the moment of the earthquake. However, an estimation of possible number of agents in the area is considered. It is not of the scope in this section to fully reproduce the evacuation of March 11th, but to introduce the model and method capabilities with the available data of a real event. Therefore, out of 2,704 residents reported in the census, 84% of the residential area was modeled and also the same percentage of population was considered. Thus, from the 2,271 residents in the model area, a 72% was taken as on-car evacuees according to (Suzuki and Imamura, 2005) questionnaire results (Fig. 4.5). Finally, assuming 4 passengers per car, 410 cars were modeled plus 631 pedestrians.

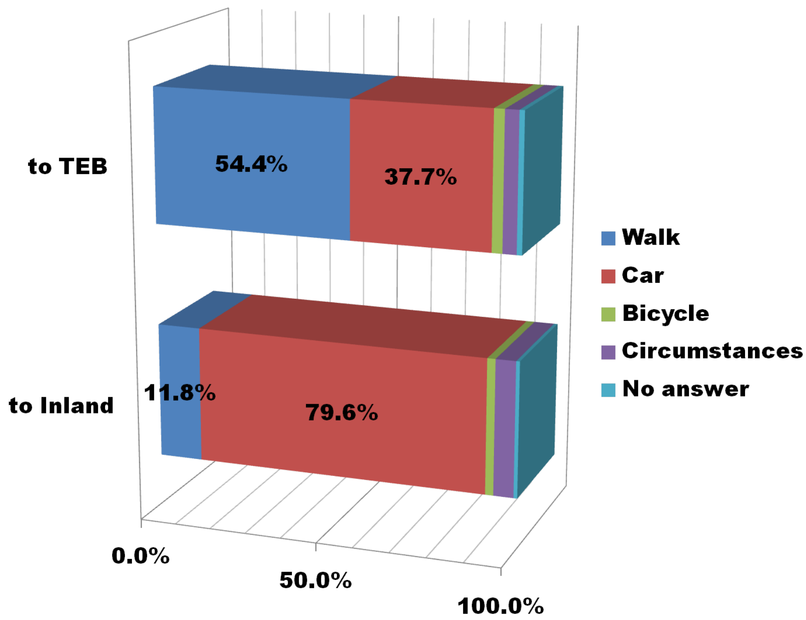


Figure 4.5: Means of evacuation - Questionnaire results of evacuation mode preference (Suzuki and Imamura, 2005). TEB means Tsunami Evacuation Building

Hazard map, shelters and routes

Before the 2011 event, Miyagi Prefecture and Sendai city were under the expectation of a 7.5 to 8.0 Mw magnitude earthquake, with a 99% probability of occurrence within the last 30 years. According to this event, the predicted damage area would be the northern part of Tohoku, the Sanriku coast, while Sendai plain might be inundated less than one kilometer and nearly 3m tsunami height. The Hazard Map prepared for this event is shown in Fig. 4.6. The delimited area washes no more than 500m of shore. However, the surprising magnitude of the Great East Japan Earthquake and Tsunami, and its unprecedented height, reached around five kilometers inland, ten times of the predicted inundation. In the Arahama village, witnesses' accounts and rescue teams stated that the majority of evacuees were found at the Arahama Elementary School, a designated evacuation building. The rest of population evacuated by car through two main roads; Exit1, the No.137 Prefectural road and Exit2, an alternative road towards inland area (Fig. 4.6). In our model, pedestrians and cars were allowed to evacuate to the evacuation building in the area, however only cars were allowed to decide either for evacuation in the area or the nearest exit to inland.

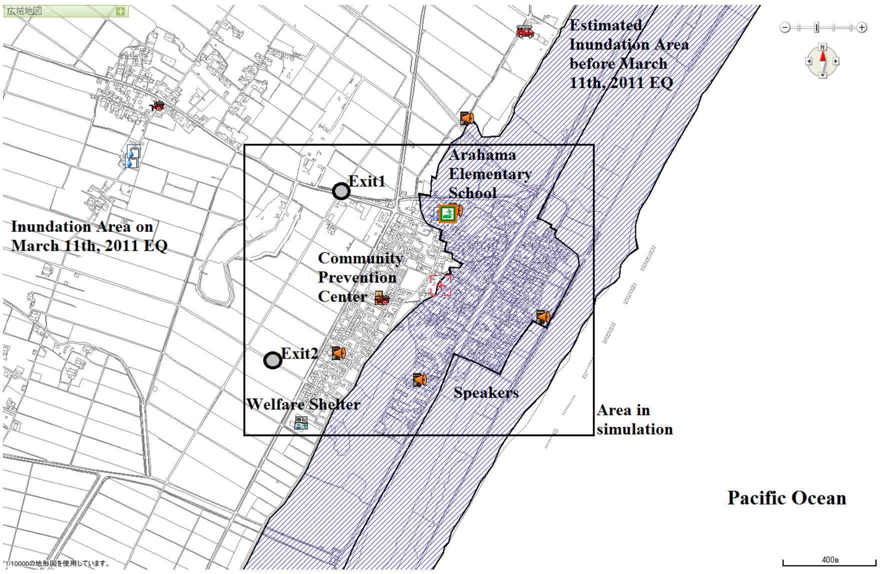


Figure 4.6: Tsunami Hazard Map before 2011 tsunami - Actual inundation includes the total area shown in the figure. Inset square shows the Area of simulation. Also Exit1, Exit2 and the Tsunami Evacuation Building (TEB) of Arahama Elementary School are annotated. (Modified from Sendai city website

4.4.3 Stochastic simulation

The use of multi agent paradigm or agent based models typically contain stochastic elements (Ormerod and Rosewell, 2009). Consequently a set of runs should be conducted to obtain the mean of outputs as an estimation of the value of interest. We conducted several trials to observe the convergence of estimated values during the number of repetitions. Therefore, 1,000 repetitions of simulations with a random initial spatial distribution of pedestrians and cars were conducted. Start time of evacuation decision is based on a random selected value in a distribution bounded between results from Suzuki and Imamura (2005) with mean of distribution 7min, and the recorded arrival time of tsunami on March 11th, equaled to 67 min (Fig. 4.7).

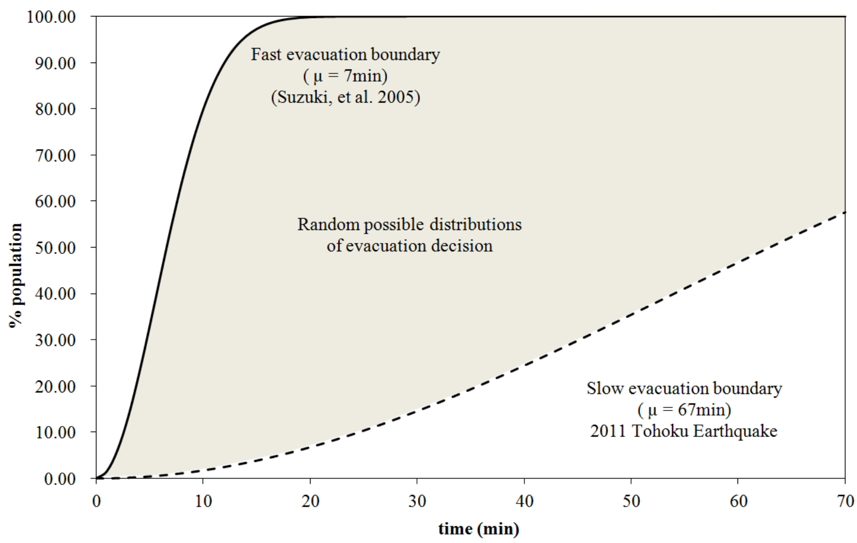


Figure 4.7: Tsunami Departure Curves - Boundary distributions for start time decision of evacuation from tsunami.

4.5 Results and discussion

Figure 4.8 shows the output snapshot of simulation at every 10 min of evacuation. Pedestrians in black and cars in magenta color evacuate to the inland area -to the left of snapshot- while tsunami approaches the coast and finally inundates. Casualties are shown as red dots and bottlenecks as white points.

Each simulation provides information such as number of evacuees sheltered plus number of evacuees who have passed one of exits (Safe); number of evacuees trapped

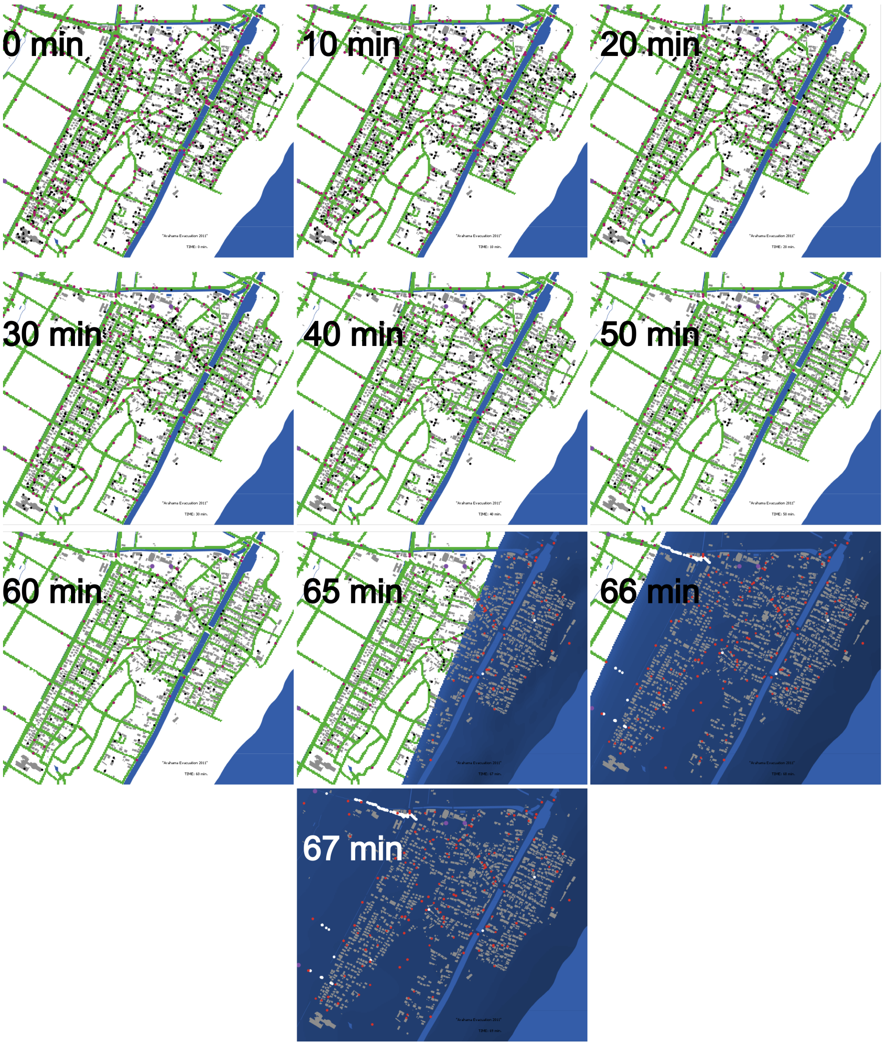


Figure 4.8: Snapshots of simulation - Snapshots every 10min of simulation and last minutes of tsunami inundation.

into tsunami and with more than 50% probability of falling (Casualty); number of evacuees in Tsunami Evacuation Buildings (TEB); number of evacuees who got to one of the exits before falling by tsunami. The average, standard deviation (S.D.) and other statistical values of the set of repetitions are shown in Table 4.2. Results show that 82.1% (S.D.=3.0%) of the population finished a safe evacuation. Apparently preferences on evacuation shelter are balanced between the three options given. An average of 21.9% (S.D.=0.5%) decided to shelter in the Tsunami Evacuation Building (TEB), while nearly 30.1% (S.D.=2.9%) and 30.0% (S.D.=2.8%) preferred to exit the area through EXIT1 and EXIT2, respectively. According to local media and census of the city office before and after the earthquake, around 90% of the population was saved from tsunami, and 520 evacuees found shelter at the Elementary School building. Although it is a difficult task to obtain through simulation the exact values mentioned, the average estimations of survivors and evacuees at TEB show a good capability of the model to reproduce a suitable emergent behavior of decision and casualty estimation in the area.

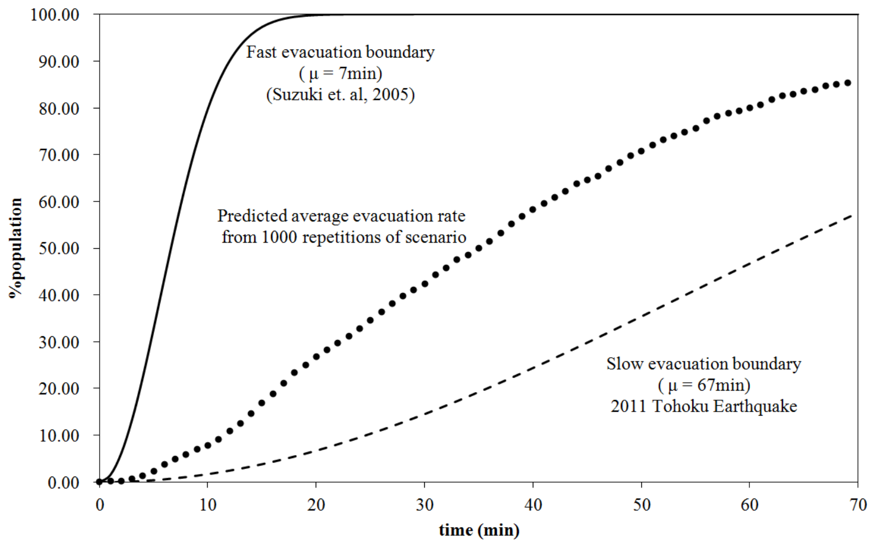


Figure 4.9: Result of evacuation decision - Average distribution of evacuation decision.

Figure 4.9 shows one of the 1000 simulations of random selected values for evacuation decision of all agents according to boundaries shown. The average distribution follows also the sigmoid shape. At the point of arrival time of tsunami (t=67min), a total of 85% of population had already decided to evacuate. An important characteristic of micro simulations is the capability to explore, at the individual level,

Table 4.2: Statistical values of the set of repetitions

	Safe	Casualty	TEB	EXIT1	EXIT2
Average	1864.66	406.34	497.55	685.10	682.00
Median	1875.00	396.00	498.00	684.00	688.00
S.D.	68.75	68.75	10.18	66.30	64.41
Variance	4726.88	4726.88	103.58	4395.05	4148.56
Skewness	-5.58	5.58	-0.04	-2.76	-2.93
Kurtosis	43.60	43.60	0.03	22.16	24.52
Coeff. of Variability	0.04	0.17	0.02	0.10	0.09
Minimum	1154.00	293.00	465.00	12.00	12.00
Maximum	1978.00	1117.00	527.00	824.00	824.00
Range Width	824.00	824.00	62.00	812.00	812.00
Mean Std. Error	2.17	2.17	0.32	2.10	2.04
Population			2271.00		
%Population	82.11%	17.89%	21.91%	30.17%	30.03%
% error	3.03%	3.03%	0.45%	2.92%	2.84%

the behavior of the model variables. For example, focusing on the departure times shown in Fig. 4.9 for all the population involved in the scenario, and taking into consideration the casualty outputs in the model, a graph of one simulation showing sheltered evacuees departure times - Survive - next to the start time of evacuation for agents caught on tsunami - Casualties - is shown in Fig. 4.10.

It is clear the influence of late departure times on the casualty estimation. The majority of resulting casualty agents decided to start the evacuation around 53 min and even over the 70min simulated here. On the other hand, the big amount of survivors decided to evacuate at much less time. Notice that even after 53 min some agents got on time to their shelter, this is due to spatial conditions of distance to the shelter, and modes of evacuation with higher speeds.

From the sheltered evacuees, we divided the modes of evacuation as pedestrians and cars and show in Table 4.3 the average distance to shelter, start time of evacuation, time of evacuation considering only the dynamic stage, the total evacuation time and the average speed. Due to the size of the model area, the distance to shelter in average is around 500m. Because we have used same random seed number and same algorithm to decide departure times for pedestrians and cars, the start time of evacuation values are similar, however in the case of moving to the shelter or time of evacuation (ToE), as expected cars are faster than pedestrians in accordance to the speed rules given. The total evacuation time is almost the same due to the great influence of the departure time. The average speed of 1.10 m/s agrees with the maximum value of 1.33 m/s explained before, same observation is applicable to car speed of 5.03 m/s (18.11 km/h). In general resulted average speed values are lower than the ruled given values, due to the dynamic condition of increasing and decreasing speed according to bottlenecks and crowd conditions.

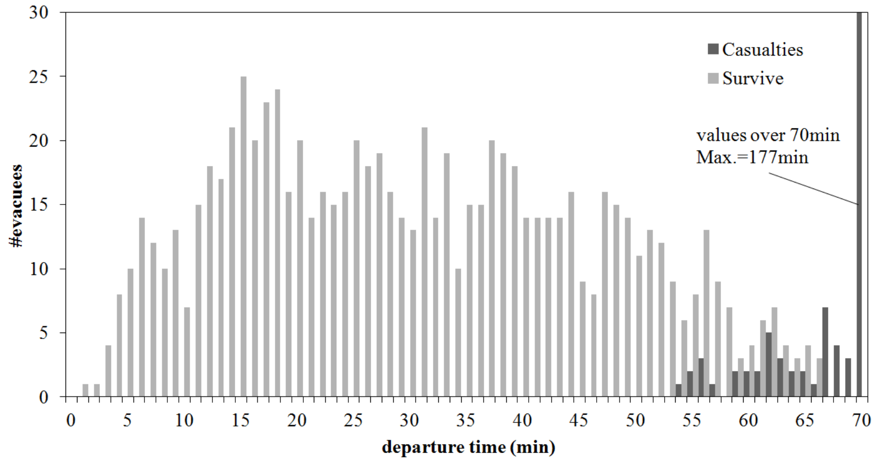


Figure 4.10: Departure times with casualty condition - Departure times of agent6s and their final condition as survivor or casualty. the influence of faster evacuation is clear.

Table 4.3: Average values of sheltered evacuees in one example of simulation

Agent	DtoSh	STE	ToE	TET	AvSp
Pedestrian	489	29.2	7.4	36.6	1.10
Car	671	32.5	2.2	34.7	5.03

DtoSh: Distance to shelter (m) STE: Start Time of Evacuation (min)
ToE: Time of Evacuation (only move)(min) TET: Total Evacuation Time (min)
AvSp: Average Speed (m/s)

On the other hand, it is not only important to obtain the final outcome of simulation in the case of sheltered evacuees or residents evacuated through exit points. A step by step tracking of the demand of shelters on time and the traffic flow through exits is possible and useful on the resource management for supporting the evacuation. Due to the stochastic characteristic of this simulation, it is difficult to show the set of 1,000 outputs, thus at this point Fig. 4.11 shows one of the repetitions' outputs. In this case, 30min after the earthquake only 37.2% of the population has reached their goal, out of this, 8.3% to the TEB, 13.6% and 15.3% to EXIT1 and EXIT2 respectively. Also, bottleneck conditions in every repetition are shown in a final snapshot of each simulation (i.e. Fig. 4.12). In general traffic was observed in the main roads leading to exit points, the entrance of the tsunami evacuation building, and near the bridge at the channel. Although these bottlenecks were not present all at the same time in a same simulation, however it was a condition observed at any time of the simulation in at least one of the repetitions, therefore they should be identified as critical points. A future work will be to explore an adequate representation of the entire set of outcomes, in order to facilitate the understanding of the evacuation process.

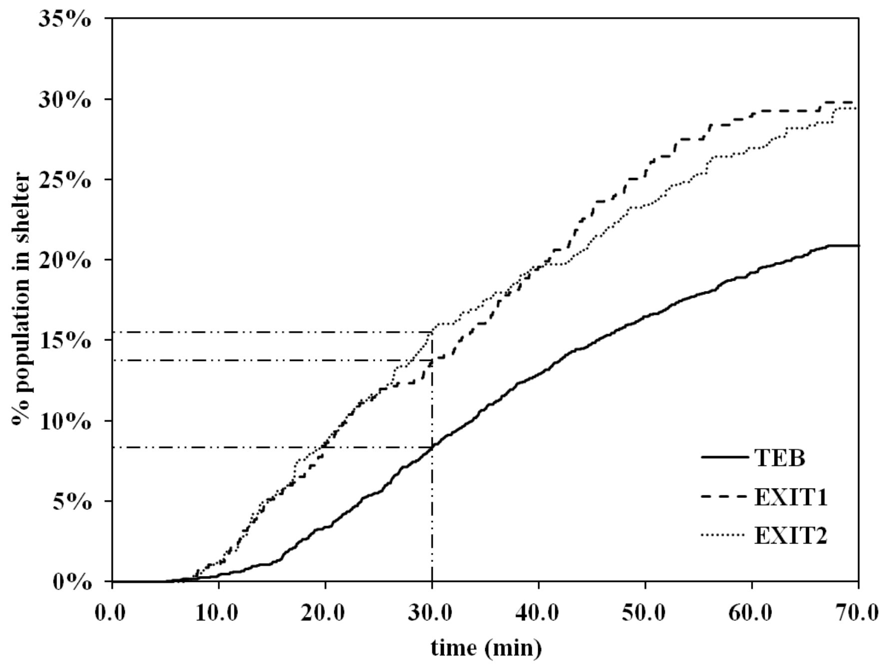


Figure 4.11: Shelter occupation - The curves show the loading of evacuees into the shelter (TEB) and through exits (EXIT1 and EXIT2) during the time of evacuation. After 30min of simulation less than 40% of population found their way to the shelter or out of the computation area.

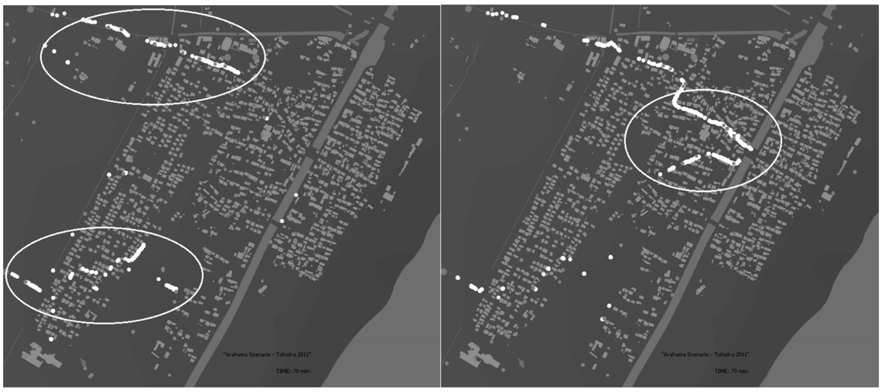


Figure 4.12: Bottleneck condition - Representative snapshots of two different repetitions of simulation. Bottlenecks can be observed in the circled areas. Near the exit points, the evacuation building and a bridge connecting to sub-areas separated by a channel

4.6 Comparing modeling methods

As a further analysis for comparison with other modeling methods, we performed 4 cases of simulation, following the approaches of start time simulation in evacuation modeling described in previous sections. The total population modeled in the area was of 2,271 agents. Case 1 is related to the "all-together" behavior; pedestrians and agents start their evacuation at the time point 0 min. Case 2 follows the worst case scenario of departure time distribution, the distribution characterized by the arrival time of tsunami as the mean of the distribution ($\mu = 67$ min). Case 3 is an optimistic scenario with 7min mean of distribution related to the so-called SP surveys. Finally Case 4 is the stochastic simulation of the methodology proposed in this study, tsunami departure time curves bounded by RP and SP surveys. Results are discussed case by case on the following criteria: number of casualties, number of evacuees in shelter, bottleneck condition. For the case of bottlenecks a snapshot of the last step of each simulation is shown in Fig. 4.13; white areas indicate that a bottleneck condition was observed at any time of simulation in that spot. The red spots represent casualty agents. Notice that in Case 1 some agents became casualty during bottleneck condition.

