



Recent Advances in Agent-Based Tsunami Evacuation Simulations: Case Studies in Indonesia, Thailand, Japan and Peru

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Abstract—As confirmed by the extreme tsunami events over the last decade (the 2004 Indian Ocean, 2010 Chile and 2011 Japan tsunami events), mitigation measures and effective evacuation planning are needed to reduce disaster risks. Modeling tsunami evacuations is an alternative means to analyze evacuation plans and possible scenarios of evacuees' behaviors. In this paper, practical applications of an agent-based tsunami evacuation model are presented to demonstrate the contributions that agent-based modeling has added to tsunami evacuation simulations and tsunami mitigation efforts. A brief review of previous agent-based evacuation models in the literature is given to highlight recent progress in agent-based methods. Finally, challenges are noted for bridging gaps between geoscience and social science within the agent-based approach for modeling tsunami evacuations.

1. Introduction

The 2004 Indian Ocean tsunami (IOT) was one of the deadliest disasters in recent history due to the extreme tsunami heights combined with insufficient warning, awareness, and early evacuation responses. Since its occurrence, the event has been used as a learning tool. This event likely marked the first time that people watched videos or pictures of a devastating tsunami event. Among those pictures, SYNOLAKIS and BERNARD (2006) noted the surprising images of tourists in Phuket, Thailand, watching the approaching tsunami without taking any protective action. Unfortunately, the Indian Ocean did not have a tsunami warning system at that time, so no warnings could reach the people in the affected areas.

However, would these people have reacted to warning information? This is an important question because tsunami risk involves not only a hazard assessment but also a social component of human behavior because evacuation is the best option for saving lives during a tsunami (SHUTO 2009).

Similarly, the 2011 Great East Japan tsunami (GEJT) was one of the most destructive tsunami events in modern history, although it provided lessons for preparing for future events. The large inundation and tsunami heights (SUPPASRI *et al.* 2012a) destroyed several towns and villages along the Japanese coast. However, the survival rate of the people living in the inundated areas was 96 % (SUPPASRI *et al.* 2012b; FRASER *et al.* 2012).

Fatality rates were lower for the 2011 GEJT event, compared with the 2004 IOT in Indonesia (SUPPASRI *et al.* 2014; MAS *et al.* 2013b), despite the numerous towns struck by larger tsunami heights. What caused these different outcomes? A plausible answer could be that not only structural countermeasures but also rapid dissemination of warning information, disaster education, tsunami awareness, and, in particular, evacuation responses contributed to strongly reducing the casualties in the 2011 GEJT. Both tsunami events confirmed the importance of early evacuation and tsunami awareness and the need to develop much more resilient communities with effective evacuation plans.

Therefore, following these lessons provided by the most destructive tsunami events in recent times, we aim to highlight the importance of tsunami evacuation planning and to present a tool to support such an activity. Four international case studies were chosen to describe practical applications of casualty and bottleneck estimation and analyses of vehicles in evacuation, human behavior and shelter demand, all

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of which contribute to tsunami mitigation and evacuation planning. The use of tsunami evacuation simulations attempts to support reconstruction activities in Japan and efforts to develop resilient communities in at-risk areas in Indonesia, Thailand and Peru.

2. Tsunami Evacuation Modeling

The second part of this section presents a comprehensive summary of agent-based models for tsunami evacuation, although the section does not provide an extensive review of all the various models available. We wish to clarify our motivation for focusing on the agent-based approach instead of other methods. First, what are agent-based models?

Agent-based model (ABM): it is a bottom-up approach in which each agent or individual part of a system is modeled as an autonomous decision-making entity. Each agent follows particular rules according for their role in the system; thus, they are able to execute various behaviors. The interaction of these parts and their behaviors develops into a macro description of the system based on an emergent phenomenon.

ABMs are flexible and capture the emergent phenomena from a natural description of a system such as a community and its individual members. Therefore, an ABM is ideal for simulating disaster emergency evacuations (MUNADI *et al.* 2012) because it provides valuable insight into the mechanisms and behavior that result in jamming or casualties.

There are several other approaches used in tsunami evacuation models that can be found in the literature, e.g., genetic algorithms (PARK *et al.* 2012), Geographic Information System (GIS) (SUGIMOTO *et al.* 2003; CLERVEAUX *et al.* 2008; WOOD and SCHMIDTLEIN 2012; DEWI 2012; FREIRE *et al.* 2012; GONZALEZ-RIANCHO *et al.* 2013) distinct or discrete element methods (DEMs) (ABUSTAN *et al.* 2012), and system dynamic approaches (SIMONOVIC and AHMAD 2005; KIETPAWPAN 2008). However, GIS approaches are traditionally top-down methods that use aggregate descriptions of a system. In evacuation, the complexity and diversity of behaviors that are interrelated produce dynamic changes that GIS models are not

well suited to tracking (CASTLE and CROOKS 2006) unless they incorporate micro-scale components provided by ABMs (JOHNSTON 2013). Similarly, system dynamic approaches might be able to track system changes throughout a simulation; however, they lack spatial complexity and require many assumptions about the system if applied to simulating evacuation procedures. In addition, DEMs apply physical laws, such as fluid dynamics, to the evacuees. Such a representation may provide a good description of large crowd behavior during an evacuation (HELBING *et al.* 2005); however, not all phenomena follow Newtonian motion because psychological forces or sudden changes in motion are likely to occur.

