Tsunami Evacuation Simulation
Case Studies for Tsunami Mitigation at Indonesia, Thailand and Japan

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Abstract: The 2004 Indian Ocean tsunami and the 2011 Great East Japan tsunami left several lessons for future events. Both tsunami events confirmed the importance of early evacuation, tsunami awareness and the need of developing much more resilient communities with effective evacuation plans. To support reconstruction activities and efforts on developing resilient communities, tsunami evacuation simulation are applied to tsunami mitigation and evacuation planning. In this paper we highlight the importance of tsunami evacuation simulation as a tool in disaster management. Case studies of application of a tsunami evacuation model developed by the authors are presented here. Applications in Indonesia, Thailand and Japan tsunami prone areas are reported. In addition, challenges and future research directions for tsunami evacuation modeling are briefly discussed.

1 INTRODUCTION

The 2004 Indian Ocean Tsunami (IOT) was reported and recorded at several locations in Indonesia, Thailand and other countries in the Andaman Sea. It was probably the first time for many people around the world to watch footages of a devastating tsunami event. (Synolakis and Bernard, 2006) referred to the surprising images of tourists in Phuket, Thailand, watching the onslaught of the tsunami without taking any protective action. Tsunami risk involves not only the hazard assessment, but also the social component of human behavior against disasters. In addition, evacuation has proofed to be the best way to save lives against tsunami (Shuto, 2009). The 2011 Great East Japan Tsunami (GEJT) was one of the biggest tsunami events in Japans modern history. The large inundation and tsunami heights reported destroyed several towns and villages along the coast. Still, there was a 96% survival rate of people living in the areas inundated (Suppasri et al., 2012). The unfortunate aftermath resulted from the 2004 IOT was attributed to the lack of warning information, tsunami awareness and early evacuation response. Conversely, the 2011 GEJT left many lessons for future events and confirmed the importance of early evacuation, tsunami awareness and development of resilient communities with effective evacuation plans. In this paper, we present four case studies of tsunami evacuation simulation conducted to support tsunami mitigation and evacuation planning in areas at risk.

2 BACKGROUND

Computation power of large amount of data has made it possible to move the tsunami evacuation modeling approach from network based (Lämmel et al., 2010) to grid based (Mas et al., 2012), potential fields (Meguro and Oda, 2005) or hybrid modeling approaches to optimize calculation times(Kato et al., 2009). Research methodologies are using much more data with finer levels of granularity through agent based modeling and high performance computing (Wijerathne et al., 2013). In addition, the interest to incorporate human behavior in evacuation models has increased (Fujioka et al., 2002; Suzuki and Imamura, 2005; Mas et al., 2012). After the 2004 IOT and 2011 GEJT, tsunami evacuation modelers are looking into practical applications of simulators, to solve particular problems that have been present in these events. Some issues that concern researchers and stakeholders are evacuation timing, bottleneck and congestions from vehicle evacuation, shelter allocation, evacuees behavior, risk communication, etc. In addition, the reconstruction process of tsunami affected areas demand for new evacuation plans following new urban layouts. The assessment of effective evacuation plans

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under new urban spatial conditions can be analyzed and evaluated first using evacuation models.

3 CASE STUDIES

Tsunami evacuation simulation is becoming an important tool to simulate the response to warnings, the estimation of casualties, the evaluation of evacuation plans and alternatives for tsunami mitigation. These experiments are guiding the development of more effective educational and mitigation programs at many countries (Bernard et al., 2006). Here, we show several examples of case studies of tsunami evacuation modeling applied to verify, analyze and evaluate real and predicted tsunami scenarios of evacuation. The authors had used in a number of cases a tsunami evacuation model developed in NetLogo (Wilensky, 2001)—an agent-based platform to simulate complex systems. First, tsunami numerical simulation is conducted using the Tohoku University Numerical Analysis Model for Investigation of Near-field tsunami No. 2 (TUNAMI-N2). In TUNAMI, nonlinear shallow water equations are discretized on a staggered-leap frog finite difference scheme (Imamura, 1996). Results of the tsunami simulation are integrated to the NetLogo environment where agents are built to escape from disaster to nearby shelters or exits within the computational area (Mas et al., 2012; Mas et al., 2013a).