- Case 1 - "all-together"
  In this case, a rapid evacuation is observed for the majority of the agents, however also fast traffic congestion for cars near one of the main roads is observed (Fig. 4.13a). Finally, casualties estimated are of 528 (23.25%) and the number of evacuees in shelter 631 (27.79%).

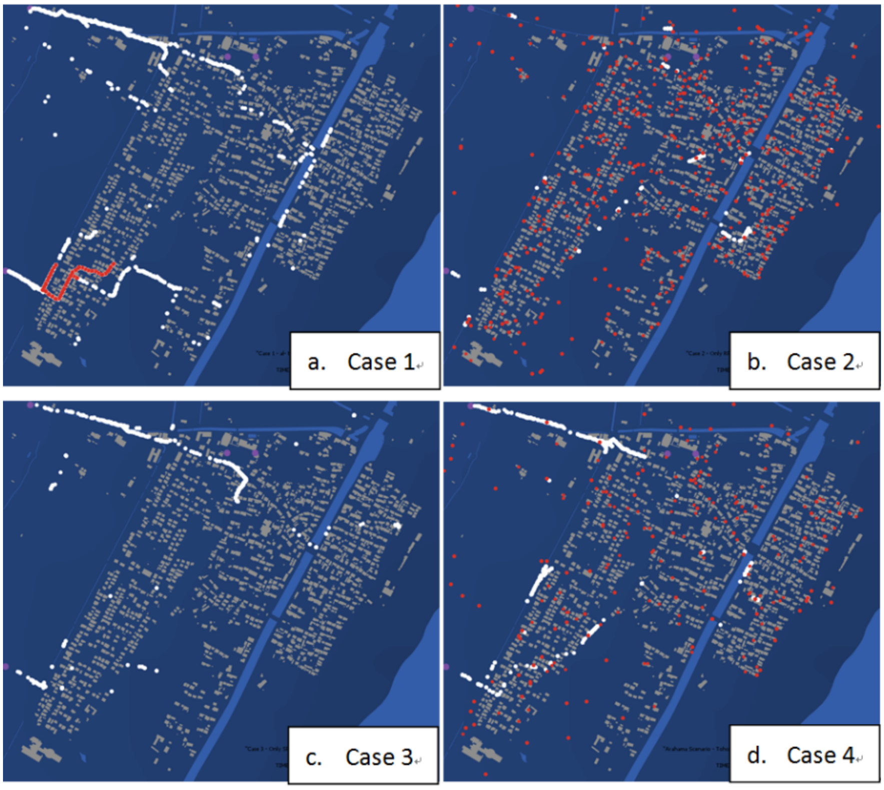


Figure 4.13: Bottleneck outcomes. - White spots show places where traffic congestion was observed at any time over simulation. Red spots are casualty agents

- Case 2 - Only RP survey ($\mu = 67$ min)
  Agents started their evacuation according to a distribution with mean value equal to the arrival time of tsunami (67 min). As a result in this case scenario, a total 996 (43.86%) casualties were estimated, while 275 (12.11%) evacuees sheltered safely. Bottlenecks were not observed as much as the previous case (Fig. 4.13b).

- Case 3 - Only SP survey ($\mu = 7$ min)
  A rapid decision for evacuation is modeled here. 7 min of mean of distribution is considered from the outputs of Suzuki and Imamura (2005) studies. In the overall aftermath of this case scenario, no casualties were observed and 631 evacuees found shelter. Bottlenecked areas are observed mainly in front of the school (TEB) until one exit along the prefectural road (Fig. 4.13c).

- Case 4 - Tsunami departure curves
  Here, the start time evacuation behavior is applied using the approach proposed in this paper. Results of studies in the area by Suzuki and Imamura (2005) are used as the lower boundary of possible behaviors with mean of distribution of 7 min, while the upper boundary of behavior is related to the recorded arrival time of tsunami on March 11th, 2011, 67 min. (Fig. 4.9). Bottlenecks were observed near the school to the road leading out of the inundation area. Minor bottlenecks in the transversal road from the airport (Southwest) (Fig. 4.13d).

The use of multi agent paradigm or agent based models typically contain stochastic elements (Ormerod and Rosewell, 2009). Consequently a set of runs should be conducted to obtain the mean of outputs as an estimation of the value of interest. We conducted several trials to observe the convergence of estimated values during the number of repetitions. Therefore, 1,000 repetitions of simulations with a random initial spatial distribution of pedestrians and cars were conducted.

Results show that 82.1% (S.D.=3.0%) of the population finished a safe evacuation, out of this a total average of 498 agents looked for the vertical evacuation in the area. According to local media and census of the city office before and after the earthquake, around 90% of the population was saved from tsunami, and 520 evacuees found shelter at the Elementary School building. Figure 4.9 shows one of the 1,000 simulations of random selected values for evacuation decision of all agents according to boundaries shown. The average distribution follows also the sigmoid shape. At the point of arrival time of tsunami (t=67min), a total of 85% of population had already decided to evacuate. Resulted values do not pretend to fully explain the evacuation procedure of Arahama village, but the use of the method proposed for departure curves and its validity through close estimations with real outcomes in the simulated event. Fig. 4.13d shows that bottlenecks are also observed near to the school and the prefectural road on the way to Exit1, however is comparatively less traffic than the "all-together" scenario.

Table 4.4: Results of Casualties and Sheltered (TEB) or Evacuated (Inland) agents for each case modeled and the estimations for the real scenario of March 11^{th}, 2011

Case	Description	Casualties	%E	TEB	%E	Inland	%E
1	"All-together"	528	86%	631	21%	1,112	24%
2	$\mu = 67$ min	996	252%	275	47%	1,000	32%
3	$\mu = 7$ min	0	100%	631	21%	1,640	12%
4	Departure Curves	406	43%	498	4%	1,367	7%
-	11th March, 2011	283(*)	-	520(*)	-	1,468(**)	-

(*) Based on Miyagi City Office and the National Governor's Association Report.
(**) Difference of the casualties and sheltered information with the 2,271 agents modeled.

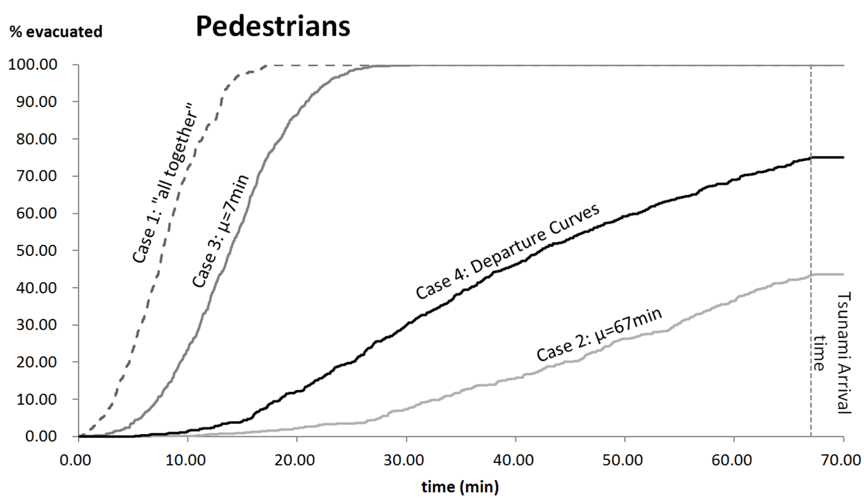


Figure 4.14: Total Evacuation time for Pedestrians. -

Table 4.4, Fig. 4.14 and Fig. 4.15 show comparative results of the four cases modeled; while Case 1 is expected to be a desired behavior of population -an immediate evacuation- it is observed that an important number of casualties result due to the

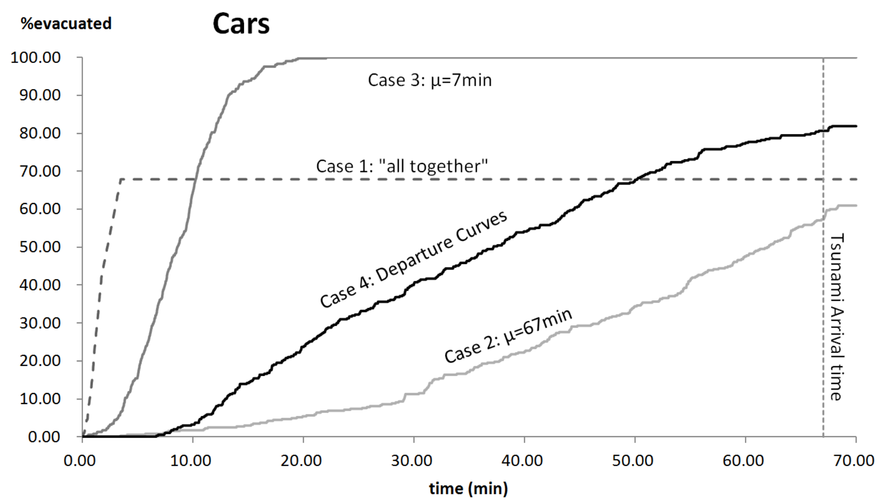


Figure 4.15: Total Evacuation time for Cars. -

evacuation by car and the traffic congestion generated because of the rapid loading of the road network (Fig. 4.15). Case 2 is considered one of the worst case scenarios, a behavior of evacuation close to the arrival time of tsunami, casualties are higher, sheltered and evacuated agents are lower. Case 3 is a relatively fast evacuation, with no casualties and all population evacuated and sheltered. Apparently this is a smooth case of evacuation where the road network presented traffic jams but were rapidly solved. Case 4 is the average of the stochastic result of 1,000 repetitions of simulation using Case 2 and Case 3 distributions as boundaries of possible behaviors. Results in this case show a better approximation with less relative errors for casualty estimation, sheltered agents in TEB and evacuated agents through exits. Further detailed comparison is possible due to the micro scale characteristic of the model, however the importance of an adequate start time of evacuation assumption has been proven here. Evacuation simulation requires the human behavior and although its complexity is difficult to entirely simulate, here Tsunami Departure Curves were proposed as a fair approximation to the overall result of behavior found in questionnaires.

4.7 Summary

A case study of the Arahama village evacuation in the March 11^{th}, 2011 Great East Japan Earthquake and Tsunami was simulated as a step for validation of the Tsunami Departure Curve (TDC) method proposed in this study, and the use of the TUNAMI-EVAC1 simulator for the casualty estimation. Despite the difficult of reproducing the complete event, results of the simulation have shown better approximations on the estimation of casualties and evacuees sheltered compared to traditional methods and the proposed TDC method. In this study we have proposed to use human behavior data from questionnaires of stated preferences and features of tsunami obtained by numerical simulation, such as the arrival time, to construct boundary distributions for a stochastic simulation of evacuation decision. Also, tsunami features of hydrodynamic conditions were used for the casualty estimation. The case study shows the capability of the model to explore individual parameters and outcomes. Evacuation models like the one introduced here allows for studying the emergent behavior of individuals in a complex process of tsunami evacuation.

Chapter 5

Applications to Tsunami Mitigation

5.1 Response Time and Casualty Estimation

Following the time components described in Post et al. (2009), the Human Response Capability (HRC) can be decomposed into the Reaction Time (RT) -the time of decision to evacuate- and the Response Time (RsT) -a time of movement from a initial at risk location to a safe area (Eq. 5.1). In TUNAMI-EVAC1, RT is defined through the Tsunami Departure Curves (see Chapter 3.2.1) and RsT is observed through the simulation process. Finally, the casualty estimation is conducted during the simulation based on the hydrodynamic features of tsunami (see Chapter 3.2.5) and the local spatial condition of agents in the risk area.

$$HRC = RT + RsT \tag{5.1}$$

In this section, we will show the application of TUNAMI-EVAC1 as a tool to explore the Response Time (RsT) of residents and the Casualty Estimation (CE) related to it. The study area selected is a small portion of land in the Phang Nga province of Thailand named Pakarang cape. The tsunami scenario is the 2004 Indian Ocean tsunami.

5.1.1 The Study Area: Phang Nga, Thailand

The study area is near the Pakarang cape in the Khao Lak beach resort area of Phang Nga province in Thailand. The district is located at the coast of the Andaman Sea and it was devastated by the tsunami resulting from the 2004 Indian Ocean earthquake. Here, between 4,000 to 10,000 people among residents and tourists were killed by the tsunami (Fig. 5.1).

Figure 5.1: Phang Nga devastated by the 2004 Indian Ocean Tsunami - Left: Before - January 13th, 2003; Right: After: Decemeber 29th, 2004. Source: Space Imaging / CRISP-Singapore

Population

The population to simulate belongs to a group of villages in the Khuekkhak subdistrict (5,172 inhabitants), in the Takua Pa district of Phang Nga province in Thailand. The total 5,172 residents are not considered as exposed population due to the spatial location of the 7 villages of Khuekkhak, thus the number of housing (275) and the maximum surveyed value of family members in the area (7) (Srivihok, 2010), resulted on the exposed simulated population of 1,925 residents. Although this is a particular tourist area, we have not considered at this stage the number of estimated tourists. We do not pretend to fully explain or assess the risk in this area, but to describe the process of application of the TUNAMI-EVAC1 model for the purpose of RsT and CE.

5.1.2 Tsunami Numerical Simulation

Tsunami source

Following the source model proposed by Suppasri (2010), which is a modified version of the original setting in Koshimura et al. (2009). Fault parameters and the tsunami source model also used in this case study, is shown in Fig. 5.2 and Table 5.1

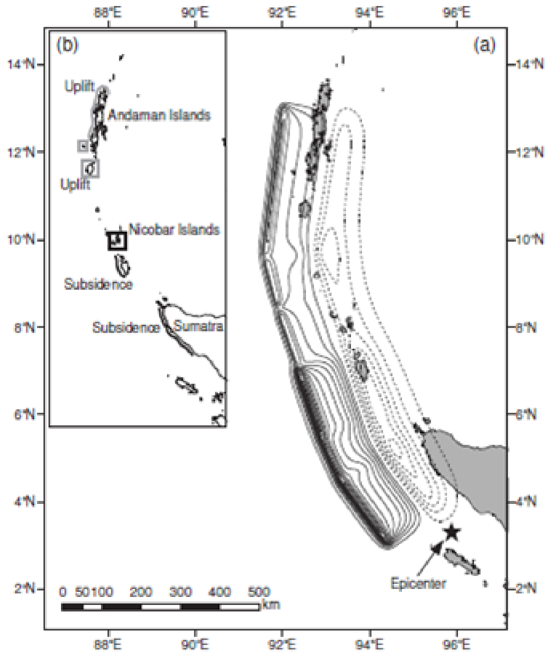


Figure 5.2: Tsunami source model - The tsunami source model of the 2004 Indian Ocean tsunami. Source: Koshimura et al. (2009)

Numerical modeling

The Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI model) was used as the tool of tsunami modeling (Imamura, 1995). A set of non-linear shallow water equations are discretized by the Staggered Leap-frog finite difference scheme. Bottom friction condition is in the form of Manning's formula constant in the whole domain.

The result of numerical simulation of tsunami is shown in Fig. 5.3. The maximum estimated height near shore is around 11m and the maximum distance of inundation from the shoreline is of 1.5km to 2.0km.

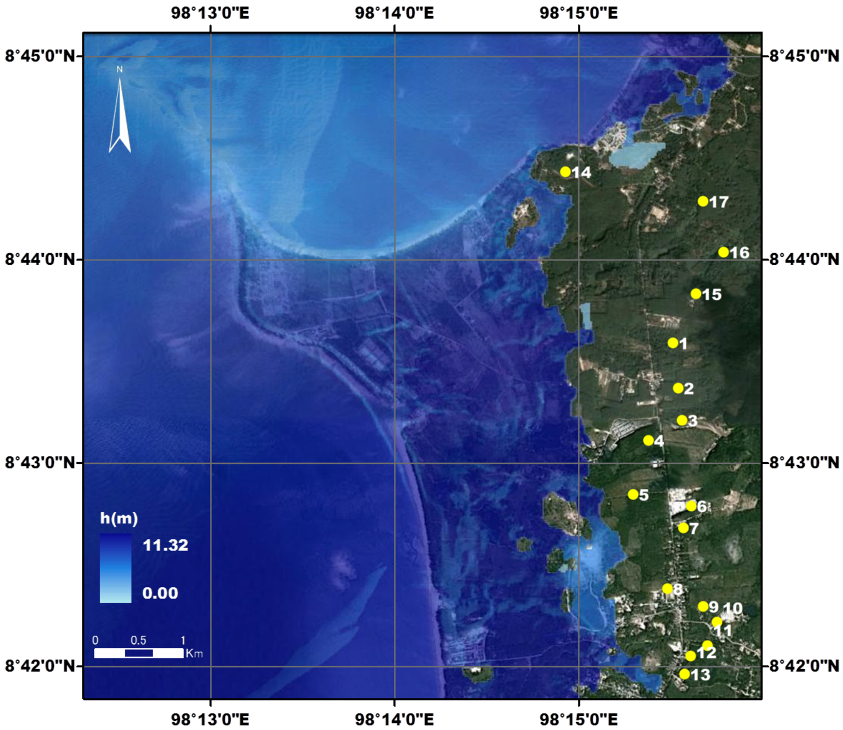


Figure 5.3: Inundation result of model in Phang Nga province - Maximum tsunami height of modeled tsunami scenario .Background image: Google Earth.

Table 5.1: Fault parameter for the 2004 Indian Ocean tsunami. Location of each fault with respect to the bottom left position. Source: (Suppasri, 2010)

Fault Parameter	Segment No.					
	1	2	3	4	5	6
Lat(N)	3.03	4.48	5.51	7.14	8.47	9.63
Long(E)	94.40	93.32	92.87	92.34	91.88	91.57
Strike(degree)	323	335	340	340	345	7
Dip(degree)	15	15	15	15	15	15
Slip(degree)	90	90	90	90	90	90
Length(km)	200	125	180	145	125	380
Width(km)	150	150	150	150	150	150
Dislocation(m)	14	12.6	12	7	7	7
Depth(km)	10	10	10	10	10	10

5.1.3 Evacuation Simulation

Building on the tsunami numerical simulation results in the study area, the evacuation process is evaluated for the design tsunami and several human behavior scenarios. As an example, we will explore the influence of the use of vehicles in the evacuation process combined with the different reaction time of residents. Vehicles are included in the model by assuming a set of percentage of evacuees in cars (passengers and drivers) among the population. Then 0%, 25%, 50%, 75% and 100% is discounted at each scenario from the total population and grouped in 4 passengers per car. Tsunami Departure Curves (TDC), explained in previous chapters (see Chapter 3.2.1), is modified using four possible scenarios of reaction. The TDC distribution characterized by a mean of distribution ($\mu = 30min$) similar to the results of a questionnaire survey applied in the area to 57 residents in different villages among Phang Nga and Phuket (south of the study area) - results are reported in Suppasri (2010). The stochastic method will be applied in a future study case (see Chapter 5.2). For this case, a simple approach of single tsunami departure curves is used. Besides the questionnaire result distribution, another three possible scenarios are considered in the evaluation; a worst case scenario of late evacuation with $\mu = 120min$ -the estimated arrival time of tsunami- and the scenarios of $\mu = 60min$ and $\mu = 90min$. Fig. 5.4 shows the rate of evacuation decision explained above with the questionnaire results provided by Suppasri (2010).

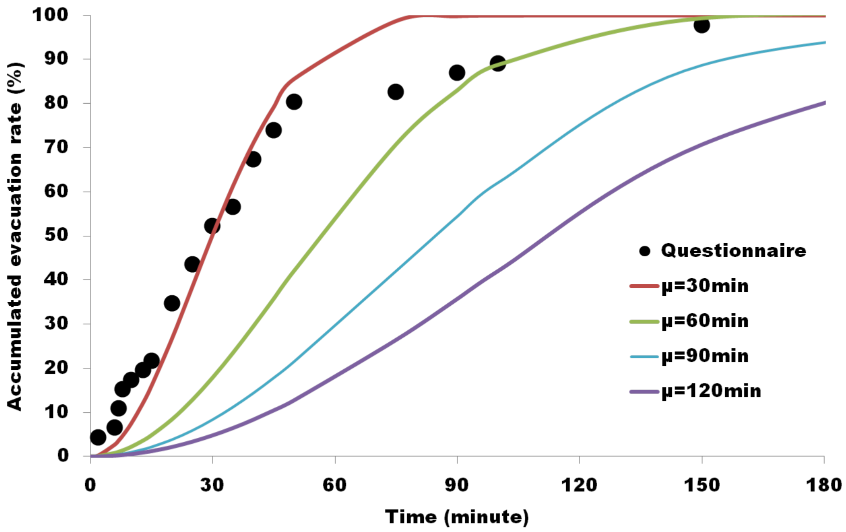


Figure 5.4: Tsunami Departure Curves for Evacuation - Questionnaire data and departure curves for simulated scenarios.

5.1.4 Results and Discussion

Results of simulation and details of agent input are shown in Table 5.2 and Fig. 5.5. Due to the small number of population involved and the large time available for evacuation, a fast reaction ($\mu = 30min$) yields to a safe evacuation despite the amount of vehicles involved for the population modeled. However, a late reaction in the population increases the estimated amount of casualties in the area. In particular, there is an important difference in the CE between the $\mu = 60min$ scenario and the $\mu = 90min$ scenario. Apparently the first hour of decision is crucial to determine the safety of the majority of the population involved. It is worth to notice that the use of vehicles in a small population contributes to reduce the CE in the area. This observation is opposite to the results obtained in the model of Arahama in the previous chapter (see Chapter 4). Increasing the population with information of the number of tourist in Phang Nga might lead to different outcomes on the use of vehicles. The TUNAMI-EVAC1 allows exploring these conditions in order to find the optimum number of vehicles allowed in evacuation for a particular number of population at risk in the area.
The HRC is shown in Fig. 5.6. It shows that despite the high used of vehicles (i.e. 100%), there is no significant differences on the HRC if the reaction is late (i.e. $\mu = 120min$). In other words, a fast reaction with a fast mean leads to a fast and successful sheltering, however a slow reaction yields always to a similar HRC in

survivors despite the mean of evacuation, and of course higher CE.
Here, with TUNAMI-EVAC1, it is possible to explore the influence of vehicles, start time of evacuation, amount of population and tsunami scenario to evaluate the feasibility of multiple possible events.

Table 5.2: Simulated scenarios in the Phang Nga Province of Thailand

No. of Pedestrians	No. of Cars	% evacuees in cars	μ			
			30	60	90	120
1925	0	0	0	74	355	675
1445	120	25	0	49	326	650
961	241	50	0	33	284	575
481	361	75	0	24	204	474
1	481	100	0	8	176	504

Further analysis can be made on the shelter capacity and demand, for this case the resulting demand of shelters is shown in Table 5.3. Shelters #1, #4, #5, #8 and #14 are the most demanded shelters in the area. A more in detailed application of shelter demand evaluation will be discussed in the following section on this chapter.