In summary, we choose to focus on ABM due to its benefits over other model techniques for capturing emergent phenomena and providing a natural description of a system. ABM is also flexible for scaling, tuning agent complexity and behavior, and has the capability to use modern data with a higher level of detail.

2.1. Agent-Based Tsunami Evacuation Modeling

One of the first tsunami evacuation models published (USUZAWA *et al.* 1997) can be found in the Japanese literature. The model simulates the evacuation of Aonae on Okushiri Island, which was affected by the 1993 Hokkaido earthquake. In this initial model, a network modeling approach, which is commonly used to simulate evacuations from hurricanes, floods, nuclear disasters and fires in buildings (WATTS 1987), was used as the modeling method. Following the research of USUZAWA *et al.* (1997), IMAMURA *et al.* (2001) described another network model for the same area, but this study included a different start time for each agent in the evacuation and control parameters to distinguish pedestrians from vehicles in the calculation. The computational method uses sequential programming, so all of the evacuees move at the same time and decisions are scheduled only at intersections or the nodes of the network. In addition, in this model, agents jump from node to node in the step that corresponds to the relationship between their speed and road length, limiting the analysis of crowding or the dynamics of pedestrians during the simulation. Later, FUJIOKA

et al. (2002) proposed a much more complex representation of evacuees by formally introducing multi-agent systems to tsunami evacuation simulations. The model represented evacuees and guides as agents with different objectives and communication capabilities. This study was one of the most advanced representations of human behavior in the tsunami evacuation field at the time. Although the model uses a combination of network- and grid-based roads, the agent collision avoidance dynamics were limited because the speed was fixed for all of the agents throughout the simulation. In addition, the model returned to the total compliance approach for the evacuation start time, which is less realistic than the different timing approach used by IMAMURA *et al.* (2001). SAITO and KAGAMI (2004) presented an agent-based model similar to the model of IMAMURA *et al.* (2001); they modeled the movement of agents using results from a questionnaire about residents' preferences for the start time of evacuations. However, preference surveys alone are not sufficient to describe evacuees' behavior because post-event surveys have demonstrated that actual behavior may differ from the expected behavior. The importance of human behavior in tsunami evacuation simulations gained the attention of researchers in the field (SUZUKI and IMAMURA 2005). Nonetheless, from the point of view of pedestrian dynamics, tsunami evacuation models lacked a clear approach for path finding because the main rule given to agents was to proceed to the next highest node in the network instead of searching for the shortest path or a specific goal. The model developed by KATADA *et al.* (2004) incorporated a routing method to find the shortest path in the network. Moreover, while previous studies tried to answer specific research questions, Katada's model moved tsunami evacuation simulations from scientific research to practical applications for tsunami mitigation, particularly for disaster education and outreach. The Tsunami Scenario Simulator (KATADA *et al.* 2000) was developed as a GIS model to investigate information dissemination during disasters; it was later modified (KATADA and KUWASAWA 2006) into the Tsunami Dynamic Hazard Map for disaster education purposes. This tool allowed citizens to dynamically observe the consequences of many of their potential evacuation decisions. Since

this modification, the literature on tsunami evacuation models using agent-based techniques has increased considerably (MEGURO and ODA 2005; NOZAWA *et al.* 2006; WATANABE and KONDO 2009; GOTO *et al.* 2012).

Increases in computational power have enabled the analysis of large amounts of data and have made it possible to shift the modeling approach from network-based (IMAMURA *et al.* 2001; LÄMMEL *et al.* 2010) to grid-based (MAS *et al.* 2012), potential fields (MEGURO and ODA 2005), or hybrid modeling approaches to improve realism in pedestrian dynamics and collision avoidance behaviors (FUJIOKA *et al.* 2002; KATO *et al.* 2009; NGUYEN *et al.* 2012a). Gradually, the research methodology has moved toward using much more data with finer levels of detail through agent-based modeling and high-performance computing (WIJERATHNE *et al.* 2013). In addition, the importance of human behavior in evacuations is increasingly being considered in models (SUZUKI and IMAMURA 2005; MAS *et al.* 2012; FUJIOKA *et al.* 2002). Following the 2004 IOT and 2011 GEJT, tsunami evacuation modelers have focused on providing practical applications of simulations to solve the particular problems that were observed in these events, such as evacuation timing, bottlenecks and traffic congestion from vehicle evacuations, shelter locations, evacuee behavior, and risk communication, among other factors. In addition, reconstruction in tsunami-affected areas requires new evacuation plans that follow new urban layouts. Effective evacuation plans to be executed under new urban spatial conditions can initially be analyzed and evaluated using evacuation models. In the next section, we describe applications of an ABM tsunami evacuation model that integrate tsunami inundation features and human behavior during evacuations.

3. Case Studies of the Practical Applications of Tsunami Evacuation Simulations

The simulation of tsunami evacuations is becoming important to investigate potential responses to warnings, estimate potential casualties, evaluate evacuation plans and explore options for tsunami mitigation. These experiments are guiding the

development of more effective educational and mitigation programs in many countries (BERNARD *et al.* 2006). Here, we demonstrate several examples of case studies of ABM tsunami evacuation modeling applied to verify, analyze and evaluate actual or predicted tsunami scenarios for evacuations. A large body of literature on agent-based tsunami evacuation models is available for several areas (WIJERATHNE *et al.* 2013; GOTO *et al.* 2012; NGUYEN *et al.* 2012b; ABUSTAN *et al.* 2012; LÄMMEL *et al.* 2010; MEGURO and ODA 2005; KATADA *et al.* 2004); however, for brevity and consistency, we will introduce case studies and mitigation-related results from one agent-based model.