3.1 Padang, Indonesia

Padang is located on the center of the west coast of Sumatra in Indonesia. After the IOT in 2004 several earthquakes occurred in the southern part of the Sunda Trench. These events put on alert the city of Padang and brought attention to an existing seismic gap. (Imamura et al., 2012) described the assessment of tsunami hazard in this area based on a megathrust earthquake scenario for tsunami simulation and using high-resolution bathymetry and topography data. The extent of the resulted inundation area covered approximately 25 km^2 with approximately 235,000 people at risk of tsunami inundation depths from 3 m to 8 m. In Padang there is a lack of vertical evacuation facilities inside the predicted inundation area. In addition, from the experiences of 2007, 2009 and 2010 tsunami warning events, it has been found that residents mainly use vehicles or motorcycles for evacuation despite traffic jam experiences. Consequently, in this case study, it was necessary to identify the time needed by the evacuees to leave the tsunami inundation area and assess the routes of possible congestion during the evacuation. Tsunami evacuation simulation was used to identify times for evacuation and bottleneck points. A total of 104,352 agents were modeled within a 15 km^2 area south in Padang city. The agent-based model was used (Mas et al., 2012), modeling residents to respond at different times to the tsunami threat and evacuate towards the exits and shelters located on the east side of the city (Figure 1).

Figure 1: Padang city. The areas of evacuation simulation and, surrounded by circles, the streets which resulted on congestion.

The timing for evacuation decision was based on results from questionnaire surveys conducted in Padang after 2007 and 2009 events. With the amount of population modeled, and the evacuation behavior for departure as input in the model, the casualty estimation, time for evacuation and points of bottleneck were identified. Fatalities were estimated on 37.7% of the population simulated in this scenario. In addition, we identified several streets congested on the north part of the study area due to high demand of some exit points. Areas near the shopping center and the traditional market center were highly congested due to the large density of population gathered. Moreover, to the south of the simulation domain, agents evacuated to high ground crossing the river through a bridge; the large number of evacuees resulted on large cues and crowd congestion.

3.2 Pakarang Cape, Thailand

The next case study is the evacuation simulation of Pakarang Cape population in Thailand (Mas et al., 2013b). The Pakarang Cape is in the Khao Lak beach resort area of Phang Nga province in Thailand, and it is located at the coast of the Andaman Sea. This area was devastated by the IOT on 2004. The Thai Meteorological Department (TMD) provided population data and its spatial distribution. A total of 2,649 residents were modeled based on a night-time population scenario. The objective was to explore the influence

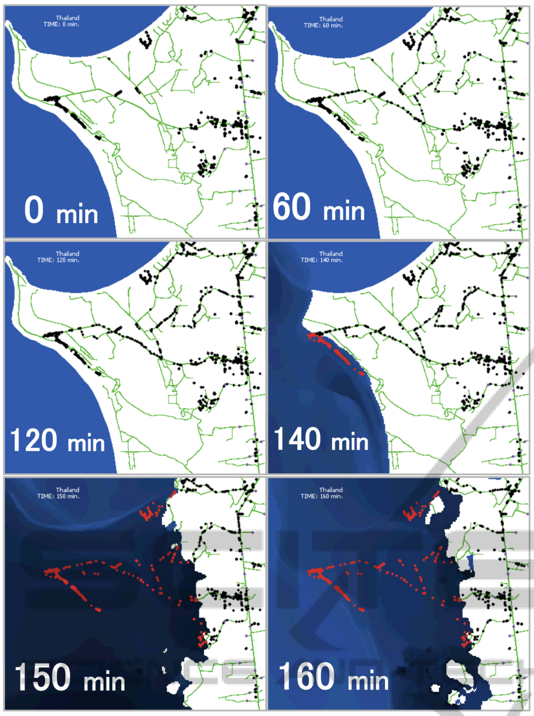

Figure 2: Snapshots of the worst-case scenario, where the evacuation is towards the shelters located on the right side of the area.