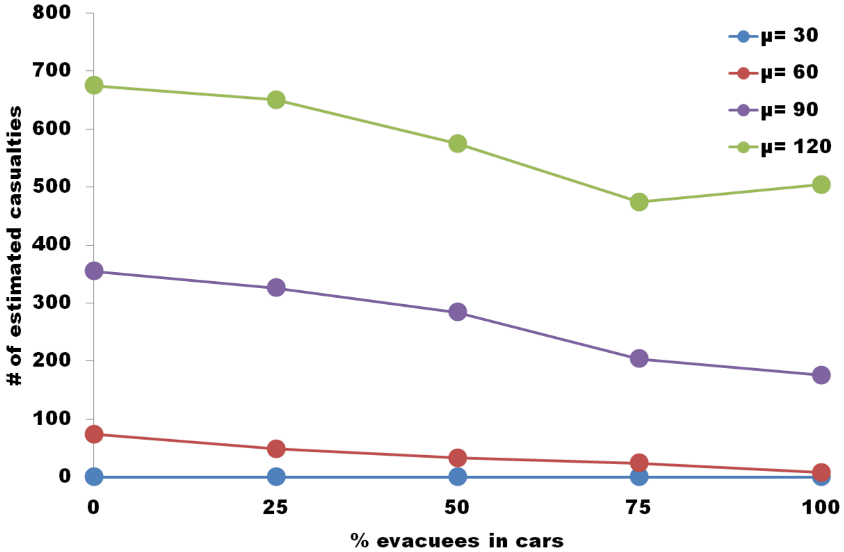


Figure 5.5: Casualty Estimation at different Start time of Evacuation and Vehicle use. - The late the start time of evacuation, the large number of estimated casualties. Also, for this particular network and number of population, the use of cars reduces the number of casualties.

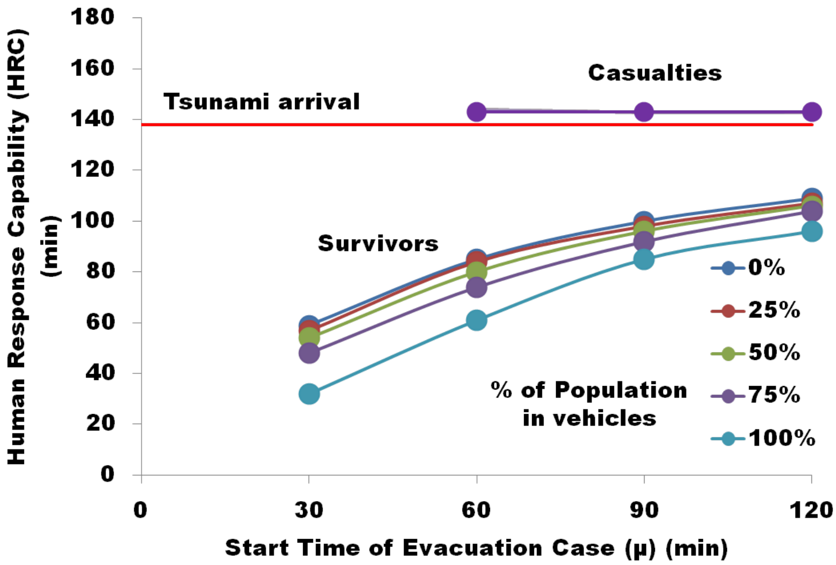


Figure 5.6: Human Response Capability. - The use of vehicles contributes considerably to the fast evacuation especially when more than 75% of population use it.

Table 5.3: Sheltered evacuees at each scenario

% evacues in car	0%				25%				50%				75%				100%			
Start time of evacuation	30min	60min	90min	120min	30min	60min	90min	120min	30min	60min	90min	120min	30min	60min	90min	120min	30min	60min	90min	120min
Shelter #1	35	35	34	29	43	43	42	37	67	87	83	73	106	94	74	66	136	156	156	136
Shelter #2	56	56	51	44	56	56	53	49	46	42	41	38	34	50	42	40	72	28	36	28
Shelter #3	91	91	84	70	80	80	73	57	80	68	74	58	63	67	68	58	40	16	44	32
Shelter #4	476	475	433	363	385	384	348	285	305	300	290	235	236	235	213	178	136	172	140	128
Shelter #5	546	526	432	325	554	539	434	325	533	485	409	332	516	475	484	401	512	532	420	316
Shelter #6	35	35	32	31	30	30	31	26	35	43	40	31	40	40	33	33	28	48	48	32
Shelter #7	7	7	7	7	11	11	15	15	25	13	13	13	34	26	22	18	28	20	28	24
Shelter #8	35	35	30	21	46	46	43	31	79	115	88	70	140	156	114	100	180	144	136	112
Shelter #9	28	28	28	25	29	29	29	28	25	21	17	16	14	18	10	10	20	24	16	12
Shelter #10	14	14	14	11	11	11	11	8	12	8	8	6	12	4	4	2	8	12	8	4
Shelter #11	14	14	13	11	20	20	20	15	10	22	10	9	26	18	22	21	12	20	20	20
Shelter #12	7	7	7	4	6	6	6	3	4	8	8	1	6	14	6	1	8	4	4	4
Shelter #13	42	42	42	38	50	50	50	47	44	64	72	58	92	84	80	55	56	68	56	52
Shelter #14	455	402	285	202	497	464	342	259	518	482	362	296	486	464	418	344	504	464	472	380
Shelter #15	21	21	20	18	27	27	26	24	28	44	43	37	52	52	35	34	60	36	48	36
Shelter #16	21	21	19	19	17	17	15	15	27	27	29	29	17	25	33	29	12	36	16	16
Shelter #17	42	42	39	32	62	62	60	50	88	64	55	49	51	75	63	61	112	136	100	88
	1925	1851	1570	1250	1924	1875	1598	1274	1926	1893	1642	1351	1925	1897	1721	1451	1924	1916	1748	1420

5.2 Shelter demand

Finding shelter during an emergency of tsunami for plain areas with a fast arrival time of waves is a challenging task for local people. The vertical evacuation to high buildings rising over the expected inundation depth in the area is one of the most suitable alternatives for this kind of urban districts. However, if the spatial distribution combined with the available capacity of these structures is not well displayed, conditions of over-demand and under-demand will be observed among them. In this section, we conducted the numerical simulation of a great earthquake in Peru similar to the historical 1746. The resulting tsunami propagation inland is integrated with a multi agent model of human evacuation. Using the stochastic simulation of initial spatial distribution of residents and starting time of evacuation behavior, we evaluate the relation capacity-demand at each official Tsunami Evacuation Building in La Punta district in Peru. The Capacity-Demand Index (CDI) is introduced as a way of mapping and identifying areas for future mitigation actions to support the evacuation process of population under risk of tsunami

5.2.1 The Study Area: La Punta, Peru

Historical Tsunami near La Punta

La Punta is part of the Constitutional Province of Callao in central Peru (Figure 5.7) and one of the six districts in First National Port city of Callao. La Punta is a peninsula in the western part of the province and is almost entirely surrounded by the Pacific Ocean, except on its northeastern side, where it is bordered by downtown Callao. It is one of the smallest districts in Peru, with 4,370 inhabitants (Instituto Nacional de Estadistica e Informatica (INEI), 2007) and a total land area of 0.75 km^2 (Figure 5.7-C). Major risk of earthquakes and tsunamis are present in this area, due to its low topography (max. 3 m) and its geographic characteristics as a peninsula with a wide head on the seaside and a narrow neck to the inland. Evacuation procedures and feasibility are of interest for the safety of La Punta residents and visitors. La Punta was affected by several historical earthquakes and tsunamis (Figure 5.7-A and 5.7-B), such as the July 9th, 1586, earthquake of magnitude 8.6 and a local tsunami height of some 5 m (Dorbath et al., 1990), although some reports give a much larger value of 24 m (Berninghausen, 1962; Bourgeois et al., 1999). Another two earthquakes on October 20th and 21st, 1687, of magnitudes 8.0 and 8.4, respectively, struck this area. The first one had generated a 5 m to 10 m local tsunami, while the second might have been located in southern areas (Dorbath et al., 1990). One of the most memorable earthquakes in the Callao region is the great earthquake of October 28th, 1746, with a magnitude 8.0 to 8.6 which completely destroyed some central Peruvian coastal cities. A tsunami of 15 m to 20 m in height resulted from this earthquake, it arrived half an hour after the ground shaking, and washed away Callao city with a 24 m run-up, killing 90% of its population (Kuroiwa Horiuchi, 2004). Two centuries later, the Peruvian central coast experienced more activity on May 24th, 1940, with a local earthquake and tsunami of 3 m in height. The October 3rd, 1974, event in front of Lima had a magnitude of 8.0 and a local tsunami height of 1.6 m (Espinosa et al., 1977; Langer and William, 1995). Since then, no large seismic activity has been reported in front of Callao area. A possible seismic gap might be located in this area, threatening La Punta and other coastal cities with a future large earthquake and tsunami.

Tsunami Evacuation Buildings

There are 19 official evacuation buildings in the district and a 20th building is located immediately outside of the district in the Callao province (Fig. 5.8).

Population

According to the census (Instituto Nacional de Estadistica e Informatica (INEI), 2007) the population age by age is shown in Fig. 5.9. We have considered 4 groups of agent type based on the age interval. Fig. 5.9 shows in a vertical line the limit of each age interval. Kids group is considered to be up to the 11 years old; Teens are counted from 12 to 17 years old; the main group named Adults varies from 18 to 59 years old; finally, the last group of pedestrians is the Elders with people over 60 years old. Table 5.4 shows the number of people at each group or agent type for three scenarios to simulate - horizontal scenario, vertical scenario and horizontal and vertical scenario. Also in all cases a 15% of pedestrians are considered to be under handicap condition.

5.2.2 Tsunami Numerical Simulation

Tsunami source

An instantaneous displacement of the sea surface identical to the vertical sea floor displacement is assumed in the model of tsunami source. The source consists of 280 sub-faults of 20x20km each proposed by Pulido et al. (2011) in the off zone of Lima. The source of tsunami simulation is a result of the slip deficit rate with the inter seismic period of 265 years since the 1746 historical earthquake in Peru (Fig.5.10).

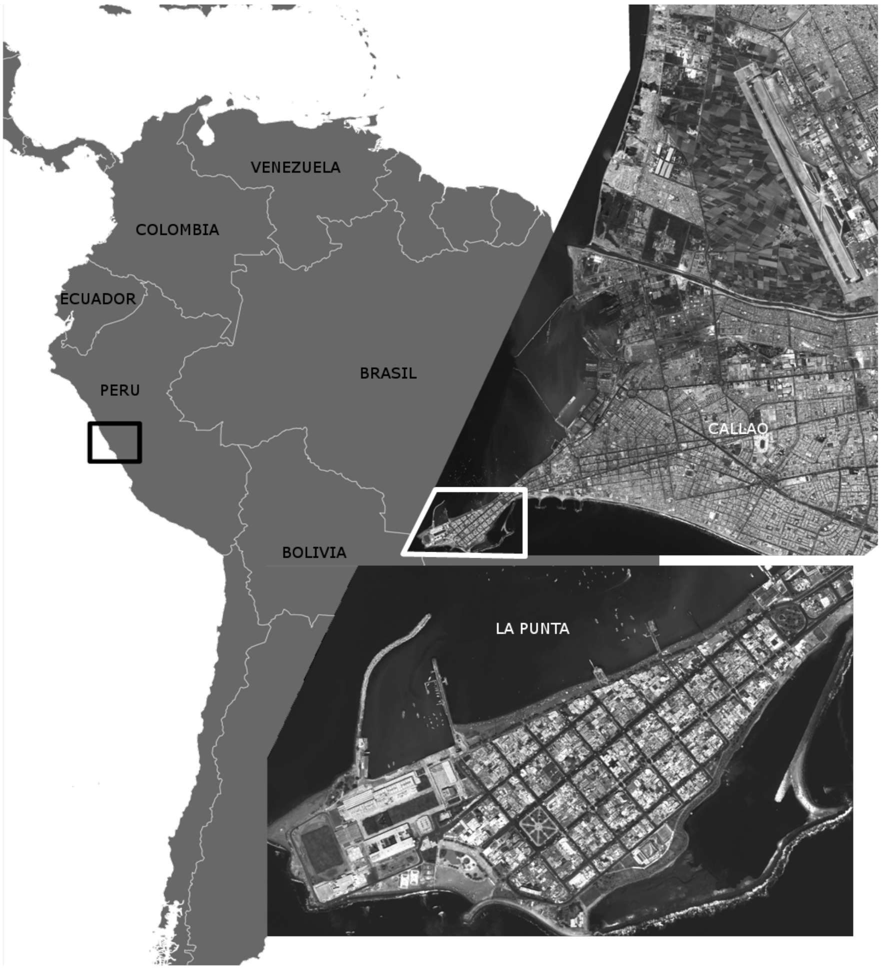


Figure 5.7: La Punta district - (A) Major earthquakes in Peru (updated from Carpio and Tavera (2002)). (B) Central Region of Peru, in front of La Punta and Callao Region. (C) La Punta peninsula district.

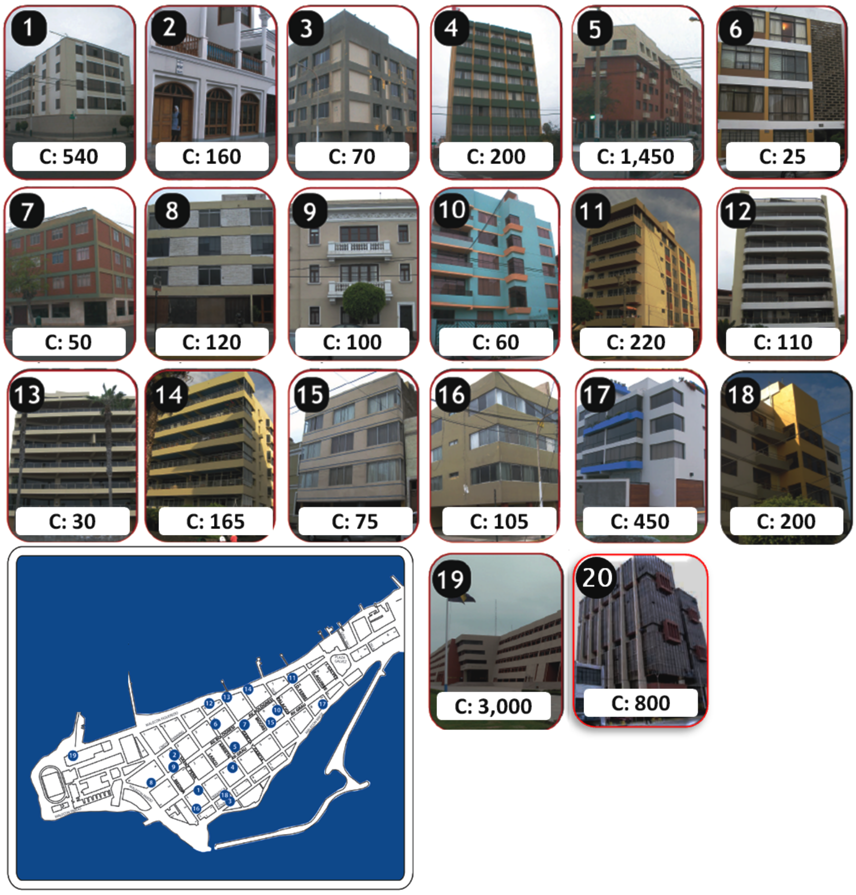


Figure 5.8: Tsunami Evacuation Buildings (TEBs) in La Punta, Callao - Peru. - The map shows the spatial distribution of TEBs.

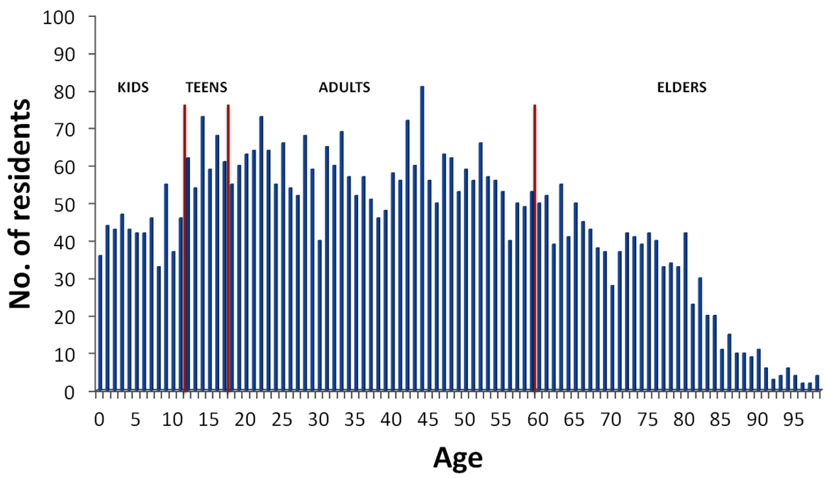


Figure 5.9: Population by age - Age distribution in La Punta and four groups of agent type for simulation.

Numerical modeling

The Tohoku University's Numerical Analysis Model for Investigation of Near-field tsunamis (TUNAMI model) was used as the tool of tsunami modeling (Imamura, 1995). A set of non-linear shallow water equations are discretized by the Staggered Leap-frog finite difference scheme. Bottom friction condition is in the form of Manning's formula constant in the whole domain.

5.2.3 Evacuation Simulation

We used the TUNAMI-EVAC1 (Mas et al., 2012d) to observe the tsunami inundation together with the resident evacuation behavior. The model was developed in NetLogo, a multi-agent programming language and modeling environment for simulating complex phenomena (Wilensky, 2001). As mentioned above, the population to model was categorized in four groups according to the age. The main difference in all these groups or agent type is the maximum possible speed during evacuation. Table 5.4 shows that teens and adults can reach to 1.33m/s (Meister, 2007).

Other types are assumed to have a speed reduction of 0.80 for Kids; 0.70 for Elders and 0.50 for handicaps of any agent type over the already reduced speed. In the case of cars the maximum speed is 30km/h (8.40m/s) (Suzuki and Imamura, 2005). The speed varies as a half tail Normal Distribution of density in the agent field of view of a 60 degrees cone with 5m distance for pedestrians and 10m for cars (Fig.3.8 in Chapter

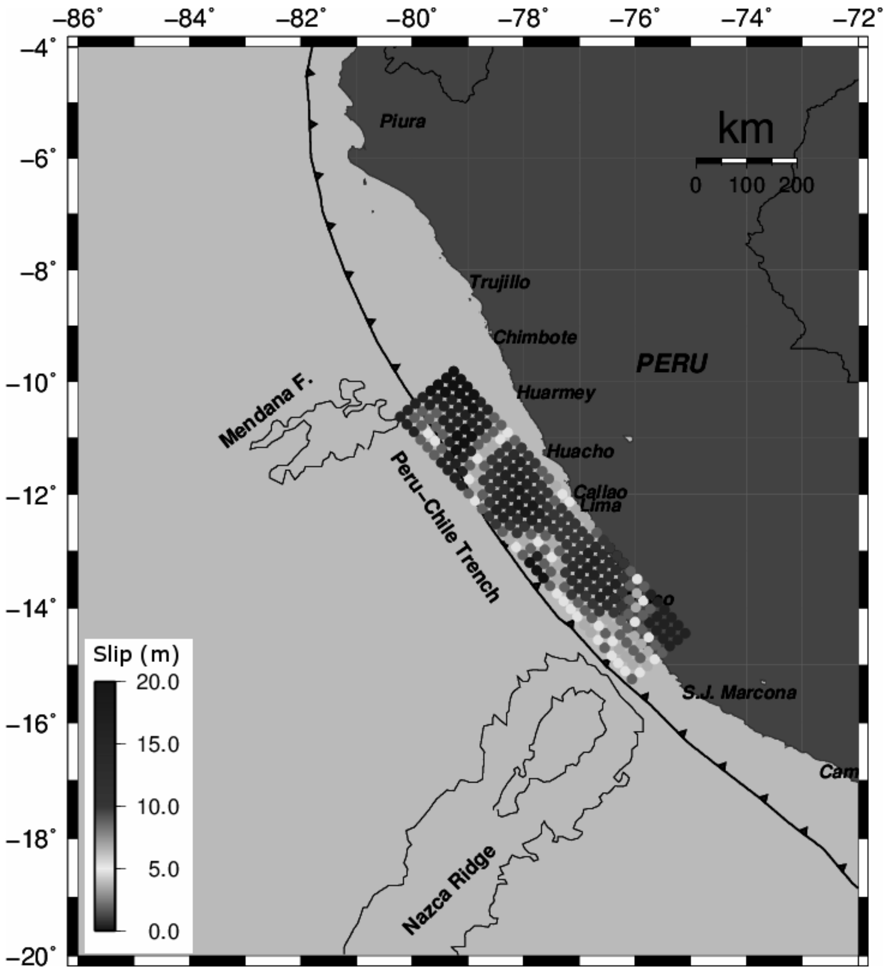


Figure 5.10: Tsunami source - Slip distribution for a possible earthquake similar to the 1746 Peru Earthquake. There are 280 sub-faults of 20x20km. (Pulido et al., 2011)

Table 5.4: Agent type number at each scenario and their maximum speed value allowed during simulation

Type	Horizontal	Vertical	Horizontal and Vertical	Max. speed (m/s)
Kids	514	514	514	1.06
Teens	377	377	377	1.33
Adults	1678	2428	1678	1.33
Elders	901	1051	901	0.93
Cars	225	-	225	8.40

(*)Units: persons

3.2.4).

Cases for simulation

For a better comprehension of the necessity of Tsunami Evacuation Buildings, we ran a case for the only horizontal evacuation with no use of TEBs. Next, as the main target of this section, the evaluation of spatial distribution of TEBs is conducted for the only Vertical Evacuation case and a combined case of Horizontal Evacuation and Vertical Evacuation, possibly the most probable scenario in a real emergency. A detail description of the assumptions and constraints at each case are described here:

1. Horizontal Evacuation.- In this case pedestrians and cars are set to choose one of the possible two exits out of the district - two streets leading to the northeast of the district (Fig. 5.11 - triangles).

2. Vertical Evacuation.- Here, the total of 20 available TEBs are in consideration for sheltering (Fig. 5.11 - circles). Evacuees - only pedestrians - choose the nearest shelter to their location regardless the capacity or condition at the shelter. Thus, if the structure is full of evacuees related to its real capacity, still evacuees are allowed to enter the building. The reason for this decision is to observe the over-demand of certain structures during the time of evacuation before the arrival of tsunami. In future evaluations further behaviors can be considered, i.e. changing shelter decision due to overcrowding of structures or selecting a shelter based not only on distance but capacity; however, these behaviors, despite the underlying rationality might not be present in a real emergency. Therefore, we leave these other conditions for future assessment and discussion.

3. Horizontal and Vertical Evacuation.- The horizontal and vertical case is a combination of the two previous mentioned scenarios. In this case, pedestrians and cars are considered. The possible sheltering or escape points are the union of all points previously shown and detailed in Fig. 5.11.

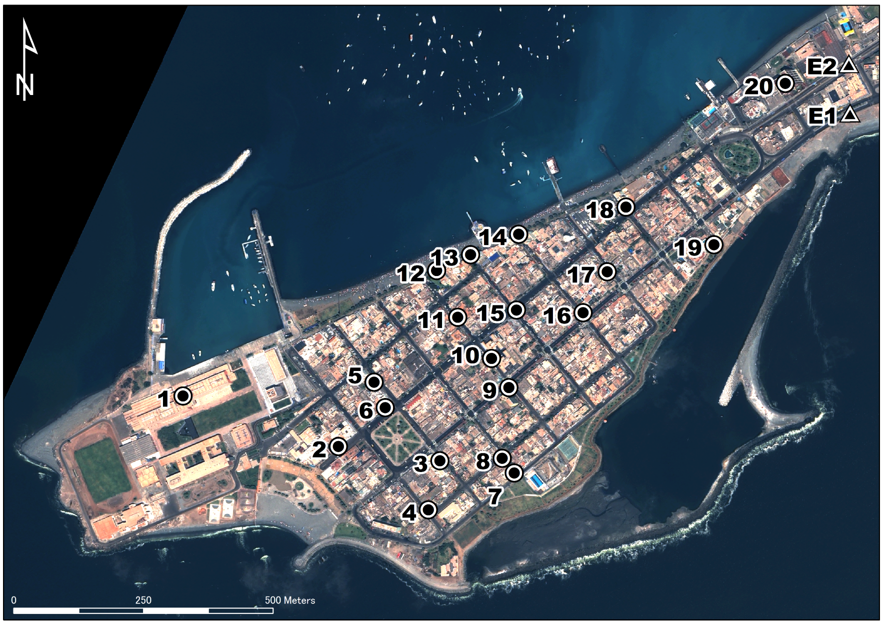


Figure 5.11: Location of shelter and exits - TEBs (circles) and Exits (triangles)

Start time of evacuation

In all cases the start time condition of pedestrians and cars follow the Tsunami Departure Curve method proposed in Mas et al. (2012c). A Tsunami Departure Curve is a set of possible departure behaviors from residents bounded by two distributions of behavior obtained by questionnaire survey and numerical simulation of tsunami (Fig.5.12).