3.1. Casualty and Bottleneck Estimation: Cases of Arahama, Japan and Padang, Indonesia

The agent-based model described in this paper incorporates tsunami inundation modeling outputs and pedestrian and vehicle agent simulation (MAS *et al.* 2012). The model was verified using the 2011 GEJT data from the evacuation in Arahama, Sendai, Japan (Fig. 1).

One thousand iterations of a stochastic simulation were conducted; each simulation provided the number of evacuees at a shelter, the number of evacuees who passed one of the exits (“safe”) and the number

of evacuees trapped by the tsunami (the probability of becoming a casualty exceeded 50 %) (Fig. 2). This information at such a high level of detail is one of the greatest advantages of agent-based modeling. In addition to emergent behavior, the behavioral details of each agent and local issues (e.g., traffic and crowd congestion due to the number of agents or the presence of slow-speed agents in front of fast agents) can be identified. The exact values from a real situation are difficult to obtain with stochastic simulations; however, the average number of estimated survivors at the tsunami evacuation building (TEB) showed that the model realistically represents some evacuation decisions and outcomes in the area.

Previous models that did not employ an agent-based approach have also been able to provide casualty estimations and sometimes identify bottleneck areas; however, because those methods (i.e., GIS and DEM) are static or aggregated, information on possible timing and details of interactions, e.g., vehicle–pedestrian interactions, cannot be determined.

The tsunami evacuation simulation demonstrated the capability of the model to identify bottlenecks and to verify the evacuation process with several behavioral conditions within a dynamic framework. The stochastic simulation and the individual level of representation in the model provide the modeler with a reasonable amount of data to analyze and identify



Figure 1

Google Earth images of the Arahama area before (April 4, 2010) and after (March 14, 2011) the tsunami. The yellow circle shows the location of Arahama Elementary School



Figure 2

Left A snapshot of the model applied to the Arahama evacuation when the tsunami inundates the study area. The *black dots* are active pedestrian evacuees; the *purple dots* are the evacuees in vehicles, and the *red dots* are fatalities caused by the tsunami. Right The last snapshot of the simulation shows bottleneck areas during the evacuation as *white dots*. These bottlenecks mainly occurred on the bridge and in front of Arahama Elementary School, which is the evacuation building

issues at both large and small scales, where agent behavior might not contribute to the safe evacuation of other individuals. For example, agents that are slow to begin evacuating increase their own risk of fatality and reduce the flow of evacuation in the network by creating bottlenecks, especially when their speed is also comparatively low.

In addition to verification of past events, ABM models can be used to assess hypothetical events such as a large tsunami affecting Padang City, Indonesia. IMAMURA *et al.* (2012) described the tsunami hazard in this area based on a mega-thrust earthquake scenario for tsunami simulation using high-resolution bathymetry and topography data. The resulting inundated area was approximately 25 km², threatening at least 235,000 people with tsunami depths from 3 m to approximately 8 m (MUHARI *et al.* 2011). Padang city lacks vertical evacuation facilities within the predicted inundation area and based on reports from tsunami evacuations during the 2007, 2009 and 2010 events (HOPPE and MARHADIKO 2009), residents mainly use vehicles and motorcycles for evacuation, despite the experiences of traffic congestion. Consequently, estimating the time needed by evacuees to leave the tsunami inundation area and determining possible congested routes during evacuation are necessary.

A total of 104,352 agents were modeled in a 15 km² area in southern Padang using agent-based modeling (MAS *et al.* 2012). Based on the size of the modeled population and the evacuation behavior that considers individual departure times, the model calculated casualty estimates, the time needed for evacuation, and bottleneck points (Fig. 3). In the simulation, the tsunami resulted in the fatalities of approximately 37.7 % of the population. The authors identified several congested streets in the northern study area due to the popular use of the exit points. In addition, the shopping center and traditional market center areas were highly congested due to the high local population density. In the south of the evacuation simulation domain, the agents evacuated to high ground by crossing the river; however, based on the tsunami simulation results, those areas are expected to be inundated due to overtopped river embankments.

The application of the tsunami evacuation simulation in these case studies clarifies the importance of evacuation start times, which cannot be explored with aggregated modeling approaches, the need for high evacuation areas, and the sensitivity of streets to congestion in highly populated urban cities, such as Padang. The same area was evaluated as a case study by LÄMMEL *et al.* (2010) a multi-agent traffic