of vehicles in the evacuation, combined with different reaction times from residents. A set of percentage of evacuees in vehicles (passengers and drivers) was assumed among the population to build several scenarios for simulation. Therefore, 0%, 25%, 50%, 75% and 100% of agents were reduced from the total population and grouped in 4 passengers to build the vehicle agent population data. The start time decision of evacuation followed several departure curves of Rayleigh distribution characterized by its mean value. The value of the mean of the distribution, which fits 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), was 30 min. In addition to the distribution curve from the questionnaire, three possible scenarios were added: a worst-case scenario with late evacuation reaction of 120 min mean value—this is the estimated arrival time of tsunami for the 2004 IOT event in this area—and two intermediate scenarios with 60 min and 90 min mean value. The fatality rate was defined as the ratio of estimated casualties over the total population involved in the simulation. Due to the long distance for evacuation, approximately 2 km, the worst-case scenario of evacuation, shown in Figure 2, is a non vehicle use and on-foot evacuation, added to the late reaction. The application of tsunami evacuation simulation in this case study showed the capability of evacuation modeling to evaluate the feasibility of evacuation. In this case, twenty scenarios of different starting time of evacuation and percentage of use of vehicles in evacuation were compared. Results suggest that, due to the long distance of shelters, small number of population and sufficient road capacity, vehicle evacuation was possible and required to ensure safety. Notice that in a larger population, traffic congestion might be possible, as we will describe on the following case study.

3.3 Sendai, Japan

(Mas et al., 2012) modeled the evacuation of Arahama town for the 2011 GEJT. Arahama was a populated village in Sendai plain area. Approximately 300 fatalities were reported in this area, where the tsunami arrived at approximately 67 min after the earthquake with a maximum tsunami height over 8 m. The extent of the inundation area reached as far as 5 km inland. In Arahama, the only official Tsunami Evacuation Building (TEB) was the Arahama Elementary School. The school is a four-story building with accessible roof. It provided tsunami shelter to approximately 520 evacuees. The tsunami evacuation simulation was conducted to 2,271 people. The majority of them, based on pre-tsunami questionnaire surveys (Suzuki and Imamura, 2005), preferred to evacuate on vehicles (72%). With 4 passengers per vehicle, 410 cars and 631 pedestrians were modeled. A stochastic simulation was performed to obtain average outputs for parameters of interest. A total of 1,000 simulation repetitions were conducted with random initial spatial distributions of pedestrians and vehicles. The evacuation start time decision was based on a randomly selected value within boundary distributions constructed with the mean of distribution fitting stated preference questionnaires and recorded arrival time of the tsunami on 11 March, 2011 (67 min) (Figure 3).

Each simulation provides information of the number of evacuees in shelters, the number of evacuees who have passed one of the exits and the number of evacuees trapped by the tsunami with more than a 50% probability of falling by the flow. This information, at such level of granularity, is one of the greatest advantages of agent-based modeling. It is not only the emergent behavior that is discovered, but also the details of common agent behavior and possible local issues that can be identified. It is difficult to obtain the exact values observed with the stochastic simulation developed in this study; however, the average estimations of survivors and evacuees at the TEB shows that the model has good capability for representation of decisions and casualties in the area. The standard