In La Punta case, two pre-tsunami or stated preference surveys were conducted in 2010 and 2011. In this case we asked people who stated will evacuate in case of an earthquake, the following question: "In the case of a near-field tsunami, how many minutes would you take to decide and prepare yourself for evacuation? (From the end of the earthquake to the beginning of your evacuation to a safe place)". Answers were given on multiple options in minutes intervals. Then, the answers are fit with the Rayleigh distribution obtaining a mean of distribution of 7min - a fast

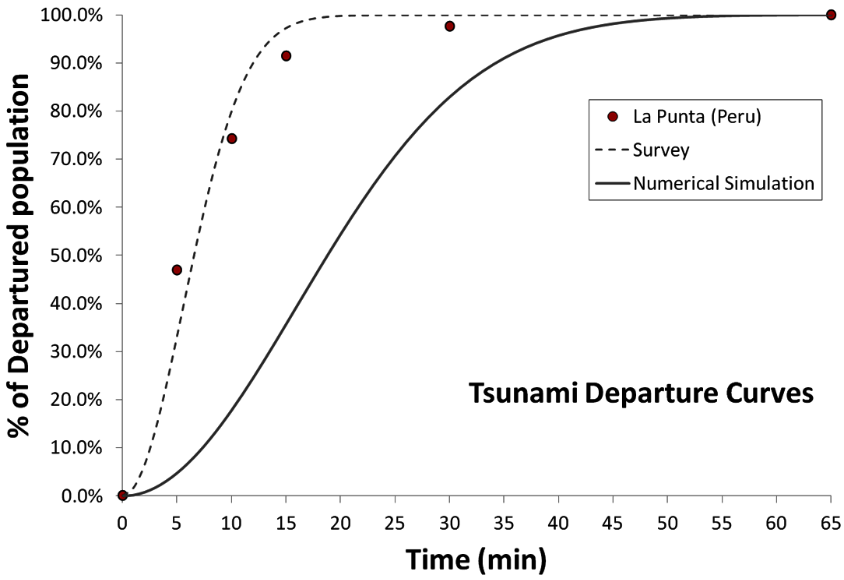


Figure 5.12: Tsunami Departure Curves - Behavior of start time is obtained through the stochastic simulation of random selected times bounded by these two distributions

evacuation compared to the expected arrival time of tsunami of 20min. Due to the lack of post-tsunami or revealed preference survey, a good approximation of the slow evacuation condition is related to a Rayleigh mean of distribution value equal to the expected arrival time of tsunami (20min) (Mas et al., 2012c). Finally the distributions characterized by the means of 7min and 20min become the boundaries of a stochastic simulation of several departure curves for tsunami evacuation.

5.2.4 Results and Discussion

Casualty Estimation

The initial condition of residents is a difficult task to simulate in evacuation procedures, due to the uncertainty on the time and date of a possible real event. In a night time scenario it might be acceptable to initialize the resident's location at their own house; however in a day time scenario the dynamic condition of people makes it difficult to assume an initial location for agents. Therefore, we accept this uncertainty in the spatial initial location of agents and start the simulation at a random location inside a house or on the street or beach. Then, in the stochastic simulation we ran 250 repetitions of scenario with different initial location of agents, in order to comprise many possible scenarios of population spatial distribution in the district. Finally the averages of results are shown in Table 5.5.

Table 5.5: Average value of casualties in three cases: a) Horizontal Evacuation; b) Vertical Evacuation and c) Horizontal and Vertical Evacuation

Type	Horizontal			Vertical			Horizontal and Vertical		
	Avrg.	S.D.	Max.	Avrg.	S.D.	Max.	Avrg.	S.D.	Max.
Kids	38	2	42	4	1	7	4	1	7
Teens	29	3	34	4	1	7	4	1	8
Adult	28	1	30	4	0	5	4	0	5
Elder	47	1	50	4	1	6	4	1	6
Cars	32	34	87	-	-	-	34	35	100
Total (pers.)	271	-	-	16	-	-	153	-	-

(*)Units: persons

The Horizontal Case shows the maximum average number of casualties, followed by the Horizontal and Vertical Case, and the only Vertical Case. Here, it is important to observe that the Horizontal Evacuation pretends to release almost 5,000 people among pedestrians and cars through only two narrow exits. As expected traffic congestion is observed along the exit roads and in particular near to the exits until the arrival of tsunami. Snapshots every 10min of simulation can be observed in Fig. 5.13. The final white dots are points of traffic and red dots final casualties. The necessity of Tsunami Evacuation Buildings can be observed through the results of this case.

For the Vertical Evacuation case, no traffic congestion was observed due to the enough space available for pedestrians and the restriction of vehicles in the scenario (Fig. 5.14). Apparently the evacuation runs smoothly with a minor number of casualties due to the late evacuation.

The third case simulated corresponds to the combined method of Horizontal and Vertical Evacuation. In this case, the number of casualties is lower compared to the only horizontal evacuation due to a distress on roads from pedestrians and some vehicles. It is observed that in several repetitions although traffic congestion was observed at the neck of the district during the evacuation, no casualties were observed at the end (Fig. 5.15). However it is probable to obtain casualties during traffic congestion as shown by some other repetitions which resulted similar to the only horizontal scenarios

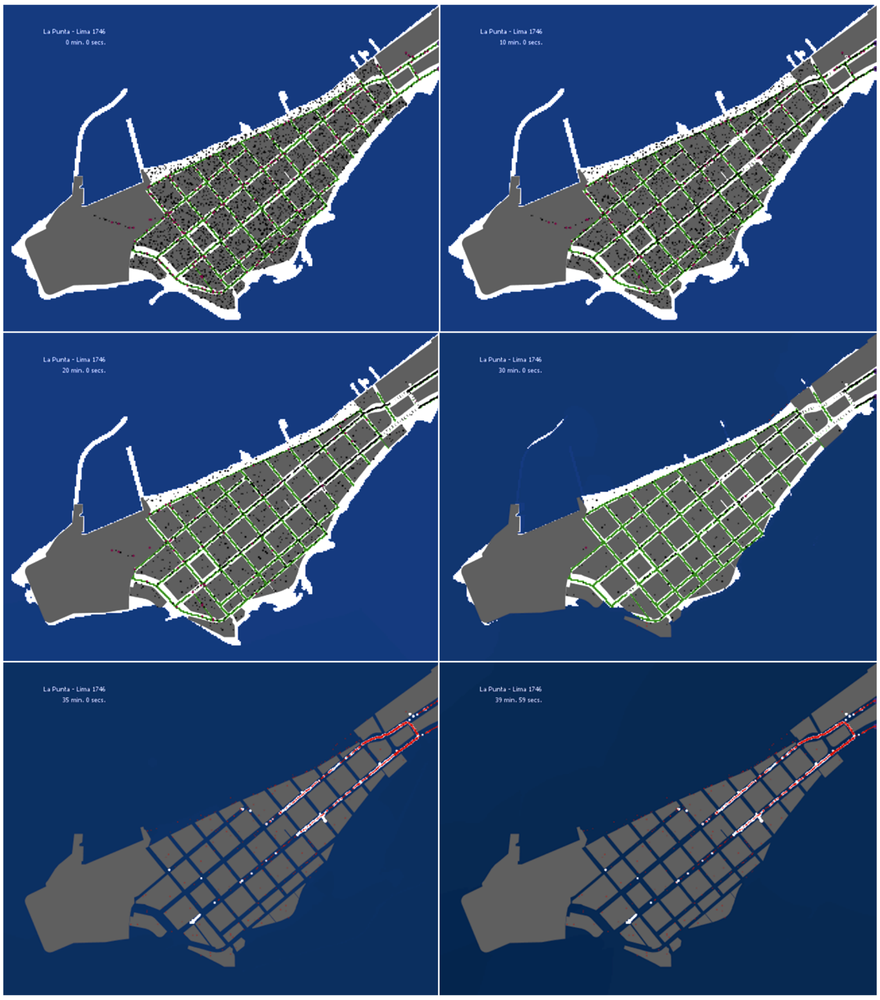


Figure 5.13: Horizontal Evacuation scenario result. - Casualties at traffic congestion are observed at the neck of the district.

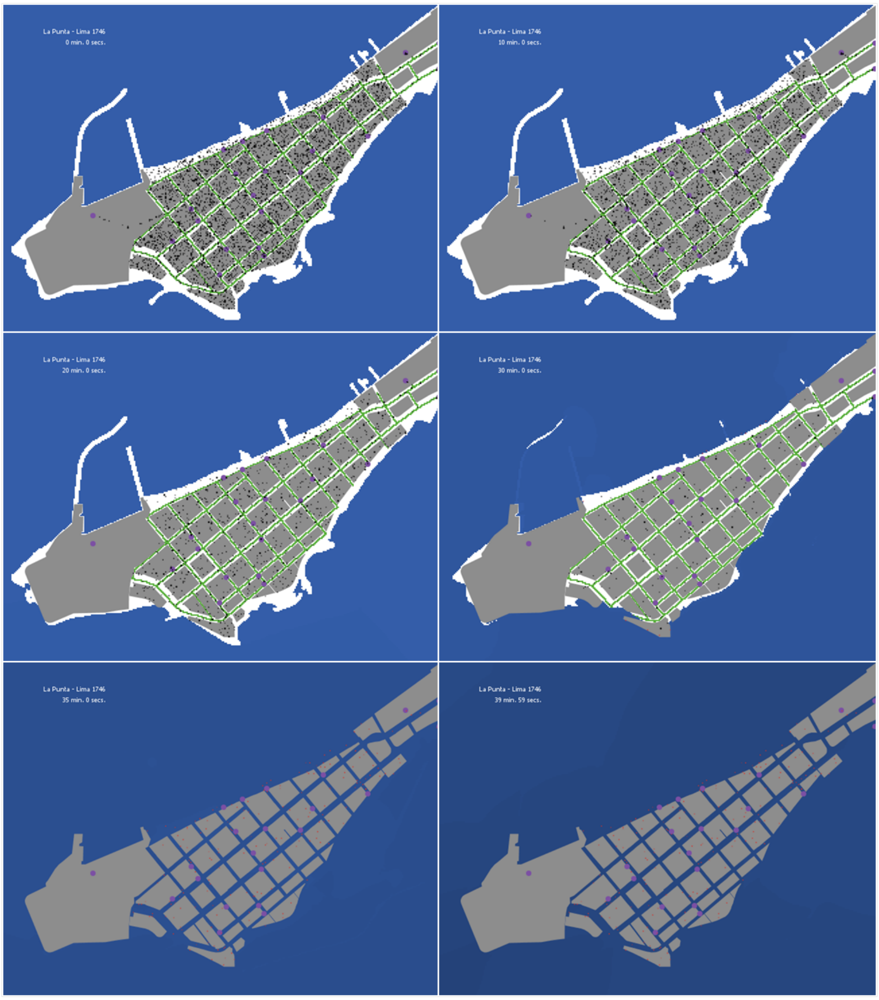


Figure 5.14: Vertical Evacuation scenario result. - Casualties are more related to the late evacuation than the congestion or crowding.

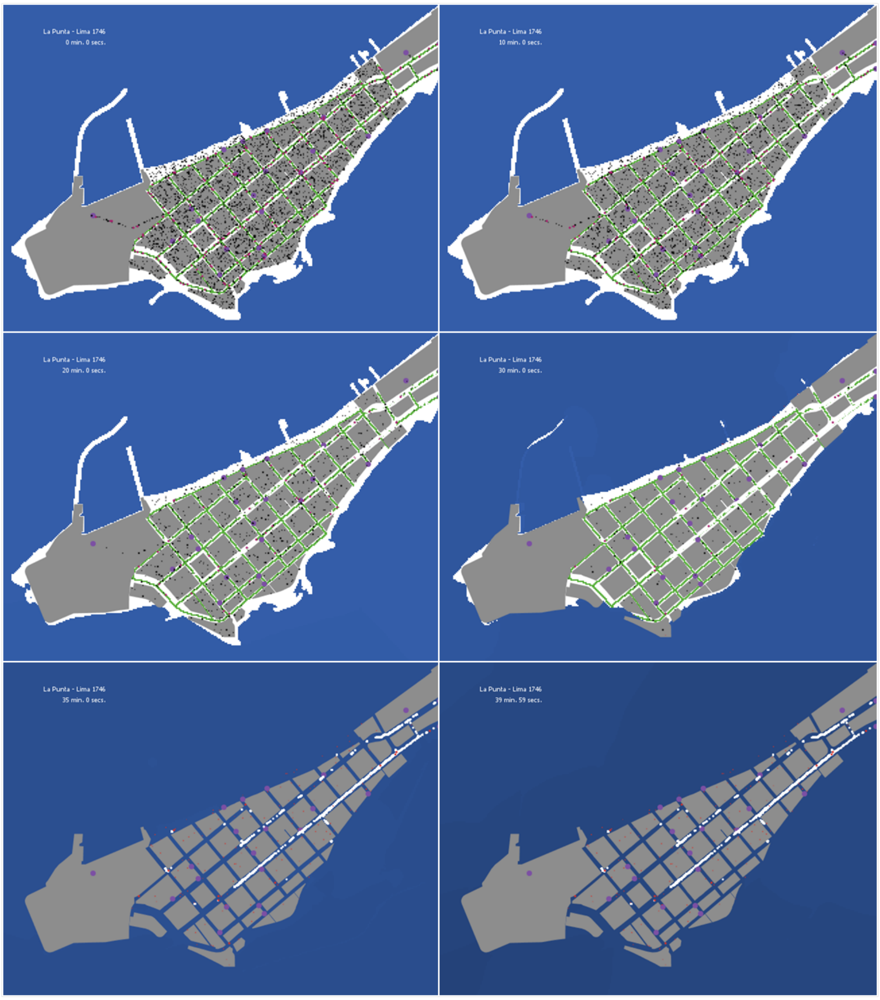


Figure 5.15: Horizontal and Vertical Evacuation scenario result. - Casualties are more related to the late evacuation than the congestion or crowding.

Shelter Demand

The detailed results of each Tsunami Evacuation Building in regard to capacity and demand number of evacuees in the Vertical and the Horizontal and Vertical cases can be observed in Table 5.6. Furthermore, also as observed in Fig. 5.16, out of twenty (20) TEBs, 13 resulted with average over-demands while seven (7) were still with available space. In the upper inset of Fig. 5.16 it is clear the difference of demand from the Vertical case to the Horizontal and Vertical case. While the latter shows a lower demand of TEBs due to the possibility of sheltering outside the area; the Vertical case had shown to be further convenient to shelter more people and expect fewer casualties. Nevertheless, it is necessary to ensure the safety of evacuees even at the over-demand shelters. As an example, building S11 with 25 persons of capacity may expect around 180 residents in the area looking for shelter. This is seven times its capacity, then a big group of people might not be able to access the roof area and will be compelled to remain at lower floors at risk of inundation.

Then, new areas for vertical evacuation around the district should be implemented because the actual spatial location of TEBs compromises the safety of residents.

Mapping the Capacity-Demand

In order to contribute with future mitigation plans and new alternatives for evacuation in La Punta, the resulting capacity-demand rate is mapped as observed in Fig. 5.17.

The relation capacity-average demand of cases showed in Table 5.6 represents the Capacity-Demand Index (CDI) following the simple relation in Eq. 5.2.

$$CDI = \frac{Demand}{Capacity} \tag{5.2}$$

In that sense, maps like the one shown in Fig. 5.17 are easy to understand for local stakeholders and laypersons. Therefore, a value of 0.0 to 0.5 indicates that less than a half of the structure has been occupied; from 0.5 to 1.0 at most the total capacity of the structure is being used. The important information comes for CDI values over 1.0, where over-demand conditions are encountered. As a result, from the CDI Map it is possible to conclude that unfortunately the nearest buildings are comparatively of lower capacity with the ones located at the head and neck of the district. Due to the behavior of shelter selection (nearest), most of the structures closer to the beach area in the north coast present an over-demand while the south population apparently may fit in the available structures.

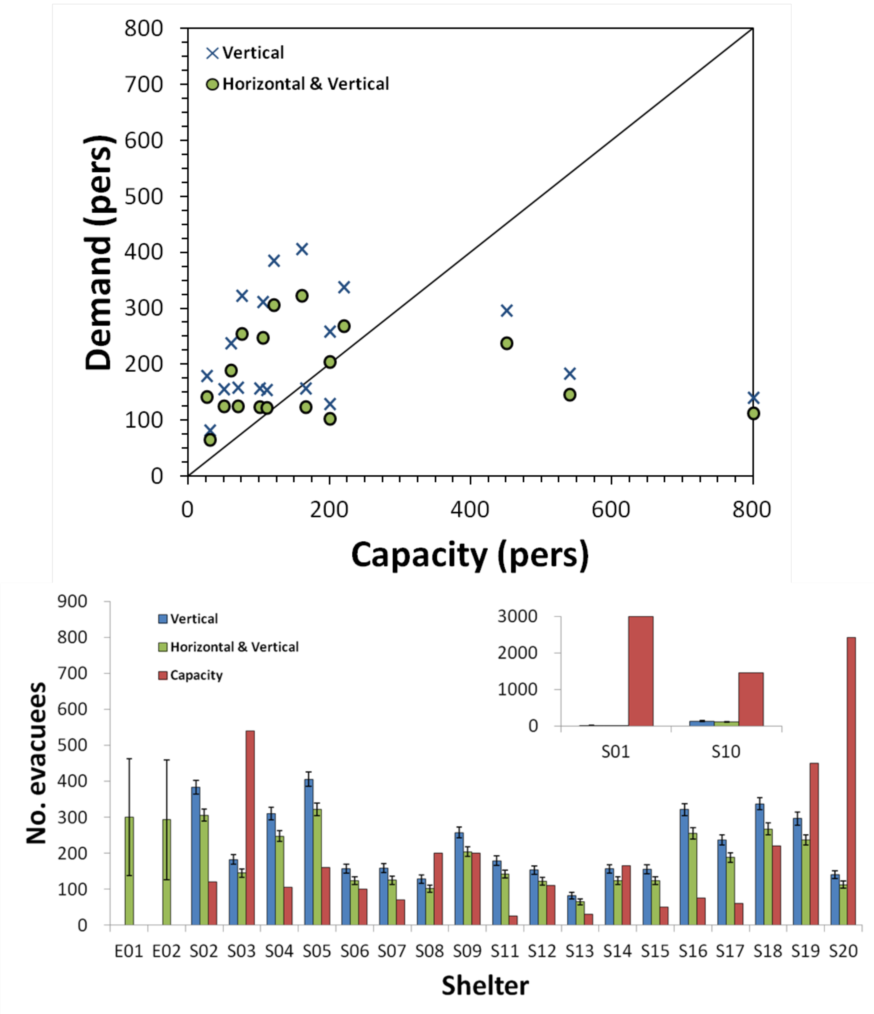


Figure 5.16: Capacity and Demand in La Punta - Out of 20 TEBs, 13 might present over-demand and 7 under-demands.

Table 5.6: Capacity and Simulation results of 20 TEBs and 2 Exits in two cases (Vertical Evac. and Horizontal and Vertical Evac.)

Code	Name	Vertical			Horizontal and Vertical			Capacity
		Avrg.	S.D.	Max.	Avrg.	S.D.	Max.	
S01	Escuela Naval	10	3	22	8	3	18	3000
S02	Av. Bolognesi No. 11	384	19	439	306	17	354	120
S03	Jr. Saenz Pena No. 275	183	13	220	145	12	182	540
S04	Jr. Tarapaca No. 155	311	18	361	247	15	287	105
S05	Jr. Saenz Pena cdra. 4	406	20	477	322	18	378	160
S06	Av. Bolognesi cdra. 1	157	12	184	124	11	164	100
S07	Jr. Larco No. 151	159	13	202	125	12	158	70
S08	Jr. Tarapaca No. 288	129	11	164	102	10	137	200
S09	Jr. Arrieta No. 295	258	16	304	204	14	246	200
S10	Jr. Arrieta No. 320	135	12	167	106	11	141	1450
S11	Jr. Arrieta No. 492	180	13	214	142	11	171	25
S12	Jr. Figueredo No. 470	154	12	185	122	11	161	110
S13	Jr. Figueredo No. 520	82	9	113	65	8	86	30
S14	Jr. Moore No. 496	157	11	196	124	11	159	165
S15	Av. Bolognesi No. 508	155	13	188	124	11	158	50
S16	Jr. Moore No. 380	322	17	373	255	16	295	75
S17	Jr. Tnte. Palacios No. 375	237	14	276	188	13	231	60
S18	Jr. Ferre No. 460	337	16	391	268	17	327	220
S19	Jr. Elias Aguirre No. 155	297	19	352	237	15	284	450
S20	Edificio SUNAT/SUNAD	141	11	174	113	10	146	800
E01	Exit 1	-	-	-	300	162	528	-
E02	Exit 2	-	-	-	293	166	500	-
	Total (pers.)	4194	-	-	3922	-	-	7930

(*)Units: persons

5.3 Summary

A group of applications of the TUNAMI-EVAC1 for the disaster mitigation and evacuation feasibility evaluation were presented here. The Human Response Capability, a combination of the reaction time (RT) obtained through the Tsunami Departure Curve method, and the response time (RsT) observed in the simulation can be evaluated for different kinds of possible scenarios of population evacuation behavior. Also, it is possible to use the TUNAMI-EVAC1 to observe the impact of different percentage of vehicles involved in the evacuation, in order to evaluate the evacuation feasibility.

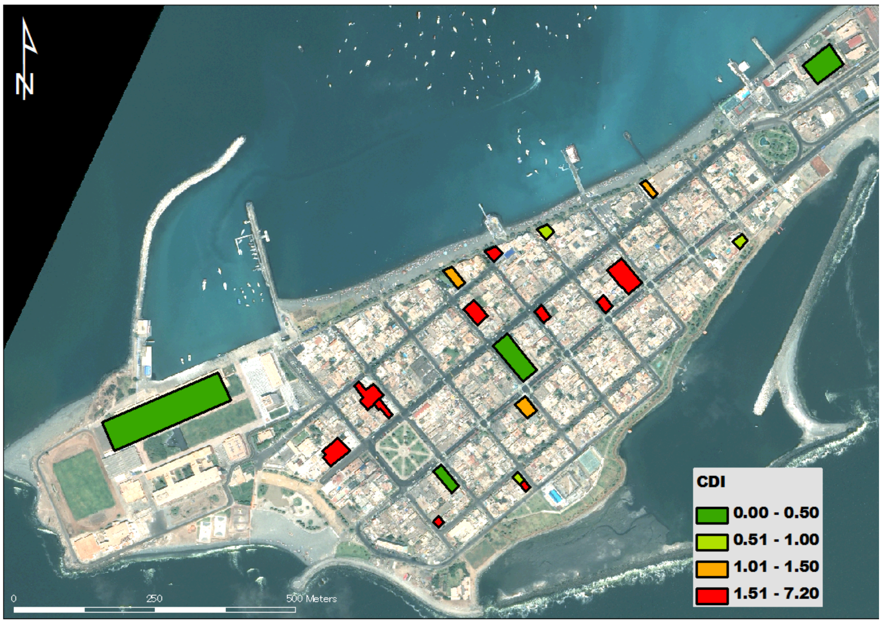


Figure 5.17: CDI mapping - Capacity-Demand mapping of TEBs. Red areas are over-demand, green areas are under-demanded. (Vertical Evacuation)

Furthermore, an evaluation of Tsunami Evacuation Building demand permits to identify shelters with possible over-demand and the potential spatial allocation of new shelters. Using TUNAMI-EVAC1 animations of the simulated scenarios, combined with the mapping of capacity demand index results, becomes a practical and easy way to share the information with local authorities and lay persons for the disaster prevention management and education.