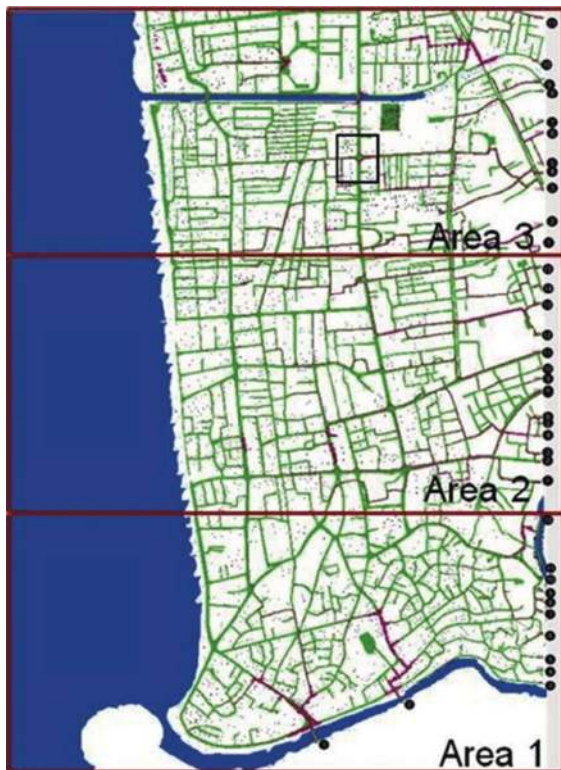


Figure 3

Simulation of evacuation areas, with the bottleneck results shown in purple. Details of other results are reported by IMAMURA *et al.* (2012)

simulator (MATSim) to represent pedestrian agents instead of vehicles. While the approach used in the MATSim simulation differs from the model presented here, similar results were obtained. The models exhibited similar results because the agent behavior in path-finding or route-planning for evacuation was primarily set to use the shortest path. LÄMMEL *et al.* (2010) noted that a risk-cost function should be added to the route-planning algorithm in MATSim; similarly, in our model, a risk-cost value for the cells near the tsunami flooding areas might be included. However, before such modifications, it is necessary to investigate the residents' preferences in an evacuation to adequately represent the evacuees. It is possible that some people prefer short routes with earlier starting times, while others prefer longer routes with lower risk. It is recommended to pursue an early starting time and low-risk routes during tsunami evacuations. Padang city is a highly populated area with narrow streets that contribute to

immediate crowding. These characteristics make this scenario suitable for modeling using the agent-based approach. However, areas with wide roads, where crowding might not be expected, may use other approaches, such as the least-cost distance (LCD) in GIS (WOOD and SCHMIDTLEIN 2012), to obtain evacuation timings. In summary, correctly applying tsunami evacuation models depends on the purpose of the simulation and the assumed agent behavior.

3.2. Vehicles in Evacuation: Case of Pakarang Cape, Thailand

Another concern for evacuation planning is the use of vehicles during evacuation. This option must be evaluated according to the characteristics of the environment and the population involved in the evacuation. MAS *et al.* (2013b) conducted an evacuation simulation for the Pakarang Cape in Thailand, located in the Khao Lak beach resort area of Phang Nga Province on the Andaman Sea, an area devastated by the 2004 IOT (Fig. 4).

A total of 2649 residents were modeled based on a nighttime population scenario. The objective in this case study was to explore the influence of vehicles on the evacuation, combined with different reaction times from the residents. A set of percentages of evacuees in vehicles (passengers and drivers) was assumed for developing several scenarios for the simulation. The evacuation rate as a function of time followed the results of a questionnaire survey (SUPPASRI 2010). In addition to this distribution, three other scenarios were considered: a late evacuation and two intermediate scenarios between the former two distributions. The results of the 20 simulated cases are shown in Fig. 5. Due to differences in reaction time and the long evacuation distance, the use or non-use of vehicles was found to contribute to fatality rates, which ranged from 6 to 34 % of the total population at risk.

The application of the tsunami evacuation simulation in this case study showed the capability of ABM to evaluate the feasibility of evacuations and on-road vehicle-pedestrian interactions. In this case, 20 scenarios with different evacuation starting times and percentages of vehicles used in the evacuation were compared. The results suggest that because of



Figure 4

Phang Nga devastation from the 2004 Indian Ocean tsunami. *Left* January 13, 2003. *Right* December 29, 2004. Source: Space Imaging/CRISP-Singapore. The *yellow inset* shows the simulated area

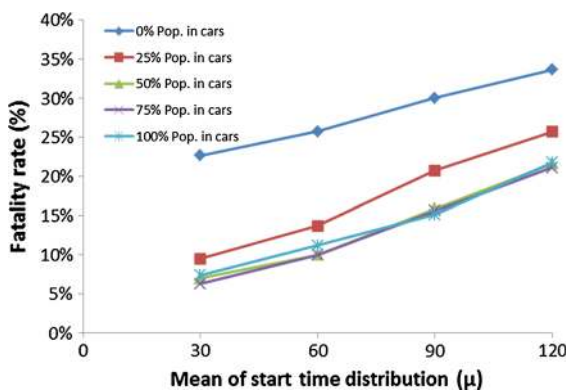


Figure 5

Fatality ratios for different evacuation timing scenarios and the percentages of the population using vehicles. Note the advantage of a fast evacuation decision and the advantage of using cars in this specific case

the distance to the shelters, vehicle evacuation might be necessary. It is possible that the use of vehicles in this area might not result in significant traffic congestion due to the small population and sufficient road capacity. Note that with a larger population than evaluated here, traffic congestion is possible, as shown in the Arahama case study. This suggests that

conclusions from tsunami evacuation simulations in one area should not be arbitrarily applied to another area, particularly with regard to restrictions on vehicles for evacuation.

