Dynamic Intelligent Swarm-Based Tsunami Evacuation Model: Case Study of the 2011 Tohoku Earthquake

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SUMMARY:
This study develops a new model for crowd evacuation simulation during catastrophic events such as the massive tsunami due to the 2011 Tohoku Earthquake. The numerical model is based on swarm intelligence and is able to predict human losses. The proposed model is applied to a case study of evacuation analysis in Yuriage area, Natori city, Miyagi Prefecture. A GIS database of inventory data for simulation is prepared and evacuation behavior is modeled based on a questionnaire survey. The number of tsunami victims is estimated by population in areas of maximum inundation. Human losses as a result of tsunami are estimated by a method which employed accumulated death toll of every area in terms of time and space, taking into account consideration of time necessary to begin to seek refuge after an earthquake, the tsunami inundation arrival time and height, and evacuation speed. As a result of this study a decrease in pre-evacuation time can decrease human losses effectively.

Keywords: Tsunami evacuation, human loss prediction, the 2011 Tohoku Earthquake, swarm intelligence

1. INTRODUCTION

The evacuation of an urban area or even regions of a city is a critically important problem in modern societies, as demonstrated by recent events such as the evacuation of Houston in the case of Hurricane Rita or the evacuation of coastal Pacific-rim cities in the case of tsunamis. The most recent example for a highly vulnerable area is the 2011 off the Pacific Coast of Tohoku Earthquake (hereafter the 2011 Tohoku Earthquake) which was the fifth largest earthquake on Earth in the last 50 years and resulted in very high and prolonged peak ground accelerations (PGA) throughout northeastern Japan. Shaking damage due to these ground motions was significant but paled in comparison with the damage caused by a massive tsunami that arrived approximately 30~60 minutes following the main shock. The resultant disaster left more than 15,000 fatalities, 6,000 injuries and 3,000 missed as of April 25, 2012.

Murakami et al. (2012) conducted a questionnaire study (such as questions about the age ratio, gender, population ratio, and other essential socioeconomic data) to analyze the emergency evacuation and behavior of evacuees before and during the disaster. They found out that many of survivors had delayed evacuation. Rather than moving immediately to high ground, many went home or looked elsewhere for family members, and some felt unconcerned, perhaps because they were not informed about the severity of the tsunami. Residents may also have relied on the seawalls and other natural tsunami defences such as sand dunes. More than 60% of the surveyed population evacuated by car, and of these, about a third got caught in heavy traffic jams. Many of those died in the disaster were elderly with the mean age in the lower 60s—and therefore likely less mobile, less able to hear warnings (via cell phone, radio, television, short wave bands and through local sirens), and less able to evacuate easily to higher ground or buildings.

In this study, we present preliminary results of on-going research on crowd evacuation dynamics for human loss prediction during catastrophic events such as tsunami which includes evacuation activity. The new method presented here has been tested and predicted death tolls resulting from the tsunami in

Yuriage due to the 2011 Tohoku Earthquake. In the further steps, the death toll will be estimated from changes in evacuees' time to start evacuating and evacuation speed.

2. TSUNAMI INUNDATION AND FATALITIES

Following the 2011 Tohoku Earthquake (Mw=9.0) that occurred on March 11, 14:46 (JST); a massive tsunami arrived at the fishing port in Yuriage of area of Natori city at 15:55 (JST). Residential areas were totally devastated. Natori city was severely damaged and the death toll exceeded 900. Tsunami inundation height at Yuriage port was 8.81m (Mikami et al. 2012). In the flat topography of Yuriage area, the tsunami inundation zone extended to approximately 4 km inland from the coast, and made evacuation progress difficult.

In total, twenty thousand people died due to the tsunami caused by the 2011 Tohoku Earthquake (Goto et al. 2012). The earthquake occurred in daytime and in most parts of east coast of Japan, the tsunami took at least half an hour to arrive at the coast line where it was expected that people in the affected areas should have been at relatively high disaster preparedness levels. The disaster also raised a crucial question about why the fatality rate was very high when the tsunami arrival time in Yuriage was about 69 minutes after the very severe earthquake.