Chapter 6

Conclusions and Future Works

This chapter describes the conclusions of this study divided in three groups: (1) Conclusions related to the model and its features; (2) Conclusions related to the theory developed for modeling; (3) Conclusions to the multiple applications shown in the previous chapter. Finally, the future works related to the improvement of TUNAMI-EVAC1 are described.

6.1 Conclusions

In response to the main objective of the study, an Integrated Simulator for Tsunami Inundation and Agent Based Evacuation was developed as a decision support tool for the evaluation of the evacuation feasibility and its use for educational purposes in several areas.

Further conclusions and findings can be summarized as follow:

6.1.1 Based on the Model features

TUNAMI-EVAC1 was developed as an easy-to-use and simple to distribute resource for the disaster management and education.

- TUNAMI-EVAC1 uses the NetLogo technology, a free open-source modeling environment fully programmable and with a smooth learning curve.
- TUNAMI-EVAC1 allows for the input of GIS based data. It smoothes the pre-process step of simulation and increases its possibility to be applied in multiple areas.

- TUNAMI-EVAC1 integrates the features of tsunami inundation, such as velocity and depth from the TUNAMI model presenting a probabilistic model to estimate casualties during the simulation.
- TUNAMI-EVAC1 presents the pedestrian and vehicle dynamic evacuation at the individual scale level of agent based simulation.

6.1.2 Based on the Modeling theory

New theories on start time evacuation decision modeling and casualty estimation in evacuation models has been developed in this field.

- The use of questionnaires to model the human behavior in evacuation was explored and findings have shown the limitations on the application of State Preference (SP) surveys or Revealed Preference (RP) surveys without a comprehensive approach.
- Stated Preference (SP) surveys show an expected fast evacuation behavior by respondents.
- Revealed Preference (RP) surveys show a distribution of evacuation adjusted to the timing of the event.
- A new method for casualty estimation in evacuation simulation was developed using a probabilistic model based on the laboratory experimental data. The use of tsunami velocity and inundation depth is combined to calculate the stability of the human body.
- Tsunami Departure Curve method was developed an proposed as a new approach of the start time evacuation decision modeling. TDC combines the use of questionnaire results and tsunami numerical simulation results to characterize the possible population behavior of evacuation decision. The stochastic process is bounded by stated preference and revealed preference surveys.
- Better approximations to the real case of evacuation were obtained in the Tsunami Departure Curve Method proposed, compared to traditional approaches.

6.1.3 Based on the multiple applications

Multiple applications were presented as an example of the utility of the model for disaster management.

- The TUNAMI-EVAC1 has demonstrated to be a useful tool for the disaster management, helping on the identification and evaluation of casualties, shelters and behavior for evacuation.
- The main purpose of a evacuation simulator model is the exploration of different scenarios to evaluate the Human Response Capability based on the Population reaction and preferences for mean of evacuation. TUNAMI-EVAC1 contributes to this purpose.
- A new application of Evacuation Simulators presented with TUNAMI-EVAC1 is the following of Tsunami Evacuation Buildings and Exits situation during the evacuation in order to evaluate the demand, resource or space necessities in a particular scenario of tsunami evacuation.

6.2 Future Works

Future works are related to the improvement of the actual version of TUNAMI-EVAC1. There is still plenty of space for improvement of the model. some ideas are related directly to the actual limitations of the simulator.

6.2.1 Related to the modeling environment

- NetLogo capabilities includes the possibility to use the model as a Java Web application, this will contribute to the local education of communities by the individual exploration of scenarios by residents or students in the area.
- Another interesting future application is the participatory simulation for evacuation. Using the HubNet resource of NetLogo a new way of education for disaster management can involve several participants into a unique scenario.
- When large scale areas and population is needed to be simulated, the migration of TUNAMI-EVAC1 from NetLogo to a more advanced tool like RePast will allow the parallelization of the model in order to obtain fast computing results.

6.2.2 Related to the status of TUNAMI-EVAC1

- It is possible to improve the dynamic pattern of movement and performance of path finding algorithm by the hybrid solution of a network for path finding and grid space for movement. This will yield to a more realistic simulation of pedestrians.

- Although TUNAMI-EVAC1 includes the simulation of vehicles in the model, a future improvement is the inclusion of roads and street driving rules to follow the real direction of traffic or the presence of traffic lights.
- Due to the topographic condition in some areas, pedestrians reduce their speed because of fatigue. This is a future challenge to integrate in the evacuation simulation.

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Appendices

Appendix A

TUNAMI-EVAC1: User Manual

A.1 Introduction

TUNAMI-EVAC1 stands for Tohoku University Numerical Analysis Model for Investigation of Evacuation No. 1. It is the first version of a new developed tool for the agent based simulation of pedestrians and vehicles involved in the tsunami evacuation of a risk area.
This User Manual explains how to use the TUNAMI-EVAC1 to run simple models based on the example given and to personalized future models. For the insights on the model please revised chapters in this document (in particular Chapter 3) and related publications of the author ((Imamura et al., 2012; Mas et al., 2012a,b,c,d)).
This manual is made up of three sections. First to Get Started with the model, the installation, directories, license and overview of the model is explained. Second, we will explain how to use the model and to understand its outputs. Finally, a customization section to explain how to use the tool to simulate different areas.

A.2 Getting Started

A.2.1 Directory structures and files

You will be provided of a folder named TUNAMI-EVAC1 containing the following subfolders:

- Output. Empty folder. It is always needed to save the outputs of simulation. If you change the name and run the model an error message will appear. Make sure you always have an Output folder here. Also new outputs overwrite any files in this folder.

- SpatialDB. A folder with the GIS data of the area to simulate.
- TsunamiDB. A folder with the TUNAMI snapshot and velocity outputs of the area to simulate.
- Model.nlogo. A file of NetLogo containing the model source code and the executable GUI of the model.
- Extensions. A folder containing extensions used in the model. These comes by default with NetLogo, however if there is any extension missing, copy from here to your NetLogo extension folder `(C:\Program Files\NetLogo 5.0.1\extensions)`

A.2.2 Installation

1. Download and Install NetLogo 5.0.1 or later version in your computer system. Be aware that newer versions might require small modifications in the code. NetLogo home page.
2. Copy the TUNAMI-EVAC1 folder to your computer.
3. TUNAMI-EVAC1 uses some extensions of NetLogo that might not come by default. Check the folder Extensions in the TUNAMI-EVAC1 folder and copy the ones that are missing in your NetLogo extension folder
`(C:\Program Files\NetLogo 5.0.1\extensions)`

A.2.3 License

NetLogo is free, open source software under the GPL (GNU General Public License), version 2, or (at your option) any later version. Also TUNAMI-EVAC1 is free open source following the NetLogo and its extensions licenses. See each extension's README for details.

A.3 Used of the Model

A.3.1 Setup

Choose from the control panel (Fig. 3.14) the scenario to simulate. You may change the *title* of the model to appear in the screen, the *number* of agents per type of agent and the *percentage* of handicap agents in the model. Also the *mean* of the boundary distributions for behavior based on the Tsunami Departure Curve method (see Chapter 3). To estimate casualties activate the *tsunami*? switch and to create a *movie*?, *snapshot*? and $output - files$? turn on the respective switch. Additionally, a behavior of shelter selection can be choose to be random or near selection ($random - shelter$? switch). After this, press *setup*.

A.3.2 Running the Model

To run the model you may press *go*. The calculation starts immediately and the world screen will show the progress of evacuation. Also plots and monitors will show the respective values and time line of reporters. In order to accelerate the calculation due to the graphic memory consumption you may *uncheck* the box of *view updates* and create snapshots or movie instead.

A.3.3 Output Data Format

Besides the snapshots and movie, you will obtain a file containing the plots records in a CSV file format. Also a $Casualty - Report.txt$ file, a $Safe - Report.txt$ file, a $Decision - Report.txt$ file, and a $Demand - Report.txt$ file containing the total number of agents involved in the respective variable at the end of each stochastic repetition of simulation. Finally, $Evacuation - Record.txt$ file will show variables of each agent in the simulation, initial location coordinates, selected shelter, longitude of selected route, final location at the simulation, final condition of casualty. This last file will be part of the statistic analysis of each evacuation scenario.

A.3.4 Analyzing outputs

According to the objective and necessity of the user. You may observe the number of casualties estimated at the end of simulation, the areas of congestion during simulation based on the screen result. A combination of behaviors, vehicles involve in the evacuation, population participating, etc. A numerous of scenario analysis may be possible.

A.4 Customization

TUNAMI-EVAC1 is based on the NetLogo programming language, therefore it is easy to learn and modified to follow the specific objectives of simulation. Layers of behavior of agents can be modified to obtain different behaviors of simulation.

For instance, layer 0, is the decision of evacuation using the Tsunami Departure Curve, however if the user would like to model an "all-together" behavior, the variable *td* of agents should be initialized with such desired timing instead of using the Rayleigh distribution. Then, it will be necessary to change `set td floor (random-td-rayleigh random-float 1 one-of s-shapes)`, in the pedestrian and car initialization routine, into `set td T`, where T is the desired time.

Similarly occurs to other behaviors in the model. Each layer can be modified to adjust to a new desired behavior.

A.4.1 Creating new models

To create a new scenario, GIS data and TUNAMI data have to be saved into the respective folders with your desired area data. After this, the new model can be explore similar to the example model. The parameters of behavior for Tsunami Departure Curves are obtained through simple questionnaire approach like the one in Appendix C.

Appendix B

TUNAMI-EVAC1: Source Code

To obtain the latest version of the code, please contact the author at
erick@tsunami2.civil.tohoku.ac.jp