3.3. Evacuation Behavior: Case of Natori, Japan

This is the second application of a tsunami evacuation model to the 2011 GEJT (Fig. 6). TAKAGI *et al.* (2014) simulated the evacuation behavior reported in Yuriage, Natori, to replicate the evacuation process and investigate the reasons for the large number of fatalities in the area. Yuriage is a small town near the Natori River located on the plains of the Miyagi Prefecture. Before the earthquake on March 11, 2011, approximately 5612 residents were living in the area. After the earthquake, 752 people were killed by the resulting tsunami, and 41 are still missing; this event resulted in one of the highest fatality rates in the plains area of Miyagi.

Reports indicate that the residents in the area evacuated to nearby shelters; however, before the tsunami arrived, the tsunami warning was elevated to reflect a larger estimated tsunami height (JMA 2013).



Figure 6

Left The study area of Yuriage in Natori, Miyagi Prefecture, Japan. From *right to left* (landwards): the *green signs* indicate the locations of the Yuriage Community Center, Yuriage Junior High School, pedestrian bridge (not official) and Yuriage Elementary School, respectively. The *green arrows* are the exit routes for vehicle evacuations. *Right* A snapshot of the model applied in Yuriage, Natori. The study area is inundated by the tsunami based on the numerical simulation results. The *black dots* are the active pedestrian evacuees; the *purple dots* are evacuees in vehicles; the *red dots* are fatalities due to the tsunami; and the *yellow dots* show the bottleneck points in the simulation

Therefore, over the next few minutes, some of the evacuees decided to conduct a secondary evacuation to a more inland shelter. Evacuees in the community center, which is a 2-story building, moved to Yuriage Junior High School, which is a 3-story building located approximately 500 m inland (Fig. 6). During this second evacuation, the arrival of the tsunami (MUHARI *et al.* 2012) resulted in pedestrian fatalities. In this case study, the model was applied to two scenarios: (1) Case A, a scenario as close as possible to the real evacuation based on the data reported by local authorities and survivors and (2) Case B, a what-if scenario in which the second evacuation was not performed. The actual reported number of fatalities during the event and the results from the simulation are shown in Table 1 and Fig. 7. From the survey reports, the community center safely sheltered 43 residents (MURAKAMI *et al.* 2012).

Figure 7 shows the evacuation sequence at each shelter in Case A; note that the community center was filled to its capacity—300 people (Table 1)—

approximately 25 min after the earthquake (~15:10 JST). At 15:14 JST, the Japan Meteorological Agency (JMA) issued its first tsunami warning upgrade for the Miyagi coast from 6 m to over 10 m (JMA 2013), which might explain why some people decided to relocate to a more inland shelter; the community center is only a two-story building (KAHOKU SHIMPO 2011), while Yuriage Junior High School is a three-floor building. In addition, information on the damage to the areas in the north where tsunami waves had already struck might also have contributed to their decision. Based on the information provided by survivors, evacuees started moving from the community center to Yuriage Junior High School at approximately 15:30 JST, which agrees with the second tsunami warning information issued by JMA (2013). Therefore, by setting 15:30 JST as the time for the second evacuation in the model, the results showed that a total of 257 evacuees were able to leave the community center before the tsunami arrived. Of the 257 people, only 82 were able to reach

Table 1

Shelter capacity near Yuriage, the outcome of the 2011 tsunami and the results from Case A and Case B

Shelter	Capacity	2011 GEJT	Case A	Case B	B – A
Community center	300	43 ^a	43	300	+257
Yuriage Junior High School	2000	~ 1000 ^b	1050	1067	+17
Yuriage Elementary School	2300	~ 870 ^b	699	759	+60
Fatalities	–	752 ^b	774	436	–338

The last column shows the reduction in the fatalities when no secondary evacuation behavior was exhibited

^a MURAKAMI *et al.* (2012)

^b Natori city in TAKAGI *et al.* (2014)

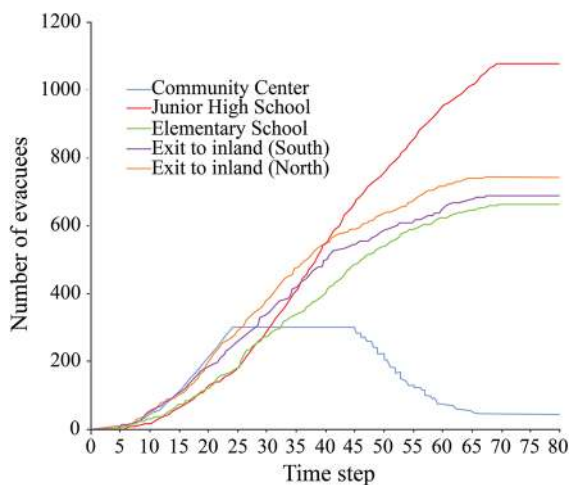


Figure 7

The simulated timeline of the evacuees in the shelters. Note the arrival at the community center (*blue line*). Approximately 25 min was necessary to fill the shelter to its full capacity; no additional evacuees arrived or left until 45 min after the event. Over the next 20 min, people relocated to the junior high school (*red line*), and the tsunami's arrival resulted in the deaths of evacuees en route

the junior high school in time. The reasons for the fatalities and for the evacuees reaching the high school or not are further explored in the simulations. We summarize some of the reasons as follows. (1) The timing of the secondary evacuation: each evacuee conducted a second evacuation between 15:30 JST and approximately 15:50 JST, when the tsunami arrived at the community center. During this 20-min period, the first people to evacuate might have arrived on time, depending on their means of transportation. (2) The means of transportation: based on the survivor accounts and the simulation results, traffic was congested on the road in front of the community center, and people who attempted to evacuate by car

might have been delayed because of this situation. However, in Case B, in which agents did not conduct a secondary evacuation and remained at the community center, the total number of fatalities was approximately 44 % less than in Case A, provided that the community center was filled to its capacity.