2.1. Inundation Situation

The study prepared a GIS database and assembled several data from National Policy Agency (NPA, 2011) and Official Statistics of Japan (2011), and map layers (Statistics Bureau, 2011) such as tsunami inundation height, tsunami arrival time, population, and demography. Fig. 1 shows the tsunami inundation map provided by Geographical Survey Institute of Japan overlaid with map of districts in Natori city. The tsunami inundation height in each area of the Yuriage is shown in Fig. 1 (Natori City Office, 2011). The inundation has the highest value in residential areas No. 4 and 5. From a documentary movie of the tsunami activity in Yuriage area prepared by NHK (NHK Special, 2011), the tsunami arrival time was also extracted and is presented on the same figure. As can be seen, the tsunami inundation arrival time in coast line of Yuriage is 15:55. Therefore the tsunami arrival time to residential areas 4 & 5 was considered as the same as the coast line. Accordingly, the tsunami arrival time to areas 3 & 6, areas 2 & 7, and area 1 is considered as 15:56, 15:57, and 15:59, respectively.

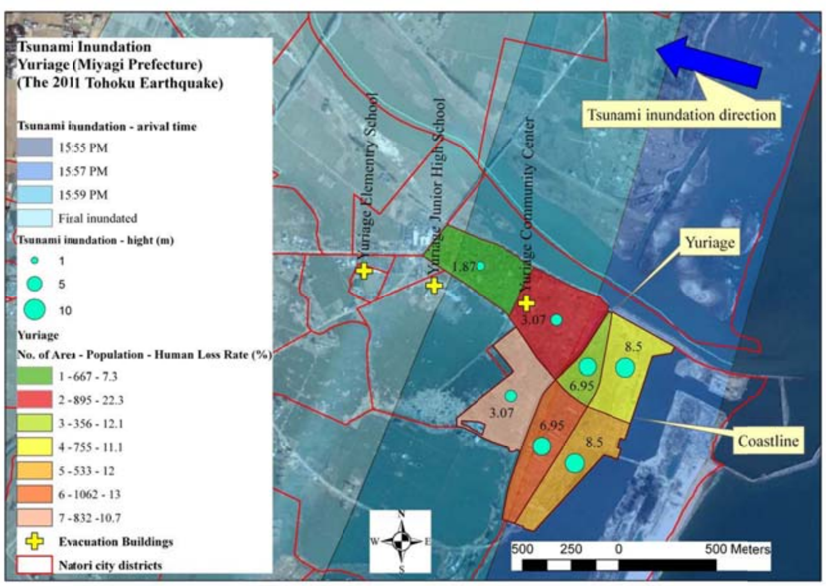

Figure 1. Tsunami inundation height over time and human loss distribution in Yuriage

2.2. Fatalities and Evacuation Activities

The population and human loss ratio in each of the seven areas in Yuriage are shown in Table 2.1 and Fig. 1. Also, in Table 2.1, number of casualties, population, human loss ratio, and ratio of houses washed away in each area are summarized. This table also depicts the number of elderly people with ages of over 75 years. According to Murakami et al. (2012), fatality rate increases as age becomes higher assuming that is because of difficulty in moving, walking, and obtaining information by handicapped and elderly people. Moreover, dividing the number of death toll in each age range from Murakami et al. (2012) by population data of inundated area in Natori city extracted from national census data of 2010, the fatality rate for each age range was calculated as represented in Fig. 2. As seen, the fatality rate increases as the age goes up.