The software used was NetLogo 5.0.1 (April 12, 2012) and the following example is for La Punta - Peru of Chapter 5 updated to August 2012. For newer versions and updates please contact the author.

```
extensions [gis pathdir]

;;*******************************************************************
;; DECLARING VARIABLES
;;*******************************************************************
;; GLOBAL VARIABLES

globals [ land-patches
          urban-patches
          sea-patches
          street-patches
          exit-patches
          teb-patches
          teb-capacity
          exit-capacity

          scale
          tsu-counter
```

```
          vel-counter
          tsunami-file-name
          Cmax-ped
          Cmax-car

          decided-kids
          decided-teens
          decided-adults
          decided-elders
          decided-cars

          safe-kids
          safe-teens
          safe-adults
          safe-elders
          safe-cars

          casualty-kids
          casualty-teens
          casualty-adults
          casualty-elders
          casualty-cars

          pop-kids
          pop-teens
          pop-adults
          pop-elders
          pop-cars

          start
          target
          space-color
          heuristic
        ]

breed [ kids kid ]
```

```
breed [ teens teen ]
breed [ adults adult ]
breed [ elders elder ]
breed [ cars car]

kids-own [ dim speed handicap stage path ini goal L heuri td ]
teens-own [ dim speed handicap stage path ini goal L heuri td ]
adults-own [ dim speed handicap stage path ini goal L heuri td ]
elders-own [ dim speed handicap stage path ini goal L heuri td ]
cars-own [ dim speed handicap stage path ini goal L heuri td ]

patches-own [zt f g h parent open? vx vy vt]
;open? 0 = NA, 1= open, 2= close

;;*****************************************************************
;; INITIAL CONDITIONS
;;*********************************************************** SETUP

to setup
  ca
  reset-ticks
  set-initial-values
  load-spatial
  load-population
  display
end

;;********************************************************* SETUP 2

to reload
  reset-timer
  clear-turtles
  clear-output
  reset-ticks
  set-initial-values
  load-population
```

```
end

;;**************************************************** INITIAL VALUES

to set-initial-values
  random-seed 100
  ;--> this ensures repetition of scenarios (replicability)
  set-default-shape turtles "dot"
  set decided-kids 0
  set decided-teens 0
  set decided-adults 0
  set decided-elders 0
  set decided-cars 0
  set safe-kids 0
  set safe-teens 0
  set safe-adults 0
  set safe-elders 0
  set safe-cars 0
  set casualty-kids 0
  set casualty-teens 0
  set casualty-adults 0
  set casualty-elders 0
  set casualty-cars 0
  set pop-kids 0
  set pop-teens 0
  set pop-adults 0
  set pop-elders 0
  set pop-cars 0
  set teb-capacity [ ]
  set exit-capacity [ ]

  if tsunami? [set tsu-counter 50900 set vel-counter 50900 ]
  ;--> change file-name
  set scale 5  ;--> very important parameter!

  set Cmax-ped ceiling (0.7 * scale ^ 2)
```

```
  ;-> congestion condition pedestrians
  set Cmax-car ceiling (0.07 * scale ^ 2)
  ;-> congestion condition cars

  if movie?
  [ movie-cancel let name (word movie-name ETA ".mov")
    ifelse file-exists? name [ let new-name user-input
  "The movie filename already exists! Type a new name or press Halt"
                              ifelse new-name != nobody
                                [ set name (word new-name ".mov")
                                  movie-start name
                                  movie-set-frame-rate
                                  movie-frame-rate ]
                                [ movie-cancel ]
                            ]
                            [ movie-start name
                              movie-set-frame-rate
                              movie-frame-rate ]
  ]
  ask patches [set plabel "" set plabel-color white
               set zt -9999 set vx -9999
               set vy -9999 set vt -9999 ]
  let dir-temp (word pathdir:get-model "//Output")
  set-current-directory dir-temp
  file-close-all
  file-open (word "Evacuation-Record" behaviorspace-run-number ".txt")
  file-print
  "type,id,x-ini,y-ini,x-goal,y-goal,x-end,y-end,L0-path,L1-path,
  td,tsh,zt,C"
  file-close
  set-current-directory pathdir:get-model
end

;;****************************************************** LOAD SPATIAL

to load-spatial
```

```
;resizing the world
;you need to change these numbers with grid size of area
let x (1620 / scale) - 1
let y (-1) * ((1235 / scale) - 1)
resize-world 0 x y 0

if scale = 5
[ set-patch-size 2 ]
if scale = 2
[ set-patch-size 1 ] ;this is the scale 2mx2m grid

;loading GIS data
let dir-temp word pathdir:get-model "//SpatialDB"
set-current-directory dir-temp
;gis:load-coordinate-system "Projection.prj"
let Land gis:load-dataset "Land.shp"
let Urban gis:load-dataset "Urban.shp"
let Streets gis:load-dataset "Streets.shp"
let Sea gis:load-dataset "Sea.shp"
let Exit-dataset gis:load-dataset "Exits.shp"
let TEB-dataset gis:load-dataset "TEB.shp"

gis:set-world-envelope ( gis:envelope-union-of
                              (gis:envelope-of Land)
                              (gis:envelope-of Urban)
                              (gis:envelope-of Streets)
                              (gis:envelope-of Sea)
                              (gis:envelope-of Exit-dataset)
                              (gis:envelope-of TEB-dataset)
                       )
set land-patches patches gis:intersecting land
set urban-patches patches gis:intersecting urban
set street-patches patches gis:intersecting streets
set sea-patches patches gis:intersecting sea
set exit-patches patches gis:intersecting exit-dataset
set teb-patches patches gis:intersecting teb-dataset
```

```
  ask sea-patches [set pcolor blue]
  ask land-patches [ set pcolor white ]
  ask street-patches [ set pcolor green ]
  gis:set-drawing-color gray
  gis:fill urban 0.05
  ask exit-patches [ set pcolor green sprout 1
                     [ set color violet
                       set size 4
                       set shape "circle" stamp die]
             set exit-capacity lput (list self 0) exit-capacity ]
  foreach gis:feature-list-of teb-dataset
  [ ask patches gis:intersecting ? [ if not only-exits? [ sprout 1
                                         [ set color violet
                                           set size 4
                                       set shape "circle" stamp die] ]
                                    set teb-capacity lput (list self 0)
                                       teb-capacity
;<- to start with capacity 0, otherwise change for
;-> gis:property-value ? "capacity") teb-capacity
;<- to read capacity from GIS data
                                     ]
  ] ;-> TEBs are with infinite capacity to observe demand
  if Bck?
  [ import-drawing "Bckgrd.png"]
  set-current-directory pathdir:get-model
  output-print (word "Spatial data: " timer " sec.")
  reset-timer
  clear-turtles
end

;;***************************************************** LOAD POPULATION

to load-population
  create-kids #-of-kids
  [ set dim 0.6 set speed 0.8 * 1.33 / scale]
```

```
create-teens #-of-teens
[ set dim 1.0 set speed 1.0 * 1.33 / scale]
create-adults #-of-adults
[ set dim 1.0 set speed 1.0 * 1.33 / scale]
create-elders #-of-elders
[ set dim 1.0 set speed 0.7 * 1.33 / scale]
create-cars #-of-cars
[ set dim 1.2 set speed 1.0 * 1.68 / scale]
;same speed but 5 times running
  let pedestrians (turtle-set kids teens adults elders)
ask pedestrians [ move-to one-of
(list one-of urban-patches one-of street-patches )
                  set color black
                  set size ( 1 / scale * dim ) * scale * 5
                  let s-shapes [ ]
                  let str 0
                  let nd 0
                  ifelse u < ETA
                  [ set str u set nd ETA]
                  [ set str ETA set nd u]
                  while [ str <= nd]
                   [ set s-shapes lput str s-shapes
                     set str str + 1 ]
                  set td floor ( random-td-rayleigh
                  random-float 1 one-of s-shapes )
                  set heuri random 5
             ;<- you can select a default heuristic if desire
                  set ini patch-here
                  set goal patch-here
                ]

ask cars [ move-to one-of street-patches
           set color magenta
           set size ( 1 / scale * dim ) * scale * 3
           let s-shapes [ ]
                  let str 0
```

```
                    let nd 0
                    ifelse u < ETA
                    [ set str u set nd ETA]
                    [ set str ETA set nd u]
                    while [ str <= nd]
                     [ set s-shapes lput str s-shapes
                       set str str + 1 ]
             set td floor (random-td-rayleigh
             random-float 1 one-of s-shapes)
             if td < 5 [ set td random one-of s-shapes ]
             ;<- if you want to delay car reaction 5 minutes
             set heuri random 5
             ;<- you can select a default heuristic if desire
             set ini patch-here
             set goal patch-here
             ;set shape "car"
           ]
  let p round ( %-of-handicap * count pedestrians / 100 )
  ask n-of p pedestrians [ set handicap true set speed speed * 0.5 ]
  set pop-kids count kids
  set pop-teens count teens
  set pop-adults count adults
  set pop-elders count elders
  set pop-cars count cars
  update-text
  output-print (word "Population data: " timer " sec.")
  set-current-plot "Preparation time"
  histogram [td] of turtles
  ask turtles-on urban-patches [set hidden? true]
  if movie? [movie-grab-view]
end

;;*****************************************************************
;; MAIN PROGRAM
;;************************************************* MAIN PROG. (GO)
```

```
to go
if ticks = 0 [reset-timer no-display]
ask turtles
[ ifelse member? patch-here urban-patches
  [ set hidden? true ]
  [ set hidden? false ]
  t.decide-to-start
  t.decide-shelter
  t.search-road
  ifelse breed != cars
  [ t.follow-path ]
  [ repeat 5 [ t.follow-path] ]
  t.search-shelter-route
]
if tsunami? [if ticks > (60 * 15) [tsunami-run vel-run]
            ]
outputs
update-text
if ticks mod movie-interval = 0 and movie? [movie-grab-view]
if ticks mod (10 * 60) = 0 and snapshots? [do-snapshots]
;<- snapshots every 10 min
if ticks mod (5 * 60) = 0 and snapshots?
[ display export-interface
(word "Model_" behaviorspace-run-number "_K" ticks ".png")
no-display ]
;<- exports interface every 5 min
tick
do-plots

;------------ FINISH CONDITION ----------
if ticks = (TS * 60)
   [ output-print (word "Total time:" timer " sec.")
     if output-files?
       [ let dir-temp (word pathdir:get-model "//Output")
         set-current-directory dir-temp
         let name (word "Safe_" behaviorspace-run-number ".csv")
```

```
        export-plot "Safe" name
        set name (word "Casualty_" behaviorspace-run-number ".csv")
        export-plot "Casualty" name
        ;set name "Monitor.csv"
        ;export-output name
        set name (word "TEBs_" behaviorspace-run-number ".csv")
        export-plot "TEBs" name
        set-current-directory pathdir:get-model
      ]
      if movie? [movie-grab-view movie-close]
      display
      export-interface
      (word "Model_" behaviorspace-run-number "_K" ticks ".png")
      do-snapshots
      Reports
      no-display
      stop
   ]

end

;;****************************************************** START DECISION

to t.decide-to-start
if stage = 0 and ( ticks = ( td * 60 ) )
                  [ set stage 1
                if breed = kids
                [ set decided-kids decided-kids + 1]
                if breed = teens
                [ set decided-teens decided-teens + 1]
                if breed = adults
                [ set decided-adults decided-adults + 1]
                if breed = elders
                [ set decided-elders decided-elders + 1]
                if breed = cars
                [ set decided-cars decided-cars + 1 ]
```

```
                   ]
end

;;************************************************* SHELTER DECISION

to t.decide-shelter
if stage = 1 [ ifelse only-exits?
                 [ ifelse random-shelter?
                   [ set goal one-of exit-patches ]
                   [ set goal one-of exit-patches
                   with-min [distance myself] ]
                   ifelse breed != cars
                   [ set stage 2 ]
                   [ set stage 4 ]
                 ]
                 [ ifelse random-shelter?
                   [ set goal one-of teb-patches ]
                   [ set goal one-of teb-patches
                   with-min [distance myself] ]
                   ifelse breed != cars
                   [ set stage 2 ]
                   [ if random-float 1 < 0.30
;-> this means 30% probability of true
                     [ ifelse random-shelter?
                       [ set goal one-of exit-patches ]
                       [ set goal one-of exit-patches
                       with-min [distance myself] ]
                       set stage 4
                     ]
                   ]
                 ]
              ]
end

;;****************************************************** ROAD SEARCH
```

```
to t.search-road
if stage = 2 [ let road-1 distance min-one-of patches with
               [pcolor = green] [distance myself]
               let road-2 distance min-one-of
               exit-patches [distance myself]
               let road nobody
               ifelse road-1 < road-2
                  [ set road min-one-of patches with
                  [pcolor = green] [distance myself] set stage 3]
                  [set road min-one-of exit-patches [distance myself]
                    set goal road
                    set stage 5 ]
               set path Astar patch-here road white 4
;<- default heuristic if you like to use random change 4 to ‘‘heuri’’
             ]
end

;;************************************************************* MOVE

to t.follow-path
if stage = 3 [ ifelse not empty? path
               [ let next first path
                 face next
                 if r.topology?-to-street next
                 [ fd adjust-speed ]
                 if patch-here = next
                 [ set path but-first path ]
               ]
               [ set stage 4 ]
]

if stage = 5 [ ifelse not empty? path
               [ let next first path
                 face next
                 if r.topology?-on-street next
                 [ fd adjust-speed ]
```

```
                 if patch-here = next
                 [ set path but-first path ]
               ]
               [ if patch-here = goal
                   [ if breed = kids [set safe-kids safe-kids + 1]
                     if breed = teens [set safe-teens safe-teens + 1]
                     if breed = adults
                     [set safe-adults safe-adults + 1]
                     if breed = elders
                     [set safe-elders safe-elders + 1]
                     if breed = cars [ set safe-cars safe-cars + 1 ]
                                        adjust-teb-capacity
                                        export-record
                                        die ]
               ]
]
end

;;**************************************************** SHELTER SEARCH

to t.search-shelter-route
  if stage = 4 [ set path [ ]
                 set path Astar patch-here goal green 4
                 set L length path
                 set stage 5
               ]
end

;;*****************************************************************
;;********************************************************* REPORTERS

to-report adjust-speed
let s 0
ifelse breed != cars
[ let pedestrians (turtle-set other kids in-cone ( 5 / scale) 60
  other teens in-cone ( 5 / scale) 60 other adults in-cone
```

```
  ( 5 / scale) 60 other elders in-cone ( 5 / scale) 60)
  let p count pedestrians with [td > [td] of self]
  let a (((3 * pi / 4) * 5 ^ 2) / 2)
  let d p / a
  set s precision ((1 / SQRT(2 * PI * 0.3 ^ 2 )) *
  EXP(-((d - 0) ^ 2)/(2 * 0.3 ^ 2))) 2
  if breed = kids [ set s 0.8 * s ]
  if breed = elders [ set s 0.7 * s ]
  if handicap = true [ set s s * 0.5 ]
]
[ let ahead-cars (turtle-set other cars in-cone ( 10 / scale) 60 )
  let p count ahead-cars with [td <= [td] of self ]
  let a ((pi * 10 ^ 2) / 2)
  let d p / a
  set s precision ((1 / SQRT(2 * PI * 0.047 ^ 2 )) *
  EXP(-((d - 0) ^ 2)/(2 * 0.047 ^ 2)) / 5.0 ) 2
  ;/5.0 because is repeated 5 times every second of computation
]
set s s / scale
report s
end

to-report r.topology?-on-street [next]
ifelse ( breed != cars )
 [ ;let pedestrians (turtle-set other kids-on next
 ;other teens-on next other adults-on next other elders-on next)
 ;not include cars pedestrians in sidewalk
   let pedestrians (turtle-set other kids in-cone ( 5 / scale) 60
   other teens in-cone ( 5 / scale) 60 other adults in-cone
   ( 5 / scale) 60 other elders in-cone ( 5 / scale) 60)
   ifelse next != nobody and count pedestrians with
   [td <= [td] of self and next != patch-here] < Cmax-ped
     [ set color black report true  ]
     [ ;output-print (word self " blocked at " patch-here)
       set color white stamp
       report false ]
```

```
 ]
 [ let ahead-cars (turtle-set other cars in-cone (10 / scale) 60)
   ifelse next != nobody and count ahead-cars with
   [td <= [td] of self and next != patch-here] < Cmax-car
   ;not include pedestrians cars in road
     [ set color magenta report true  ]
     [ ;output-print (word self " blocked at " patch-here)
       set color white stamp
       report false ]
 ]
end

;;****************************************************************

to-report r.topology?-to-street [next]
   let pedestrians (turtle-set other kids in-cone
   ( 5 / scale) 60 other teens in-cone
   ( 5 / scale) 60 other adults in-cone
   ( 5 / scale) 60 other elders in-cone ( 5 / scale) 60)
   ifelse next != nobody and count pedestrians with
   [td <= [td] of self and next != patch-here] < Cmax-ped
     [ set color black report true  ]
     [ ;output-print (word self " blocked at " patch-here)
       set color white stamp
       report false ]
end

;;****************************************************************

to do-snapshots
let dir-temp (word pathdir:get-model "//Output")
set-current-directory dir-temp
let name (word behaviorspace-run-number "K_" ticks ".png")
export-view name
set-current-directory pathdir:get-model
end
```

```
;;***************************************************************

to adjust-teb-capacity
ifelse not member? patch-here exit-patches
[ let new-teb [ ]
  let pos 0
  foreach teb-capacity
  [ if goal = item 0 ?
     [ let cap item 1 ?
       ifelse breed = cars
       [ set cap cap + 4 ]
       [ set cap cap + 1 ]
       set new-teb replace-item 1 ? cap
       set pos position ? teb-capacity
     ]
  ]
  set teb-capacity replace-item pos teb-capacity new-teb
]
[ let new-exit [ ]
  let pos 0
  foreach exit-capacity
  [ if goal = item 0 ?
     [ let cap item 1 ?
       ifelse breed = cars
       [ set cap cap + 4 ]
       [ set cap cap + 1 ]
       set new-exit replace-item 1 ? cap
       set pos position ? exit-capacity
     ]
  ]
  set exit-capacity replace-item pos exit-capacity new-exit
]
end

;;**************************************************************
```

```
to update-text
if scale = 5
[ ask patch 75 -20 [set plabel title]
  ask patch 75 -28 [set plabel clock ]
]
if scale = 2
[ ask patch 75 -20 [set plabel title]
  ask patch 75 -28 [set plabel clock ]
]
end

;;************************************************************

to-report clock
let minutes floor (ticks / (60 ))
let seconds floor
(((ticks / (60 )) - (floor (ticks / (60 )))) * (60))
report (word  minutes " min. " seconds " secs.")
end

;;*************************************************************

to do-plots
set-current-plot "Decision"
if pop-kids > 0
[ set-current-plot-pen "kids"
  plot (decided-kids / pop-kids) * 100
]
if pop-teens > 0
[ set-current-plot-pen "teens"
  plot (decided-teens / pop-teens) * 100
]
if pop-adults > 0
[ set-current-plot-pen "adults"
  plot (decided-adults / pop-adults) * 100
```

```
]
if pop-elders > 0
[ set-current-plot-pen "elders"
  plot (decided-elders / pop-elders) * 100
]
if pop-cars > 0
[ set-current-plot-pen "cars"
  plot (decided-cars / pop-cars) * 100
]

set-current-plot "Safe"
if pop-kids > 0
[ set-current-plot-pen "kids"
  plot (safe-kids / pop-kids) * 100
]
if pop-teens > 0
[ set-current-plot-pen "teens"
  plot (safe-teens / pop-teens) * 100
]
if pop-adults > 0
[ set-current-plot-pen "adults"
  plot (safe-adults / pop-adults) * 100
]
if pop-elders > 0
[ set-current-plot-pen "elders"
  plot (safe-elders / pop-elders) * 100
]
if pop-cars > 0
[ set-current-plot-pen "cars"
  plot (safe-cars / pop-cars) * 100
]

set-current-plot "Casualty"
if pop-kids > 0
[ set-current-plot-pen "kids"
  plot (casualty-kids / pop-kids) * 100
```

```
]
if pop-teens > 0
[ set-current-plot-pen "teens"
  plot (casualty-teens / pop-teens) * 100
]
if pop-adults > 0
[ set-current-plot-pen "adults"
  plot (casualty-adults / pop-adults) * 100
]
if pop-elders > 0
[ set-current-plot-pen "elders"
  plot (casualty-elders / pop-elders) * 100
]
if pop-cars > 0
[ set-current-plot-pen "cars"
  plot (casualty-cars / pop-cars) * 100
]

set-current-plot "TEBs"
set-current-plot-pen "TEB#1"
plot (item 1 item 0 teb-capacity)
set-current-plot-pen "TEB#2"
plot (item 1 item 1 teb-capacity)
set-current-plot-pen "TEB#3"
plot (item 1 item 2 teb-capacity)
set-current-plot-pen "TEB#4"
plot (item 1 item 3 teb-capacity)
set-current-plot-pen "TEB#5"
plot (item 1 item 4 teb-capacity)
set-current-plot-pen "TEB#6"
plot (item 1 item 5 teb-capacity)
set-current-plot-pen "TEB#7"
plot (item 1 item 6 teb-capacity)
set-current-plot-pen "TEB#8"
plot (item 1 item 7 teb-capacity)
set-current-plot-pen "TEB#9"
```

```
plot (item 1 item 8 teb-capacity)
set-current-plot-pen "TEB#10"
plot (item 1 item 9 teb-capacity)
set-current-plot-pen "TEB#11"
plot (item 1 item 10 teb-capacity)
set-current-plot-pen "TEB#12"
plot (item 1 item 11 teb-capacity)
set-current-plot-pen "TEB#13"
plot (item 1 item 12 teb-capacity)
set-current-plot-pen "TEB#14"
plot (item 1 item 13 teb-capacity)
set-current-plot-pen "TEB#15"
plot (item 1 item 14 teb-capacity)
set-current-plot-pen "TEB#16"
plot (item 1 item 15 teb-capacity)
set-current-plot-pen "TEB#17"
plot (item 1 item 16 teb-capacity)
set-current-plot-pen "TEB#18"
plot (item 1 item 17 teb-capacity)
set-current-plot-pen "TEB#19"
plot (item 1 item 18 teb-capacity)
set-current-plot-pen "TEB#20"
plot (item 1 item 19 teb-capacity)
set-current-plot-pen "Exit#1"
plot (item 1 item 0 exit-capacity)
set-current-plot-pen "Exit#2"
plot (item 1 item 1 exit-capacity)
end

;;**************************************************************

to outputs
ask cars [ if [zt] of patch-here > 0.50
[ set casualty-cars casualty-cars + 1
;(Suga, 1995 in Yasuda, 2004)
                                          set color red
```

```
                                          stamp
                                          export-record
                                          die ] ]
let pedestrians (turtle-set kids teens adults elders)
ask pedestrians [ let HZ [zt] of patch-here
                  if HZ >= 0
                  [ ifelse HZ <= 0.85
                    [ let z -12.37 + 22.036 * [zt] of patch-here +
                    11.517 * [vt] of patch-here
                      let fz 1 / ( 1 + exp (15.48 - z) )
                      if fz > 0.50
  [ if breed = kids [ set casualty-kids casualty-kids + 1 ]
    if breed = teens [set casualty-teens casualty-teens + 1]
    if breed = adults [set casualty-adults casualty-adults + 1]
    if breed = elders [set casualty-elders casualty-elders + 1]
                        set color red
                        stamp
                        export-record
                        die
                      ]
                    ]
  [ if breed = kids [ set casualty-kids casualty-kids + 1 ]
    if breed = teens [set casualty-teens casualty-teens + 1]
    if breed = adults [set casualty-adults casualty-adults + 1]
    if breed = elders [set casualty-elders casualty-elders + 1]
                      set color red
                      stamp
                      export-record
                      die
                    ]
                  ]
                ]
end

;;*********************************************************************
```

```
;to output-shelters ;turtle procedure
;  file-close-all
;  let dir-temp word pathdir:get-model "//Output"
;  set-current-directory dir-temp
;  file-open "Shelter-Report01.txt"
;(word "Exit-Report" run-number ".txt")
;  file-print (word who " " e.shelter-pref)
;  file-close
;  set-current-directory pathdir:get-model
;end

to export-record ;turtle procedure
  let dir-temp (word pathdir:get-model "//Output")
  set-current-directory dir-temp
  file-close-all
  file-open
  (word "Evacuation-Record" behaviorspace-run-number ".txt")
  ifelse [color] of self = red
  [ set stage 1 ]
  [ set stage 0 ]
  if path = 0
  [set path [ ]]
  file-print
  (word breed "," who "," [pxcor] of ini "," [pycor] of ini ","
  [pxcor] of goal "," [pycor] of goal "," [pxcor] of patch-here ","
  [pycor] of patch-here "," L "," (L - length path) "," td ","
   precision (ticks / 60) 1 "," [zt] of patch-here "," stage )
                   ;stage=0 safe stage=1 casualty
  file-close
  set-current-directory pathdir:get-model
end

;;*****************************************************************

to tsunami-run
   let dir-temp word pathdir:get-model "//TsunamiDB"
```

```
   set-current-directory dir-temp
   set tsunami-file-name (word "out" tsu-counter ".asc")

   let inundation gis:load-dataset tsunami-file-name
   gis:set-world-envelope-ds (gis:envelope-of inundation)
   gis:apply-raster inundation zt
   ask patches with [zt > 0]
   [ set pcolor scale-color blue zt 20 -20 ]
   display
   no-display
   set tsu-counter tsu-counter + 1 ;because data is at 1min output
   set-current-directory pathdir:get-model
end


to vel-run
   let dir-temp word pathdir:get-model "//TsunamiDB"
   set-current-directory dir-temp

   ;import Veloc in X
   set tsunami-file-name (word "vxr" vel-counter ".asc")
   let velocities gis:load-dataset tsunami-file-name
   gis:set-world-envelope-ds (gis:envelope-of velocities)
   gis:apply-raster velocities vx

   ;import Veloc in Y
   set tsunami-file-name (word "vyr" vel-counter ".asc")
   set velocities gis:load-dataset tsunami-file-name
   gis:set-world-envelope-ds (gis:envelope-of velocities)
   gis:apply-raster velocities vy

   ask patches [ set vt (vx ^ 2 + vy ^ 2 )]
   set vel-counter vel-counter + 1
   set-current-directory pathdir:get-model
end
```

```
to Reports
let dir-temp (word pathdir:get-model "//Output")
set-current-directory dir-temp
file-close-all
file-open (word "Demand-Report.txt")
file-print (word 1 "," (item 1 item 0 teb-capacity))
file-print (word 2 "," (item 1 item 1 teb-capacity))
file-print (word 3 "," (item 1 item 2 teb-capacity))
file-print (word 4 "," (item 1 item 3 teb-capacity))
file-print (word 5 "," (item 1 item 4 teb-capacity))
file-print (word 6 "," (item 1 item 5 teb-capacity))
file-print (word 7 "," (item 1 item 6 teb-capacity))
file-print (word 8 "," (item 1 item 7 teb-capacity))
file-print (word 9 "," (item 1 item 8 teb-capacity))
file-print (word 10 "," (item 1 item 9 teb-capacity))
file-print (word 11 "," (item 1 item 10 teb-capacity))
file-print (word 12 "," (item 1 item 11 teb-capacity))
file-print (word 13 "," (item 1 item 12 teb-capacity))
file-print (word 14 "," (item 1 item 13 teb-capacity))
file-print (word 15 "," (item 1 item 14 teb-capacity))
file-print (word 16 "," (item 1 item 15 teb-capacity))
file-print (word 17 "," (item 1 item 16 teb-capacity))
file-print (word 18 "," (item 1 item 17 teb-capacity))
file-print (word 19 "," (item 1 item 18 teb-capacity))
file-print (word 20 "," (item 1 item 19 teb-capacity))
file-print (word 21 "," (item 1 item 0 exit-capacity))
file-print (word 22 "," (item 1 item 1 exit-capacity))
file-close

file-open (word "Decision-Report.txt")
file-print
(decided-kids + decided-teens + decided-adults +
decided-elders + (decided-cars * 4) )
```

```
file-close

file-open (word "Safe-Report.txt")
file-print
(safe-kids + safe-teens + safe-adults + safe-elders +
(safe-cars * 4))
file-close

file-open (word "Casualty-Report.txt")
file-print
(casualty-kids + casualty-teens + casualty-adults +
casualty-elders + (casualty-cars * 4))
file-close

set-current-directory pathdir:get-model
end

;*************************************************************
;              Rayleigh Distribution calculator
;                     revised by Erick Mas
;                          June 2011
;                     revised July 2012
;*************************************************************
;To call the library write the name and the two parameters
;                      rayleigh t ta
; where, "t" or "x-ray" is the x axis of the distribution
;and "ta" or "s-ray" is the
;mode of distribution and u-ray the mean

to-report cum-rayleigh [ x-ray u-ray]
;calculates the Rayleigh cumulative distribution
  let s-ray u-ray * (sqrt (2 / pi ))
  report 1 - exp ( - ( (x-ray ^ 2) / ( 2 * (s-ray ^ 2) ) ) )
end

to-report random-rayleigh [ x-ray u-ray ]
```

```
  let s-ray u-ray * ( sqrt ( 2 / pi ) )
  report
  ( x-ray / s-ray ^ 2 ) * exp ( - ( x-ray ^ 2) / (2 * (s-ray ^ 2 )))
end

to-report random-td-rayleigh [ f-ray u-ray ]
  let s-ray u-ray * ( sqrt (2 / pi ))
  report ( sqrt ( -2 * s-ray ^ 2 * ln(1 - f-ray) ) )
end

;;*******************************************************************
;; A star searched by patches
;; Developed by E. Mas
;; October 2011
;; modified June 2012
;; revised July 2012
;;*******************************************************************

to-report Astar [ setup-start setup-target setup-color behavior ]
  set start setup-start
  set target setup-target
  set space-color setup-color
  set heuristic list behavior behavior
  ask patches with [open? != 0]
  [ set f 0 set g 0 set h 0 set parent nobody set open? 0]
  ask target [set pcolor space-color]
;1) Begin at the starting point A and
;add it to an open list of squares to be considered.
;The open list is kind of like a shopping list.
;Right now there is just one item on the list,
;but we will have more later.
;It contains squares that might fall along the path you want to take,
;but maybe not. ;
Basically, this is a list of squares that need to be checked out.

  ask start [set open? 1 set parent self]
```

```
while [ [open?] of target != 2 ]
[ if count patches with [open? = 1] = 0 [report []]

;choose the lowest F score square from all those that are
;on the open list.

  let open-agentset patches with [open? = 1]
  ask open-agentset [ fgh-values ]
  let current one-of open-agentset with-min [f]

;4) Drop it from the open list and add it to the closed list

  ask current [set open? 2]; sprout 1
  [ set shape "bot" set color red stamp die ] ]
;  display

;5) Check all of the adjacent squares.
;Ignoring those that are on the closed list or unwalkable
;(terrain with walls, water, or other illegal terrain),
;add squares to the open list
;if they are not on the open list already.
;Make the selected square the parent of the new square

  let walkable [neighbors with [pcolor = space-color]] of current
  ask walkable [ if open? != 2 ;not close
                     [ ifelse open? != 1 ;not open
                       [ set open? 1
                         set parent current
                       ]

;6) If an adjacent square is already on the open list,
;check to see if this path to that square is a better one.
;In other words, check to see if the G score for that square is lower
;if we use the current square to get there. If not, dont do anything.
;On the other hand, if the G cost of the new path is lower,
```

```
;change the parent of the adjacent square to the selected square
;Finally, recalculate both the F and G scores of that square.
;If this seems confusing, you will see it illustrated below.

                 [ let previous-parent parent
                   ifelse path-cost self > new-path-cost current self
                   [ set parent current fgh-values ]
                   [ set parent previous-parent fgh-values ]
                      ]
                   ]
               ]
]
ask target [set pcolor green]
report show-path
end

to-report path-cost [candidate]
let cost 0
let brush candidate
ask brush [ set cost cost + g ]
while [ brush != start ]
[ ask [parent] of brush [ set cost cost + g]
  set brush [parent] of brush
]
report cost
end

to-report new-path-cost [ current candidate ]
ask candidate [set parent current fgh-values]
let cost path-cost candidate
report cost
end

to fgh-values
set g precision distance-nowrap parent 2
set h precision #heuristic 2
```

```
set f path-cost self + h
end

to-report show-path
let brush target
let my-path [ ]
set my-path fput brush my-path
while [ brush != start ]
[ set my-path fput ([parent] of brush) my-path
  set brush [parent] of brush
]
report my-path
end

to-report #heuristic
;  let heuristic [me]

  if first heuristic = -1
  [report 0]

  if first heuristic = 0
  [ report precision distance-nowrap target 2 ]

  if first heuristic = 1
  [ let xdiff abs(pxcor - [pxcor] of  target )
    let ydiff abs(pycor - [pycor] of  target )
    let result ( xdiff + ydiff )
    report result ]

  if first heuristic = 2
  [ let D  1
    let D2 1.414214
    let xdiff abs(pxcor - [pxcor] of target)
    let ydiff abs(pycor - [pycor] of target)
    let h_diagonal min (list xdiff ydiff)
    let h_straight xdiff + ydiff
```

```
    let result D2 * h_diagonal + D * ( h_straight - 2 * h_diagonal )
    report result ]

  if first heuristic = 3
  [ let D  1
    let D2 1.414214
    let xdiff abs(pxcor - [pxcor] of target )
    let ydiff abs(pycor - [pycor] of target )
    let h_diagonal min (list xdiff ydiff)
    let h_straight xdiff + ydiff
    let result D2 * h_diagonal + D * ( h_straight - 2 * h_diagonal )

    ;; tie-breaker: nudge H up by a small amount
    let h-scale (1 + (16 / 8 / world-width * world-height))
    set result result * h-scale
    report result ]

  if first heuristic = 4
  [ let result distance-nowrap target
    let h-scale (1 + (16 / 8 / world-width + world-height))
    set result result * h-scale
    report result ]
end
```

Appendix C

Questionnaire template

One of the advantages of TUNAMI-EVAC1 and the Tsunami Departure Curves method is that it does not required a large questionnaire survey, which becomes annoying for participants and hard in the post process for local stakeholders. Thus, it only requires four questions besides the regular general information of participants:

1. In the case of a near-field tsunami, would you be willing to evacuate?
   - Yes
   - No
2. In the case of a near-field tsunami, where would you evacuate to?
   - Building in the area (Vertical Evacuation)
   - Shelter outside the area (Horizontal Evacuation)
   - No idea. In this case a random selection is possible in TUNAMI-EVAC1.
3. In the case of a near-field tsunami, which mean of transportation would you use to evacuate?
   - On foot
   - Vehicle. If it is necessary to difference type of vehicles, TUNAMI-EVAC1 needs to be slightly modified to add new agent types.
4. In the case of a near-field tsunami, how many minutes would you take to decide and prepare yourself for evacuation? (From the end of the earthquake to the beginning of your evacuation to a safe place)

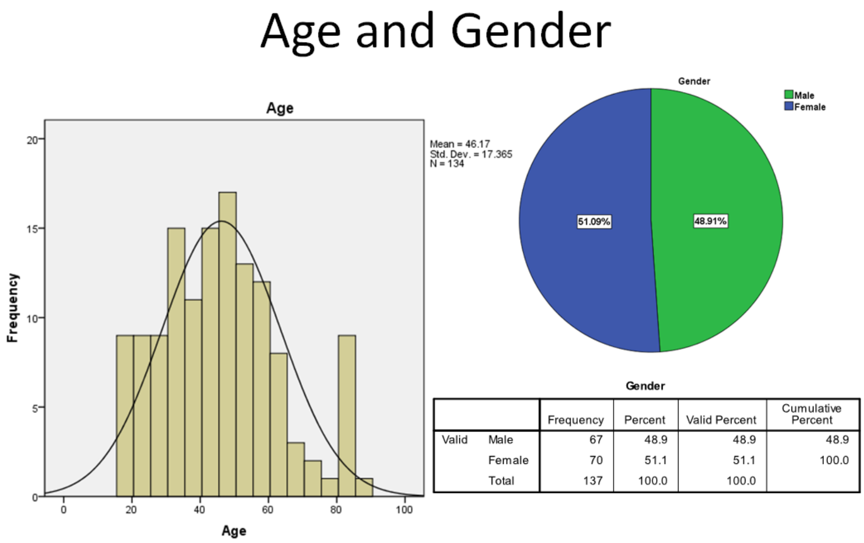
- ..... mins. Also the use of intervals is possible and take the low boundary of interval as the value for the Tsunami Departure Curves calculation.

Appendix D

Results of Questionnaire in La Punta

D.1 Questionnaire survey results 2010

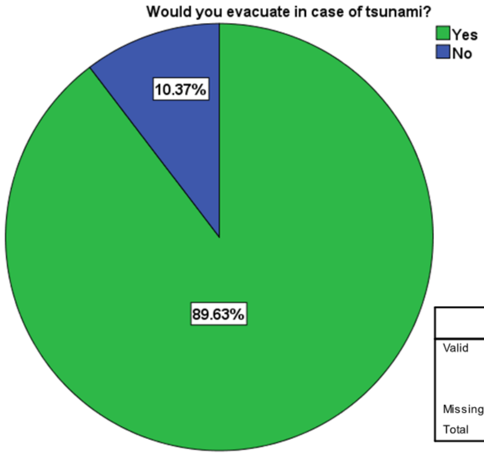
A Tsunami Evacuation Behavior Questionnaire was conducted in La Punta - Callao in September 2010. Results of the survey to 137 participants will be presented here.