This case study shows the advantage of agent-based models. Unlike aggregate and static approaches, modeling low-level component behavior and event scheduling is possible in agent-based models. The immense amount of available data related to the GEJT makes it possible to utilize agent-based approaches to examine an evacuation process defined by more than the sum of its parts instead of a global picture with several assumptions. In addition, agent-based models are powerful tools that can be applied to verify and analyze the effects of evacuees' decisions on the outcomes of the evacuation process. Future evacuation plans and activities for the reconstruction process and urban planning can be supported by the results from tsunami evacuation agent-based models. For example, in the Natori area, a new urban layout has been proposed in which new structural countermeasures and resident relocations would be considered. With a more efficient population distribution, improved road networks, shelter availability, and shorter distances to high ground, a lower tsunami risk is expected. However, a tsunami warning can still trigger a massive evacuation in this area, and the characteristics of such a potential evacuation need to be investigated to avoid accidents or fatalities. Plans for a layout suitable for tsunami protection and a massive evacuation can be explored using agent-based tsunami evacuation simulations.

3.4. Shelter Demand: Case of La Punta, Peru

La Punta is a peninsula in the western part of Callao Province. The area is entirely surrounded by the Pacific Ocean, except on its northeastern side where it is bordered by downtown Callao. This district is one of the smallest in Peru, with 4370 inhabitants and a total land area of 0.75 km². Historically, earthquakes and tsunamis have struck the area of La Punta in 1586, 1687 and 1746. More than 250 years of seismic inactivity in this region suggests the seismic gap is large enough to trigger earthquakes with an 8.9 magnitude (PULIDO *et al.* 2013) (Fig. 8).

Tsunami mitigation and preparedness activities have been conducted in La Punta; however, difficulties in conducting frequent evacuation drills with wide population participation suggested it was prudent to apply tsunami evacuation simulations to evaluate the actual conditions of the shelters and the evacuation timing in the area. According to local

authorities, 20 official TEBs exist, with enough space to accommodate the entire population (Fig. 9). The authors used the agent-based tsunami evacuation model (MAS *et al.* 2013a) to investigate a tsunami inundation and the resident evacuation behavior.

A detailed description of the assumptions and constraints for each simulated case can be found in MAS *et al.* (2013a). In addition to the casualty estimate, more detailed and interesting information is found for the TEBs regarding their capacities and the numbers of evacuees that arrived. At 13 of the 20 evacuation buildings, demand exceeded the available capacity; at the other seven buildings, capacity exceeded the demand, and available space remained. As a consequence, for a total of 4370 residents and buildings with a total capacity for 7930 people, the spatial characteristics of each shelter location produced an imbalance in the preference and number of evacuees during the simulated event. This situation may raise new issues during evacuations, such as

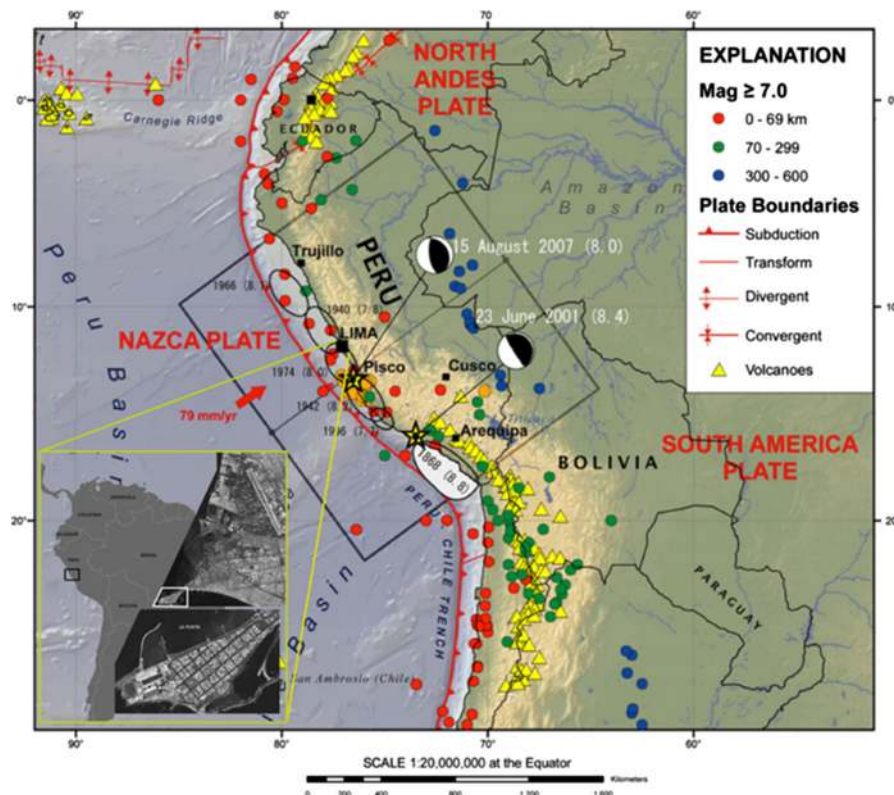


Figure 8

The location of La Punta in Peru and the tectonic settings of the earthquakes in the surrounding regions (modified from YAMAZAKI and ZAVALA 2013; MAS *et al.* 2013a)