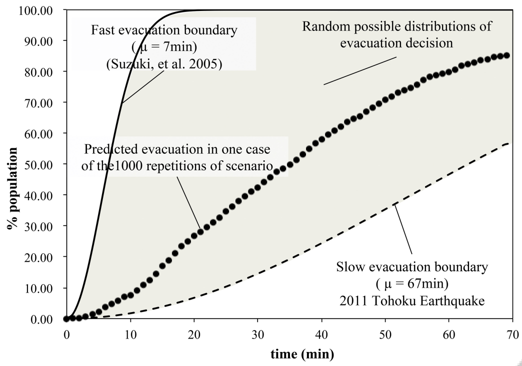

Figure 3: The area within the boundary distributions contains the possible values and distributions of evacuation behavior used in the simulation. The dotted line is the resulting evacuee behavior taken from one scenario of the 1,000 repetitions of random selection.

error of predicted values versus the official information is 43% for the case of casualty estimation (model: 406, data: 283). Due to the uncertainty in the initial population distribution, the actual number of passengers in vehicles and the possible use of non-official buildings as shelters, the casualty estimation could not be accurately predicted. However, good results were met for the number of evacuees sheltered at the TEB with 4% error (model: 498, data: 520) and 7% for the rest of the population evacuating inland. In addition, time-history plots of shelter demands and traffic flow through exits were developed in the model to support on the allocation of future new shelters and distribution of relief resources.

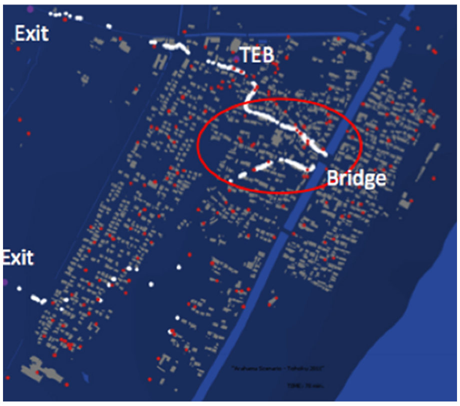

Figure 4: The last snapshot of simulation showing in white the areas of traffic congestion during evacuation. Traffic congestion was confirmed with survivors for the segment in front of the Tsunami Evacuation Building (TEB).

Traffic was generally observed on the main roads leading to the exit points, at the entrance of the tsunami evacuation building and near the bridge at the channel (Figure 4). Although these bottlenecks did not occurred at the same time, they were observed at some point during at least one of the repetitions. All of these bottlenecks should be identified as possible critical points. The application of tsunami evacuation simulation in this case showed the capability of the model to identify bottlenecks and verify the process of evacuation with several behavioral conditions. The stochastic simulation and the individual level of representation in the model gives the modeler a reasonable amount of data to analysis and identify issues not only at the large scale, but also on local agent behaviors that might not contribute to a safe evacuation.

3.4 Natori, Japan

In (Takagi et al., 2014), the evacuation behavior reported in Natori, Yuriage was simulated to verify the evacuation process and the reasons for the large number of fatalities in the area. Yuriage is a small town near the Natori River in the plain area of Miyagi Prefecture. Before the earthquake, approximately 5,612 residents were living in the area. Due to the earthquake, 752 people were killed by the tsunami and 41 are still missing. It was reported in this area that residents evacuated to nearby shelter areas, however after tsunami warnings were increased (Japan Meteorological Agency (JMA), 2013), some evacuees decided to conduct a second step evacuation to a far inland shelter. Tsunami arrived when evacuees where moving to a second shelter and killed some of them. We found that the number of fatalities could have been reduced provided people would have evacuated directly to the second shelter from the start. The model was applied in two scenarios of simulation: Case A: a scenario as close as possible to the real evacuation, based on reported data by local authorities and survivors; Case B: a scenario where the second evacuation was not performed. The actual reported number of fatalities in the event and the results from simulation are shown in Table 1. Figure 5 shows the sequence of evacuation at each shelter in Case A, where the Community Center was already full after approximately 25 min from the earthquake (15:10 JST).