		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Male	67	48.9	48.9	48.9
	Female	70	51.1	51.1	100.0
	Total	137	100.0	100.0	

Figure D.1: Age and Gender - Sample over 20 years old with predominant adults and relatively equal number of participants in both genders.

Evacuation decision

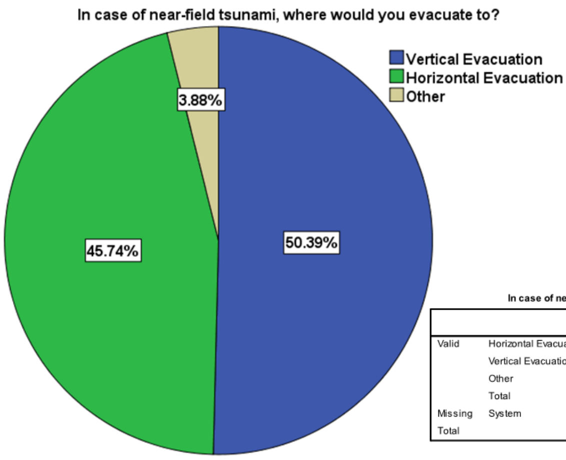


Would you evacuate in case of tsunami?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	121	88.3	89.6	89.6
	No	14	10.2	10.4	100.0
	Total	135	98.5	100.0	
Missing	System	2	1.5		
Total		137	100.0		

Figure D.2: Evacuation decision - The great majority of sample expects to evacuate in the case of a tsunami.

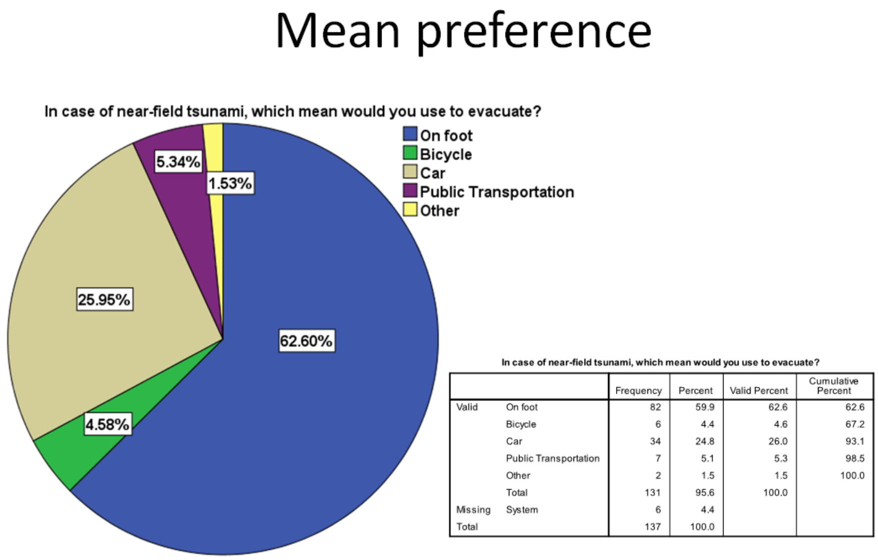
Shelter preference



In case of near-field tsunami, where would you evacuate to?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Horizontal Evacuation	59	43.1	45.7	45.7
	Vertical Evacuation	65	47.4	50.4	96.1
	Other	5	3.6	3.9	100.0
	Total	129	94.2	100.0	
Missing	System	8	5.8		
Total		137	100.0		

Figure D.3: Shelter Preference - A slight preference for the Vertical Evacuation.



In case of near-field tsunami, which mean would you use to evacuate?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	On foot	82	59.9	62.6	62.6
	Bicycle	6	4.4	4.6	67.2
	Car	34	24.8	26.0	93.1
	Public Transportation	7	5.1	5.3	98.5
	Other	2	1.5	1.5	100.0
	Total	131	95.6	100.0	
Missing	System	6	4.4		
Total		137	100.0		

Figure D.4: Mean Preference - Considerably large preference for on foot and car evacuation.

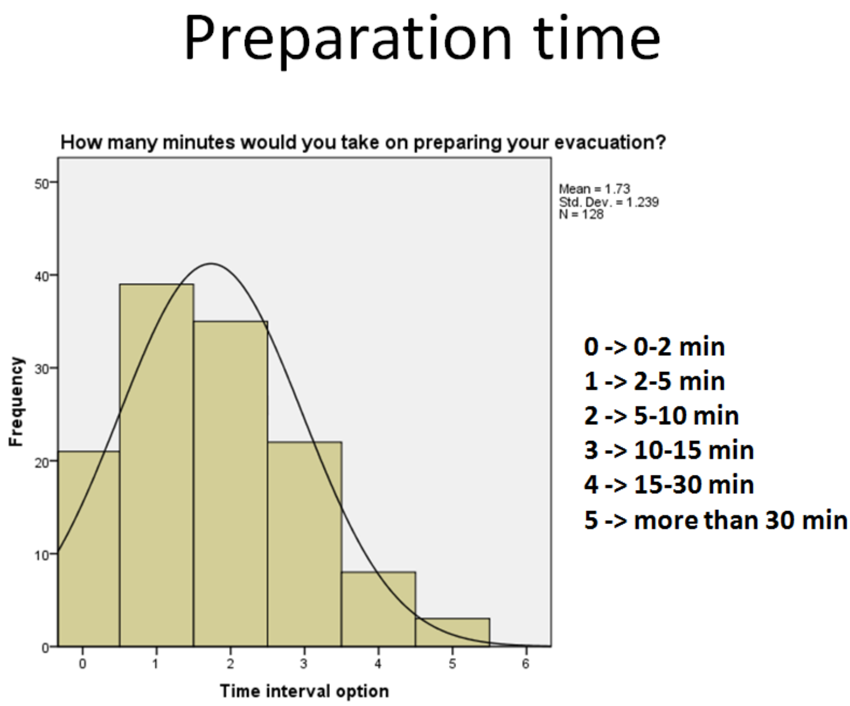
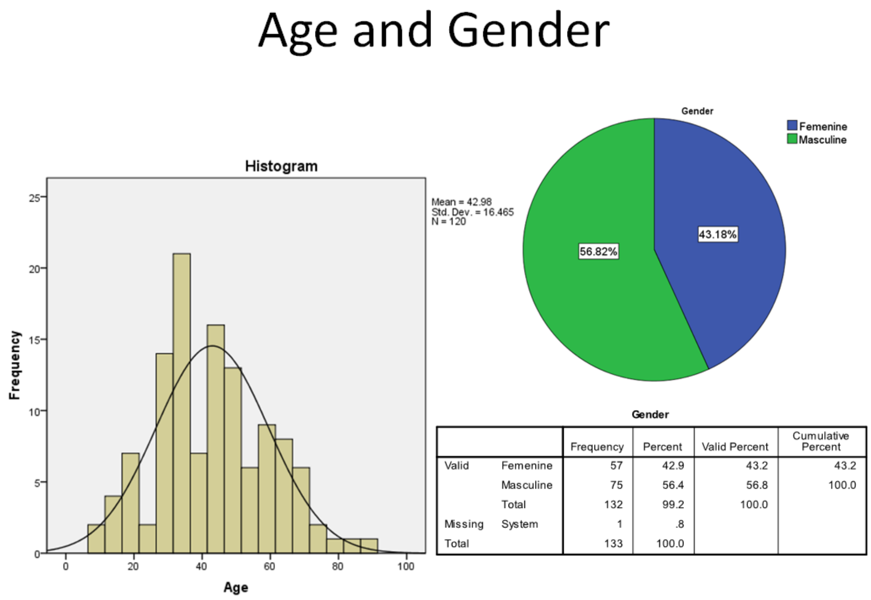


Figure D.5: Start time of evacuation - The majority expects to evacuate within the first 10 min after the earthquake.

D.2 Questionnaire survey results 2011

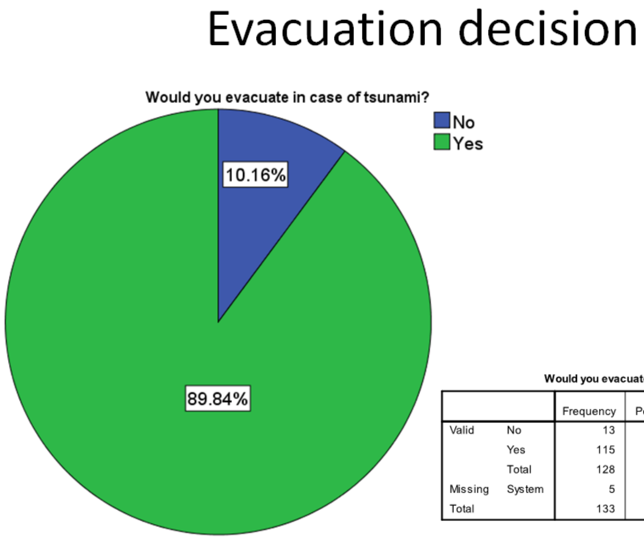
A Tsunami Evacuation Behavior Questionnaire was conducted in La Punta - Callao in September 2011. Results of the survey to 133 participants will be presented here.



Gender

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Femenine	57	42.9	43.2	43.2
	Masculine	75	56.4	56.8	100.0
	Total	132	99.2	100.0	
Missing	System	1	.8		
Total		133	100.0		

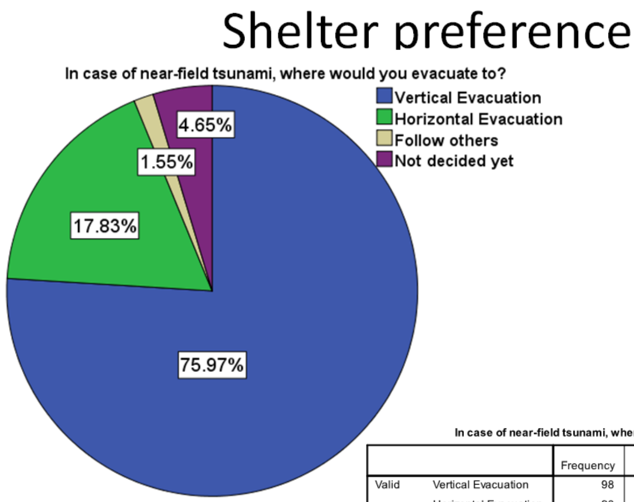
Figure D.6: Age and Gender - Sample is predominant adult with average 42 years old and slightly more number of male participants.



Would you evacuate in case of tsunami?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	13	9.8	10.2	10.2
	Yes	115	86.5	89.8	100.0
	Total	128	96.2	100.0	
Missing	System	5	3.8		
Total		133	100.0		

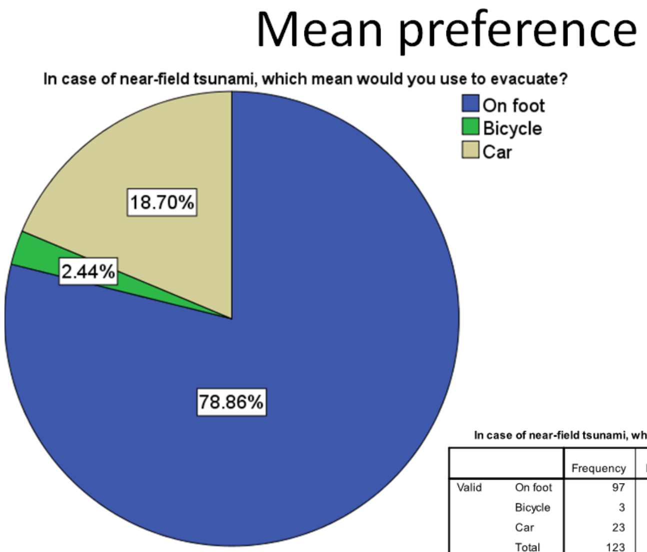
Figure D.7: Evacuation decision - The great majority of sample expects to evacuate in the case of a tsunami.



In case of near-field tsunami, where would you evacuate to?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Vertical Evacuation	98	73.7	76.0	76.0
	Horizontal Evacuation	23	17.3	17.8	93.8
	Follow others	2	1.5	1.6	95.3
	Not decided yet	6	4.5	4.7	100.0
	Total	129	97.0	100.0	
Missing	System	4	3.0		
Total		133	100.0		

Figure D.8: Shelter Preference - A clear preference for the Vertical Evacuation.



In case of near-field tsunami, which mean would you use to evacuate?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	On foot	97	72.9	78.9	78.9
	Bicycle	3	2.3	2.4	81.3
	Car	23	17.3	18.7	100.0
	Total	123	92.5	100.0	
Missing	System	10	7.5		
Total		133	100.0		

Figure D.9: Mean Preference - Considerably large preference for on foot and car evacuation.

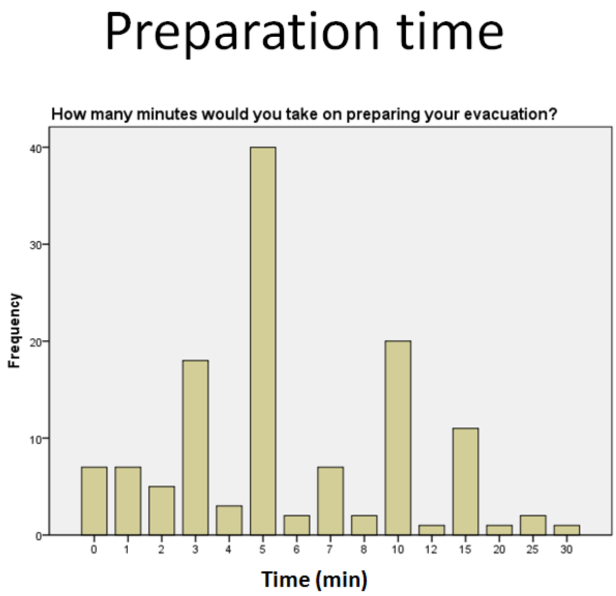


Figure D.10: Start time of evacuation - The majority expects to evacuate within the first 5 min after the earthquake.

Appendix E

Risk Perception Approach for the Start Time Evacuation Decision

A new approach for modeling the start time evacuation decision in the event of a tsunami is presented. The decision model uses the Risk Perception Level (RPL) as the driven variable of human behavior. Risk Perception is assessed through information gathered from experience, environmental conditions, official warning information and social influence as a frequency defined by the time pressure of the event. To develop this framework, Reference Risk, Prospect Reference Theory, Subjective Judgment Matrices and Bayesian Learning were used. For the verification of the model, a questionnaire survey was conducted in La Punta, which is a tsunami-prone district of the Callao Region in Peru. Respondents were asked about their expectations for decision and preparation times in the event of a tsunami, and the answers were compared with the model outputs and with a traditional method of emergency planning. The results from the model showed an improvement over the traditional method in the prediction of an accumulated group of decision times. The capability of the model to perform individual analysis also gives the framework a promising future.

E.1 Risk Perception

Risk Perception is defined as the subjective judgment of a risk (Gierlach et al., 2010). It involves developing an idea of how risky the situation is and then developing feelings of safety or fear. Sociological and anthropological studies have shown that perception and acceptance of risk have their roots in social and cultural factors (Slovic, 1987). Social influence transmitted by friends, family, and neighbors also contributes to response to hazards (Short, 1984).

E.2 Assessment of Risk Perception Stages

In a point of time an individual or agent perceives a related level of risk perception q_K. The assessment of risk perception is divided on these three stages.

E.2.1 Predecision Stage

The Predecision Stage is the nonthreatening scenario or situation in which an individual holds a prior belief of risk (q_0), an idea or perception of how threatening the situation could be if a specific hazard would happen. Such prior belief is known here as the Normal Risk Perception Level (q_0) obtained directly from questionnaires using a Reference Risk approach (Viscusi, 1990), also applied by other researchers in assessing risk perception (Gierlach et al., 2010; Liu and Hsieh, 1995).

E.2.2 Decision-making Stage

The Decision-making Stage refers to all the decision-making processes of an agent and the consequent assessment of a posterior risk perception (q_K). The resulting outcome might be a change of behavior (e.g., evacuate). In this particular stage, along with the change of perceived situations, such as receiving new information or sense modifications in the environment, a new risk perception is triggered. For the assessment of this stage in the model, parameters obtained from questionnaire survey and a learning process of risk through a Bayesian fashion are used and will be explain further.

E.2.3 Action Stage

This stage refers to the moment when the agent cannot stand the current risk level - q_K equal to a certain q_Z,- then, an action (start evacuation) has to be performed. This moment finishes the start evacuation decision model. The value threshold for q_Z is determined using Subjective Judgment Matrices (SJM) from questionnaire surveys.

E.3 Learning process of risk

According to the decision-making stage, a posterior risk perception level q_K has to be mapped; therefore, an agent has to take certain variables from his individual experience and from the state of the world to conceive a posterior risk. Those variables are:

- The prior belief of risk or q_0 level of risk based on a life-time experience.
- The sensed risk from the environment or short-term experience of risk (M).
- The available information of risk through official sources (I) or social sources (S).

To explore the relation of q_K, q_0, M, I and S; a model to describe the learning process on risk taken from economic fields on risk and uncertainties formulated in the literature (Tatano, 1999; Viscusi, 1989) and modified by the authors will be used. It is assumed that individuals regard disaster risk as a random variable $\theta \in < 0, 1 >$ which follows the Beta distribution (Eq. E.1).

$$f(\theta) = B'(\alpha, \beta)\theta^{\alpha-1}(1-\theta)^{\beta-1} \tag{E.1}$$

Where: $f(\theta)$ is the Probability Distribution Function (PDF) of the Beta Function, α and β are parameters of the beta distribution, and $B'(\alpha, \beta)$ is the Inverse of Beta Function The initial perceived risk level or prior belief of risk of disaster is q_0, expressed as follows (Eq. E.2):

$$q_0 = \int_0^1 \theta f(\theta) = \frac{\alpha}{\alpha + \beta} \tag{E.2}$$

The agent can revise his perception of risk by comparing his prior belief with the actual information available from immediate experience (M) or multiple sources (I,S). From the Bayes' theorem, the individual revises his subjective distribution of disaster risk in the following way:

E.3.1 Disaster Risk Learning through short-term experience (M)

With an agent assumed in a grid world -for computational and modeling reasons in NetLogo- the perceived piece of world related to him will be p surrounding cells. As the agent explores the environmental risk in those p surrounding cells, a cell binomial condition s is defined with values of 0 for a nonthreatening space or 1 for a threatening space. Then, the number of successful trials (trials with a value of $s = 1$) is denoted as m in a time point K (Eq. E.3).

$$m_K = \sum_{j=1}^{p} s_j \tag{E.3}$$

Also, for an interval $h : J, K;(\forall h \exists J, K; J < K, h.start = J, h.end = K$, usually $J = 0)$, the short-term experience of successful trials in time point K is an accumulated memory value M_K (Eq. E.4).

$$M_K = \sum_{h=J}^{h=K} m_h \tag{E.4}$$

Finally, with a maximum exploration of p cells, a spatial accuracy factor $\sigma = 1/p$ is defined for the estimation of the perceived spatial memory individual risk Q_M; then at time point K, the distribution of the subjective risk is (Eq. E.5):

$$f_K(\theta|\sigma M) = \frac{f_K(\sigma M|\theta)f(\theta)}{\int_0^1 f_K(\sigma M|\theta)f(\theta)d\theta} = B'(\alpha + \sigma M, \beta + \sigma K p)\theta^{\alpha+\sigma M-1}(1-\theta)^{\beta+\sigma K p-1} \tag{E.5}$$

and the expected value of (Eq. E.5) is (Eq. E.6):

$$Q_M = \int_0^1 f_K(\theta|\sigma M)d\theta = \frac{\alpha + \sigma M}{\alpha + \beta + \sigma K p} = \frac{\gamma q_0 + \sigma M}{\gamma + K} \tag{E.6}$$

where γ is the parameter of the prior belief ($\gamma = \alpha + \beta$).

E.3.2 Disaster Risk Learning from Official and Social Information (I,S)

Following Liu and Hsieh (1995) and Viscusi (1989) in the Bayesian learning framework used previously, the individual's risk perception is reflected by the posterior assessment; that is, the agent will use the new information that he receives to update his prior belief. As stated by Viscusi and Liu, [...] the individual's risk perception is a weighted average of his prior belief, and the new risk information he has received. [...]. In our notation, prior belief is q_0, new information is I or S, and weights are γ and ξ_I or ξ_S. Therefore, Q_I and Q_S are obtained similar to (Eq. E.5) and expressed by (Eq. E.7) and (Eq. E.8).

$$Q_I = \frac{\gamma q_0 + \xi_I I}{\gamma + \xi_I} \tag{E.7}$$

$$Q_S = \frac{\gamma q_0 + \xi_S S}{\gamma + \xi_S} \tag{E.8}$$

The weighted values of prior belief (long-term experience), official information and social information are γ, ξ_I and ξ_S, respectively. Values for these parameters are obtained through questionnaires and the application of Subjective Judgment Matrices (SJM) (Crawford and Williams, 1985). Parameters I and S are also considered binomial information, which could be "evacuate" or "no evacuate". In general, an agent does not revise his environmental risk and receives official information and social information constantly or always at the same time, thus, the values of Q_M, Q_I and Q_S cannot be added or weighted at the same time. At this stage, it is considered that agents hold an intention of evacuation. Therefore, a maximization of the opportunity of evacuation is performed through the election of the maximum last assessed Q in time point K (Eq. E.9).

$$q_K^i = max\{q_0, Q_M, Q_I, Q_S\} \tag{E.9}$$

E.4 Subjective Judgment Matrices

Peters and Slovic (1996) conclude that people respond to hazards according to their perceptions of risk. Slovic (1987) called it intuitive risk judgments; here, risk perception is understood as a subjective judgment about the characteristics and severity of a risk. However, the decision to evacuate, from a risk perception point of view, is based on information pulled together in a relative preference from one to another. This decision can be express as a hierarchical structural problem following an Analytic Hierarchy Process (AHP) (Saaty, 1986). In the AHP, at least three levels of hierarchies are present: the goal, the criteria and the alternatives. Fig. E.1 shows the hierarchy problem for the evacuation decision.

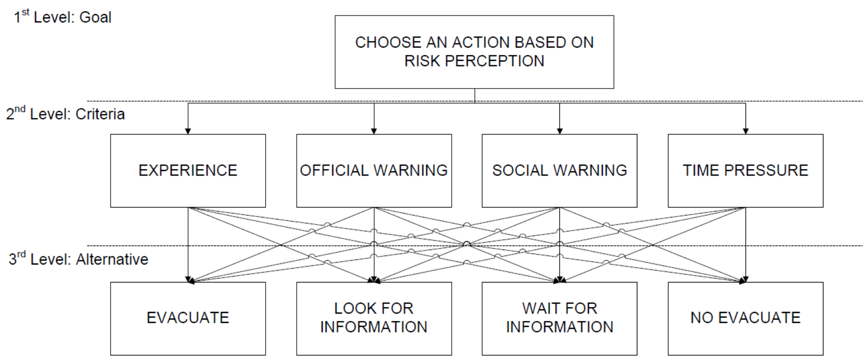


Figure E.1: Analytical Hierarchy Problem - The alternatives and criteria are combined using pairwise comparisons.