Figure 9

Tsunami evacuation buildings in La Punta. The 20 buildings can accommodate a total of 7930 evacuees in the district of 4370 residents. The *bottom-left inset* shows the locations of these buildings

conducting a secondary evacuation—as in the case of Natori in Japan discussed previously—that delays evacuation and may cause a higher number of fatalities. To inform the local authorities and stakeholders of these results, the capacity–demand rate of the shelters was mapped. The capacity demand index was constructed to represent and easily communicate the spatial issues of the availability of shelters in La Punta (Fig. 10).

The tsunami evacuation ABM was used to reveal the necessity of vertically directed evacuations, particularly in low-lying areas such as La Punta. The outcomes of this study contributed to the identification of risks that could not be identified using static approaches (e.g., GIS least-cost distance analysis, shelter location–allocation solutions, or a

direct comparison of the available space versus the number of residents without considering the spatiotemporal issues). The dynamics of a tsunami evacuation simulation are valuable characteristics that should be explored and applied in tsunami mitigation and evacuation planning.

4. Challenges and Future Perspectives

Each time a tsunami occurs, lessons are gathered and shared; unfortunately, not all lessons are fully learned. Similarly, tsunami evacuation research has substantially improved since the 2004 IOT. The future of tsunami evacuation research, as seen by the authors, concerns the comprehensive geophysics of

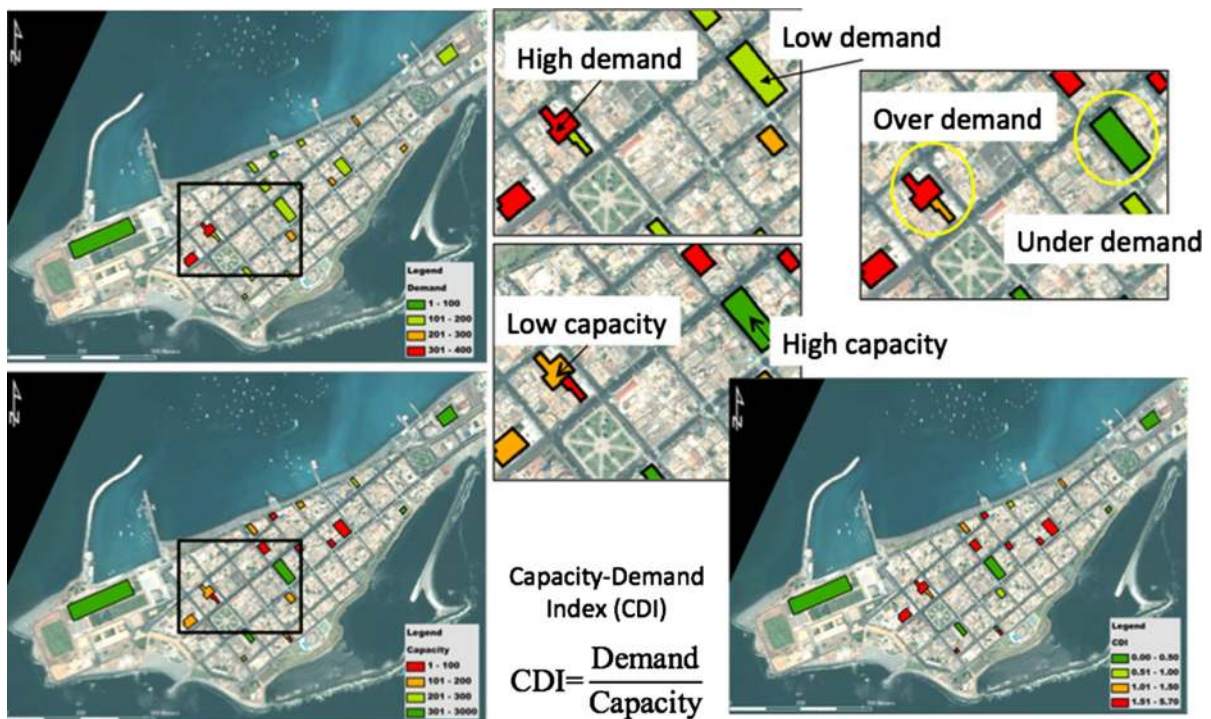


Figure 10

The *top-left inset* shows the evacuee demand for shelter, while the *bottom-left inset* shows the capacity of shelters. The *black square* marks the zoomed-in area with the high/low demand and low/high capacity example of over/under demand evaluations. The *bottom-right picture* is the CDI mapping result for outreach purposes

tsunamis and the physical and psychological traits of the evacuees, all of which would be built into an integrated modeling technique. Efforts to integrate tsunami simulations and social simulations using agent-based modeling (MAS *et al.* 2012, 2013a) and to use supercomputers (WIJERATHNE *et al.* 2013) to bridge gaps between geoscience and social science connect risk assessments with risk management. With these tools, evacuation issues can be understood in a more comprehensive manner. Challenges and emerging issues worth our attention are as follows:

1. Human behavior: Modeling human behavior is not an easy task, but it is not impossible because humans do not behave randomly (KENNEDY 2012). Psychological parameters (VORST 2010), such as evacuees' cognitive and emotional behaviors that affect decision-making or levels of stress and panic should be included. However, capturing individual characteristics in mathematical equations is difficult (PAN *et al.* 2007). Human

behavior in tsunami evacuations has been studied using questionnaires. Survey responses provide insight into people's risk perceptions (CHARKNOL and TANABORIBOON 2006; BIRD 2009; GIERLACH *et al.* 2010) and their experiences in real evacuations in post-tsunami events (LACHMAN *et al.* 1961; KATADA *et al.* 2005; SAITO 1990; MAS *et al.* 2011). The statistical outcomes of preference and revealed surveys are incorporated into the agent-based model presented here to stochastically assess uncertainties in human behavior. In the future, we should explore artificial intelligence and cognitive science models in conjunction with agent-based approaches for tsunami evacuation modeling. Agent-based modeling practitioners use these fields quite often to model human behavior (WRAY and LAIRD 2003; SHENDARKAR and VASDEVAN 2006; DUNIN-KEPLICZ and VERBRUGGE 2010).

2. Verification and validation (V&V) of models: Because of the nature of ABMs, which are based

on simulations rather than equations that can be tested in the laboratory or analytically solved, the process of V&V is difficult (ORMEROD and ROSEWELL 2009). However, replication may aid the model verification process. Specifically, if two distinct implementations of a conceptual model are able to produce the same results, then that outcome supports the hypothesis that the original model correctly implemented the conceptual model (RAND and WILENSKY 2006). Another way to confirm the “inner validity” of the model is by “alignment”, which refers to using a different programming language and ABM toolkit to re-implement the model (CASTLE and CROOKS 2006). For validation, real-world data must be collected for comparison with model output; this can be done through controlled evacuation drills. Finally, aggregated data on tsunami evacuations or evacuation drills, such as the number of fatalities in an area or the number of evacuees in shelters, are available, but the validity of the dynamics of the evacuees from the starting point to their shelter and the accuracies of the behavioral models used for agents are uncertain.

3. Use of earthquake disaster “big data”: To address the challenges in the two items above, human behavioral models and real-world data can be collected from mobile technologies, which record user locations, speeds, directions, etc. This information was tracked during the 2011 GEJT from mobile phones, car navigation systems and social media. This massive amount of data is known as “Shinsai big data” or earthquake disaster big data. These data can elucidate what occurred on the ground on the day of the tsunami, characteristics of evacuee behaviors, and issues in the process of mobilization; in other words, the collective mind of the society at risk can be explored to calibrate behavioral models and to validate evacuation models. Additionally, virtual big data can also be created to gather additional information on human behavior. Here, we introduce the concept of “virtual big data”, which is the information gathered via cloud gaming (LIU *et al.* 2014) to create a library of human behavior in evacuation scenarios. In the future, real-time big data may be

used to support the evacuation of residents during an event.

Other expectations in the field of agent-based modeling that apply to tsunami evacuation models of this nature are discussed by HELBING and BALIETTI (2011), who envision a new way of performing research using supercomputers in data-rich situations. These authors foresee a massive simulation platform with various types of data (i.e., demographic, socio-economic, and geographic) and simulation approaches (i.e., agent-based and equation-based) in large-scale environments within the next 10–15 years (HELBING and BALIETTI 2010).

5. Conclusions

The 2004 IOT and the 2011 GEJT were the two most destructive tsunamis in recent years. Both events emphasize the necessity for effective evacuation plans and rapid evacuation behavior. In addition, the events provided large amounts of data that have been or will be used to produce, verify, validate and improve models to represent the evacuation of populations. Tsunami evacuation models have been developed using several techniques; here, we discussed the agent-based modeling approach because we considered it to be suitable for exploring human behavior and rapid low-level environmental changes using available high-resolution data. An agent-based model was applied to assess tsunami risk and evacuation scenarios in Indonesia, Thailand, Peru and Japan. As described in the case studies, agent-based models benefit tsunami mitigation and evacuation planning by describing the individuality of the evacuees and allowing for the observation of emergent behavior within the dynamics of agent interactions. Agent-based models are flexible and provide a natural description of a particular system. From the perspective of tsunami hazard mitigation, the model presented here provides estimates of casualties, an analysis of evacuee behavior in a two-step evacuation process, identifies bottlenecks, uncovers limitations in shelter capacity and evaluates the use of vehicles in evacuations. All of these outcomes are associated with evacuation planning and cannot be

observed solely through evacuation drills or questionnaire surveys. Finally, several challenges to agent-based modeling exist. Past evacuation simulations for tsunamis were unable to model large-scale scenarios and various human traits; present research is considering much finer levels of detail in simulations with a huge amount of data using high-performance computational techniques. Future research should focus on comprehensive and integrated simulations by incorporating complex agent behavior. Engineering, social, psychological and educational sciences should work together to effectively understand, build, apply and share evacuation simulations and outcomes.

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