At 15:14 JST, tsunami warning was upgraded for Miyagi coast from 6 m to above 10 m (Japan Meteorological Agency (JMA), 2013). Based on information provided by survivors, approximately 15:30 JST was the time for evacuees to start moving from the Community Center to the Junior High School, this agrees with the time of the tsunami warning upgrade. Thus, in the model we set 15:30 JST as the time for the second evacuation. Similar to simulation results, it was reported that in the Community Center 43 people survived (Murakami et al., 2012). In addition, results

Table 1: Shelter capacity near Yuriage, the outcome of the 3.11 tsunami and results from Case A and Case B. The last column shows the reduction on fatalities when no re-evacuation behavior was performed.

Shelter	Capacity	3.11	Case A	Case B	A-B
Community Center	300	43	43	300	+257
Yuriage Junior High School	2000	1000	1050	1067	+17
Yuriage Elementary School	2300	870	699	759	+60
Fatalities	**	762	774	436	-338

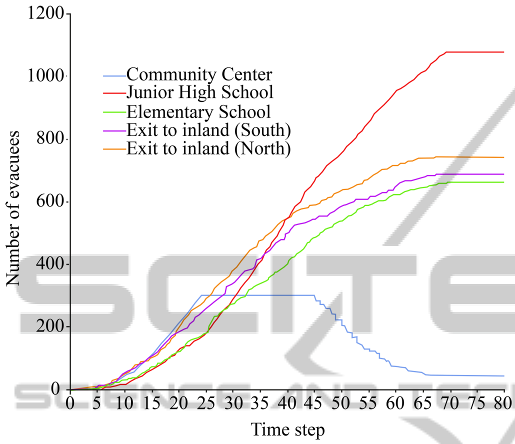

Figure 5: The time-history of evacuees in shelters from the simulation. Notice the arrival and second evacuation to/from the Community Center (blue line).

Figure 6: Yuriage, Natori inundated by tsunami numerical simulation results. Black dots are evacuees in progress as pedestrians; purple dots are evacuees on vehicle, red dots are fatalities caught by tsunami and yellow dots show the points of bottleneck during the simulation.

show that a total of 257 evacuees were able to leave the Community Center before the arrival of tsunami, but only 82 were able to reach the Junior High School on time (Figure 6).

Some reasons for the number of fatalities may be: (i) *The short time for re-evacuation*: each evacuee conducted a second evacuation in between 15:30 JST to approximately 15:50 JST—the time when tsunami arrived to the Community Center; (ii) *The traffic jam*: based on survivor's accounts, the road in front of the Community Center was congested with vehicles and people who tried to re-evacuate on car. Conversely, as in Case B, where evacuees do not perform a second evacuation from the Community Center, the total amount of fatalities could have been reduced approximately 44%. Tsunami evacuation modeling is a powerful tool that can be applied to understand the effects of evacuees decisions on the outcomes of their evacuation process. In addition, future evacuation plans and activities for reconstruction process and urban planning can be supported by the results provided from these kind of models.

4 FINAL COMMENTS

Each time when a tsunami occurs, lessons are gathered and shared, then, tsunami research shows a progress (Shuto, 2009). Similarly, tsunami evacuation research has substantially improved since 2004 IOT. The future of tsunami evacuation research, as seen by the authors, is the comprehensive approach of the geophysics of tsunami and the psychology of the evacuee behavior built into an integrated modeling technique. There are several ongoing efforts (Mas et al., 2012; Mas et al., 2013a; Wijerathne et al., 2013), however, still data to verify and validate the human behavior in emergency and models to adequately represent the complexity of the mind are few. A clear representation of the human complexity into a computing agent needs to be built from theories in psychology of disasters and techniques in artificial intelligence simulation. In addition, it is important to complement the information available with data from real events to verify and validate models of behavioral and urban simulation. In the case of tsunami evacuation models, using data from one of the most recorded events, 2004 IOT or 2011 GEJT, can be conducted to benefit the validation and improvements of current models. In this paper, we highlighted the importance of tsunami evacuation simulation through case studies of practical application in Indonesia, Thailand and Japan. Tsunami evacuation feasibility, casualty estimation, bottleneck identification, shelter allocation and other applications were modeled to support tsunami mitigation activities.

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