The decision problem is to choose an action driven by the risk perception. Choosing an action is based on four main criteria: individual experience, official warning obtained from any source, social warning or social influence obtained through communication, and the time pressure related to the expected time of arrival of the tsunami. These criteria are used to evaluate the following alternatives: to evacuate, to look for information (active behavior), to wait for information (passive behavior) or to not evacuate (normalcy bias). To solve this problem, a series of pairwise comparisons (Saaty, 1977) are performed, and a derived numerical scale of measurement is assigned (a_{ij}). In the decision-making process for an individual, each alternative has an estimate utility u_i. A pairwise comparison is a ratio of u_i/u_j that gives a measure of preference between the i-th alternative over the j-th alternative. Saaty (1977) suggested a procedure to estimate the vector of utilities $u_1, \dots, u_n$ by constructing a matrix of subjective estimates of the ratios of utilities of all possible pairwise comparisons (Eq. E.10). In this case, $a_{ij} = u_i/u_j$ and the diagonal of the matrix should be $a_{ii} = u_i/u_i = 1, i \in [1, 4]$. Additionally, the lower off-diagonal elements are determined by the upper off-diagonal elements, thus $a_{ji} = 1/a_{ij} = a_{ij}^{-1}$. An estimate of the ratio scales is the eigenvector (Saaty, 1977), but in (Crawford and Williams, 1985), it is proven that the Geometric Mean Vector (GMV) ($\bar{v}$) (Eq. E.11) can also be applied. Consequently, in this study, the GMV was used. As Fig. E.1 suggests, objects at each level of the hierarchy depend on the objects of the next lower level; thus, an estimation of the influence of each object in a level on all objects in superior levels can be assess. These influences are recognized as the parameters mentioned previously (γ, ξ_I, ξ_S).

$$\begin{pmatrix} 1 & a_{12} & \dots & a_{1(n-1)} & a_{1n} \\ a_{12}^{-1} & 1 & \dots & a_{2(n-1)} & a_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ a_{1(n-1)}^{-1} & a_{2(n-1)}^{-1} & \dots & 1 & a_{(n-1)n} \\ a_{1n}^{-1} & a_{2n}^{-1} & \dots & a_{(n-1)n}^{-1} & 1 \end{pmatrix} \tag{E.10}$$

$$\bar{v} = \frac{\prod_{j=1}^{n} a_{ij}^{1/n}}{\sum_{i=1}^{n} \prod_{j=1}^{n} a_{ij}^{1/n}} \tag{E.11}$$

Normalized Geometric Mean Vector

where a_{ij} is the pairwise comparison of the element i to the element j; n is the size of the matrix and i and j are the elements for comparison in the hierarchical problem as well as rows and columns in the matrix.

E.5 Model of Start Time of Evacuation

For the agent behavior, a database of input parameters from the questionnaire is given to each agent (q_0, also q_Z, γ, ξ_I, ξ_S and τ from SJM), who will assess his posterior risk on a time frequency proportional to his time pressure τ parameter, using official information Q_I, social information Q_S and spatial risk information Q_M. The posterior perceived risk is determined through the maximization of q_0, Q_I, Q_S

and Q_M, as shown in Eq. E.10. Then, this new posterior risk is compared to the Risk Perception for Evacuation (q_Z) for the condition of an individual evacuation decision. In Fig. E.2, we observe the model flow with a frequent assessment of Q_M by each agent depending on his own time pressure τ. Also, besides the deterministic modeling structure, a situational model is added by the occasional assessment of Q_S and Q_I depending on agent random spatial movement with the possibility of agent-to-agent communication to exchange information, and/or the issuance of new official information. Both conditions automatically trigger the assessment of a new posterior risk q_K. For the model verification, outputs were compared to preparation times for evacuation obtained from the questionnaire; also, a traditional approach (Southworth, 1991; Tweedie et al., 1986) of mobilization curves for the estimation of evacuation times was used to compare model outputs.

E.6 Model verification

E.6.1 Tsunami hazard, risk and exposure in Peru and La Punta

La Punta is part of the Constitutional Province of Callao in central Peru (Fig. E.3) and one of the six districts in the First National Port city of Callao. La Punta is a peninsula in the western part of the province and is almost entirely surrounded by the Pacific Ocean, except on its northeastern side, where it is bordered by downtown Callao. It is one of the smallest districts in Peru, with 4,370 inhabitants (Instituto Nacional de Estadistica e Informatica (INEI), 2007) and a total land area of 0.75 km^2 (Fig. E.3-C). Major risk of earthquakes and tsunamis are present in this area, due to its low topography (max. 3 m) and its geographic characteristics as a peninsula with a wide head on the seaside and a narrow neck to the inland. Evacuation procedures and feasibility are of interest for the safety of La Punta residents and visitors. La Punta was affected by several historical earthquakes and tsunamis (Fig. E.3-A and E.3-B), such as the July 9^{th}, 1586, earthquake of magnitude 8.6 and a local tsunami height of some 5 m (Dorbath et al., 1990), although some reports give a much larger value of 24 m (Berninghausen, 1962; Bourgeois et al., 1999). Another two earthquakes on October 20^{th} and 21^{st}, 1687, of magnitudes 8.0 and 8.4, respectively, struck this area. The first one had generated a 5 m to 10 m local tsunami, while the second might have been located in southern areas (Dorbath et al., 1990). One of the most memorable earthquakes in the Callao region is the great earthquake of October 28^{th}, 1746, with a magnitude 8.0 to 8.6 which completely destroyed some central Peruvian coastal cities. A tsunami of 15 m to 20 m in height resulted from this earthquake, was

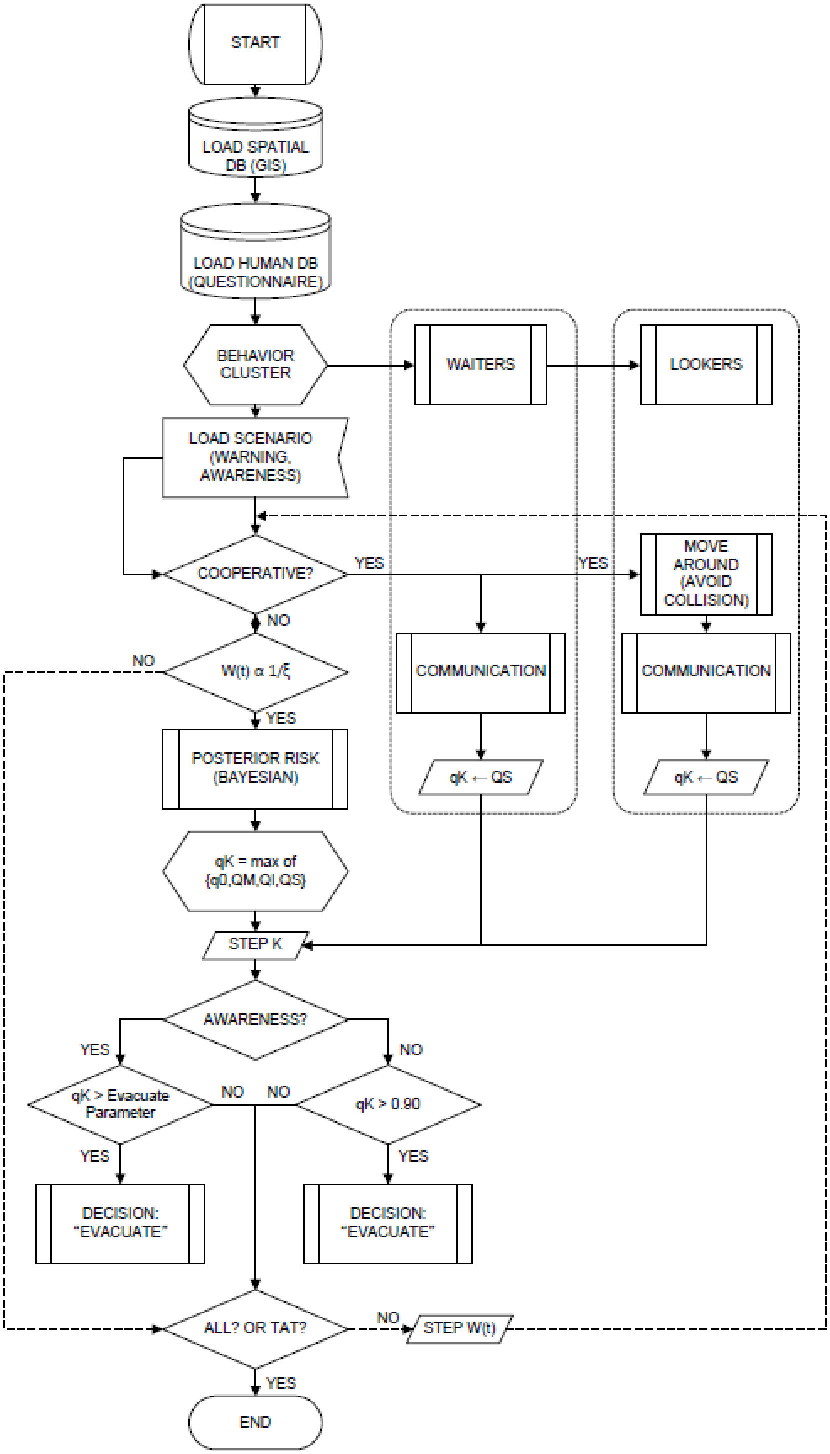


Figure E.2: Model flow - The process of decision for an individual in the model.

reported half an hour after the ground shaking, and washed away Callao city with a 24 m run-up, killing 90% of its population (Kuroiwa Horiuchi, 2004). Two centuries later, the Peruvian central coast experienced more activity on May 24^{th}, 1940, with a local earthquake and tsunami of 3 m in height. The October 3^{rd}, 1974, event in front of Lima had a magnitude of 8.0 and a local tsunami height of 1.6 m (Espinosa et al., 1977; Langer and William, 1995). Since then, no large seismic activity has been reported in front of Callao area. A possible seismic gap might be located in this area, threatening La Punta and other coastal cities with a future large earthquake and tsunami.

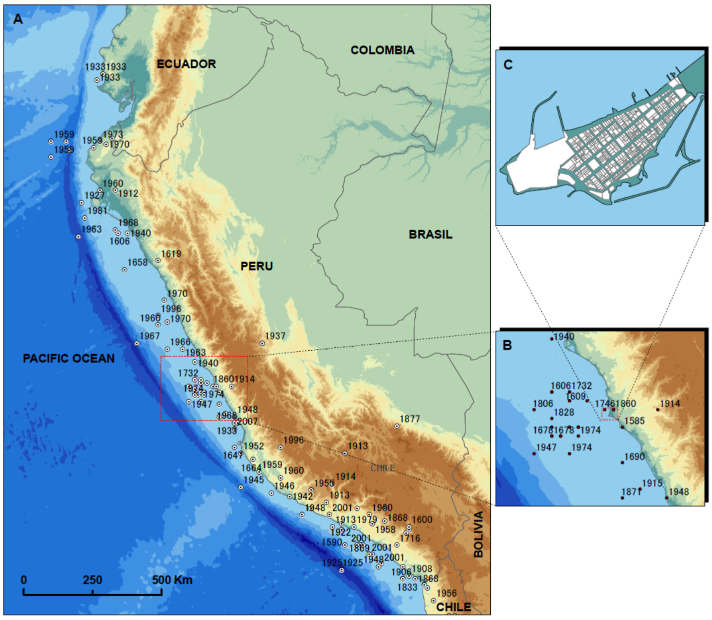


Figure E.3: Peru and La Punta - At risk area of La Punta district in Peru.

E.6.2 Questionnaire survey

A questionnaire survey was conducted to residents and visitors in La Punta to obtain parameters of risk perception (Bird, 2009). The questionnaire addressed three main objectives:

1. to obtain a value of Risk Perception Level in a natural or normal state of affairs (q_0)
2. to estimate the Risk Perception Level for Evacuation Decision (q_Z)
3. to identify the sample's evacuation knowledge, experience and individual perspectives.

The target population were residents and regular visitors. A total of 137 respondents were considered in this study, and 74 individual behaviors were modeled using the proposed framework.

E.7 Results and Discussion

Similar to Viscusi (1989) and Viscusi (1990), participants were asked about their reference risk like this: "Out of 100% of residents in La Punta, how many do you think will survive in a future tsunami?". The answers in Fig. E.4 express the prior belief or Normal Risk Perception (q_0). Moreover, applying the Subjective Judgment Matrix calculation for each individual's pairwise comparison answers, Fig. E.5 is obtained as the Risk Perception Level for Evacuation (q_Z).

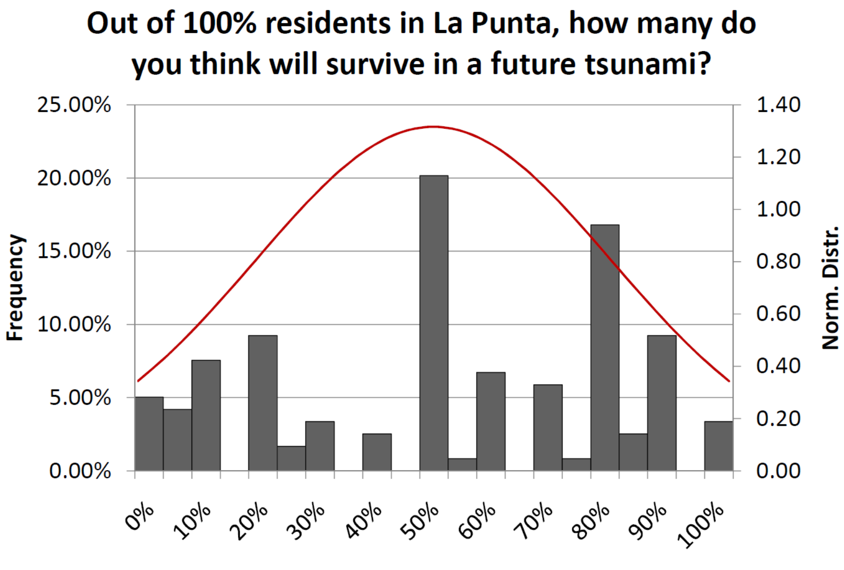


Figure E.4: Normal Risk Perception - Mean = 0.50; Std. Dev = 0.30; N = 119

E.7.1 Questionnaire results

Risk perception in a natural or normal state of affairs, referred as Normal Risk Perception (NRP, q_0), shows a mean of 50% with a standard deviation of 30%; thus individuals can assess their NRP in between $50\% - 30\% = 20\% and 50\%+30\%=80\%$. This is a large dispersion of data, which expresses the individuality of perception of risk. However, when we see the results of the Risk Perception for Evacuation (RPE, q_Z), the mean 91% and standard deviation of 6% suggests a range of decisions between

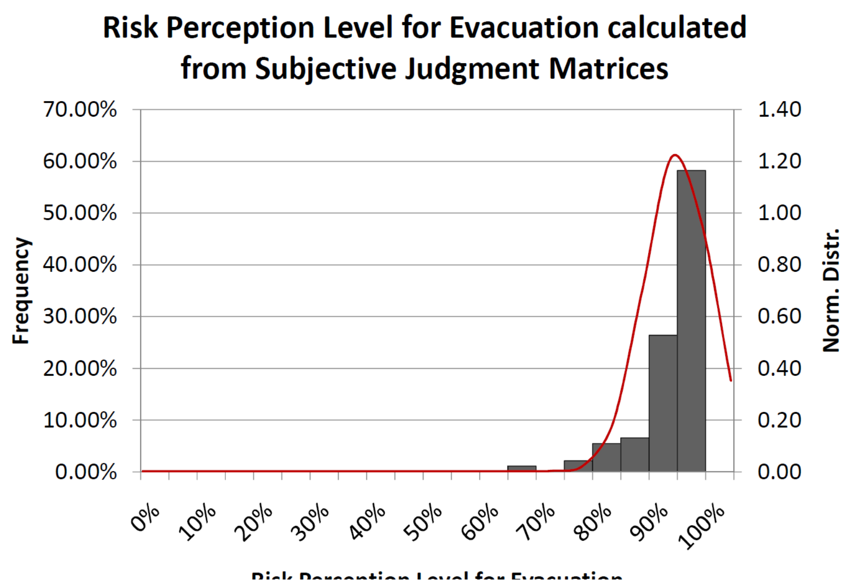


Figure E.5: Risk Perception Level for Evacuation - Mean = 0.91; Std. Dev = 0.06; N = 91.

85% and 97% of RPE level. Therefore, individuals agreed on a level of risk for their evacuation decision. In other words, individual behavior is expressed in the variability of NRP. Also, a common level of preference for evacuation at approximately 90% shows the group agreement on risk level (RPE) for a scenario worthy of evacuation.

E.7.2 Model outputs

To verify the model, calculated individual times for a decision regarding evacuation were compared with respondents who stated intentions of evacuation in the questionnaire. Moreover, a methodology from emergency planning (Southworth, 1991; Tweedie et al., 1986) was used as a benchmark for comparison. Tweedie et al. (1986) used a methodology based on probabilistic mobilization time curves for estimating times required for the partial or total evacuation of an Emergency Planning Zone (EPZ) (Eq. E.12). An EPZ is defined as the area with a population within a 10-mile radius of a hazard point such as a Nuclear Power Plant. An evacuee mobilization time curve is also called a traffic loading curve and is defined as the timing of the evacuee response or traffic departure time. Although tsunamis and nuclear hazards have different characteristics, areas of influence, such as EPZ, are not considered. Since the interest of this research is to look into human decision making regarding evacuation after a warning advisory, the use of this method for comparison is acceptable. The mobilization curve based upon the Rayleigh probability distribution function is of the form:

$$F_t = 1 - \exp^{\left(\frac{-t^2}{T}\right)} \tag{E.12}$$

where F_t is the percentage of the population mobilized by time t and T is a parameter the analyst can adjust to control both the slope of the traffic loading curve and the maximum time at which all evacuees are assumed to have mobilized. As we observed, the shape and value of T are determined using local stakeholders' opinion when a stated intention of evacuation from the population has not been collected. For this study, questionnaire data helped to give the mobilization curve a more realistic shape with the original definition of the Rayleigh distribution, where the parameter $T = 2\sigma^2$ and an estimation of the parameter σ is (Eq. E.13):

$$\hat{\sigma} = \sqrt{\frac{1}{2N}\sum_{i=1}^{N} t_i^2} \tag{E.13}$$

where N is the number of respondents with estimated time t_i. Due to the characteristic of the preparation time options in the questionnaire, time intervals of 0-2 min, 2-5 min, 5-10 min, 10-15 min, 15-30 min, and more than 30 min, we defined three conditions (Fig. E.6). The first condition, a slow evacuation (SE) distribution, uses the upper boundary of the interval and leads to $\sigma = 9.79$. the second condition, a fast evacuation (FE) distribution, is the lower boundary of the interval, with $\sigma = 5.23$. The third condition, $\sigma = 7.49$, represents the average evacuation (AE) using the middle point of the interval.

For comparison purposes, questionnaire data, model output and mobilization curve estimations were set to the worst case scenario, a slow evacuation decision. Therefore, the following mobilization curve used was the upper boundary of the interval (SE). Fig. E.7 shows the perceived time of decision obtained in the questionnaire, model outputs and the mobilization curve of preparation time for evacuation (SE). A Normalized Root Mean Square Error (NRMSE) of 26% for the model and 50% for the traditional distribution, in relation to the questionnaire data, shows an improvement on the predicted method proposed here. The comparison of model outputs with previous traditional methods of start-time decision shows a clear improvement on the consistency with the sample estimated times. Moreover, while mobilization curves give an accumulate estimation of evacuees, our method is based on the individual simulation, and an analysis of individuals is thus possible.

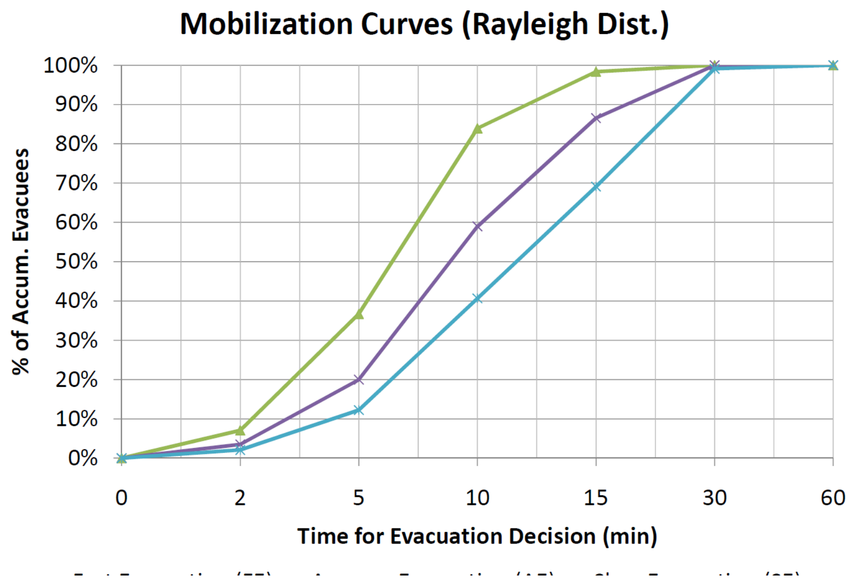


Figure E.6: Mobilization curves - Rayleigh distribution of questionnaire answers based on the mobilization curve method

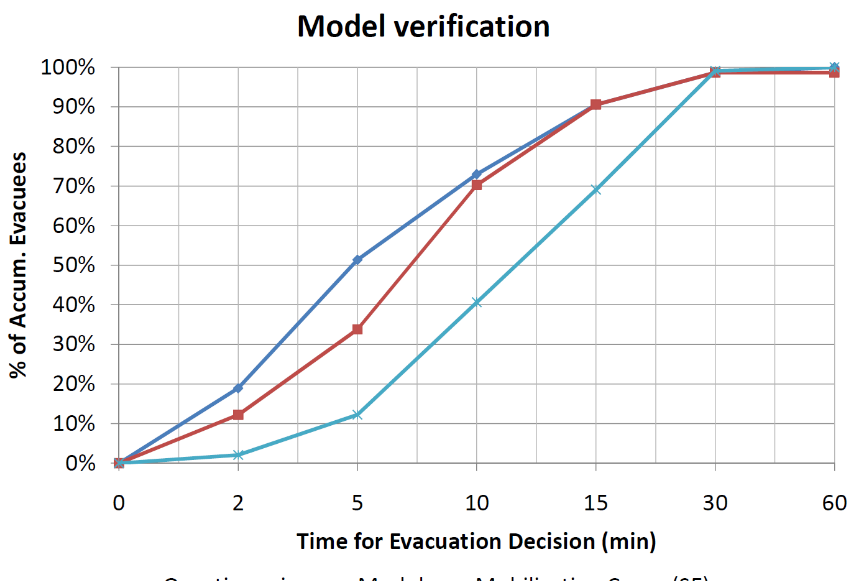


Figure E.7: Model verification - Comparison of questionnaire answers and model prediction of start time decision of evacuation, also the slow evacuation of mobilization curve method. model predictions are closer than the mobilization curve method.

Additionally, a successful Wilcoxon test ($H_0 : \mu_Q = \mu_M, p = 0.178 > \alpha = 0.05$) was performed to confirm the reliability of questionnaire data and model outputs. In contrast to traditional models for the start time of evacuation, which are based directly on information from survey data of past experiences, residents' estimations or expert opinions, where a simple and unique scenario can be simulated; in this study, a mathematically based framework model integrated with survey parameters allows for a different situation of modeling in an individual and cooperative dynamic simulation with an emergent behavior.

E.8 Conclusions

We have proposed a risk perception approach for evaluating human decisions for the start time of evacuation in a tsunami event, integrating decision theory and Bayesian learning. The proposed model considers human behavior based on risk perception components such as experience, warning information, social influence and time stress. Traditional models for Start-Time Evacuation are directly based on survey data of past experiences, residents' estimations or expert opinions. In this study, a mathematical based framework model integrated with survey parameters allows for a different situation of modeling in an individual and cooperative dynamic simulation. Values for risk perception (NRP and RPE) can be obtained from questionnaire data using reference risk and subjective judgments. The present framework of risk perception for start-time evacuation decision has proven to be a better prediction of residents' expected decision time than a traditional Rayleigh distribution. Twenty-six percent NRMSE of the model shows an improvement on precision compared to 50% NRMSE from mobilization curves.

Appendix F

An improvement of the Steiner's A* algorithm in NetLogo

To obtain the latest version of the code, please contact the author at
erick@tsunami2.civil.tohoku.ac.jp