Table 2.1. Fatalities, population and damage rate of houses (Murakami and Kashiwabara, 2011)

Yuriage areas	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
Number of human loss	49	200	43	84	64	138	89
Population	667	895	356	755	533	1062	832
Human loss ratio (%)	7.3	22.3	12.1	11.1	12.0	13.0	10.7
Ratio of elders - age over 75 (%)	11.8	14.6	17.3	16.5	7.4	9.7	4.9
Ratio of houses washed away (%)	21	81	100	100	96	90	91

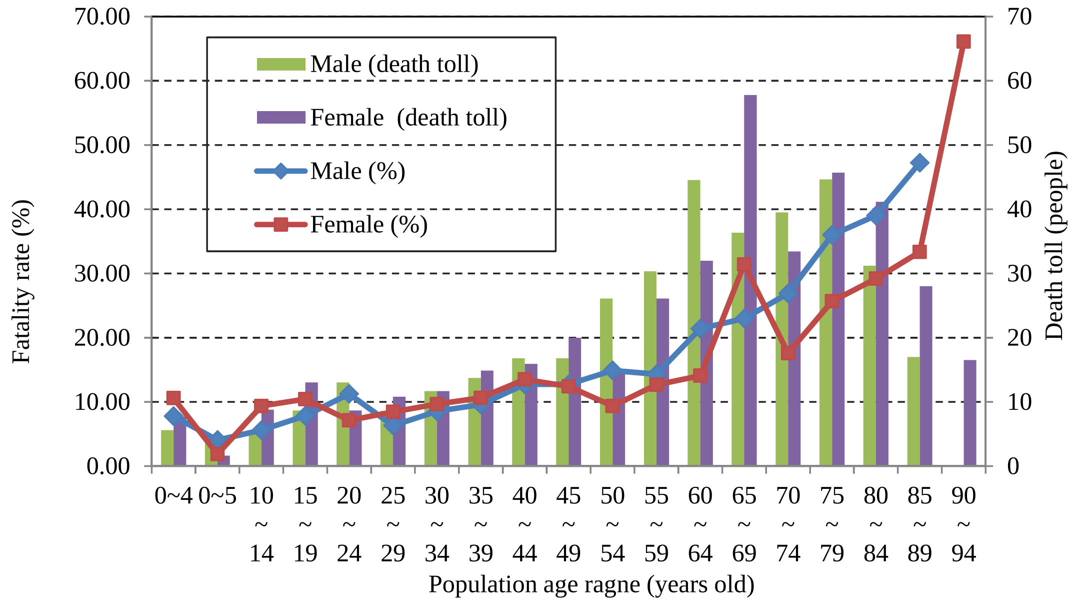

Figure 2. Fatality rate in Yuriage

3. EVACUATION ACTIVITIES

When a tsunami runs up on land, the buildings in the inundated areas are damaged often to such an extent that they may be washed-away, collapse completely or be flooded. Human loss is difficult to predict, because it depends on evacuees evacuation activities. The topography of Yuriage area of Natori city is a nearly flat coastal plain with most elevation less than 5m. Hence, prompt evacuation to nearby natural hills was not possible. Besides, based on the tsunami hazard map, most parts of the Yuriage residential area was out of tsunami inundation zone (Murakami et al. 2012). Yuriage has three evacuation places which are reinforced concrete (RC) buildings namely: 1) Yuriage Community Center, a 2 storey building; 2) Yuriage Junior High School, a 3 storey building; and 3) Yuriage Elementary School, a 3 storey building. Fig. 3 shows the evacuation places in Yuriage.

Murakami et al (2012) performed a preliminary interview survey in Yuriage district during March 31 through April 2, 2011, with basic questions of the location at the time of earthquake, hearing of tsunami warning, type of information media, evacuation behavior and threat to life and plotted evacuation routes on a map. The results indicated that there were several reasons including, delay in tsunami warning message, extensive use of automobiles, and traffic congestion around the Community Center and the Yuriage Junior High School that may have caused disruptions in the evacuation processes.

More specifically, fatality rate in area 2 is highest among the seven residential areas in Yuriage. The results of the survey indicate that the evacuation rate in the 2010 Chile tsunami was lowest in the area 2, which may have lead people to mistakenly think they live in a safety zone since they are 1km to 1.4km distant from the coast line (Murakami et al. 2012). Therefore this mistaken knowledge may have caused them to start evacuating late. Moreover, the wireless system located in the Municipality Office for emergency information was unfortunately disabled due to the strong shaking by earthquake; thereby tsunami warning and evacuation order did not work properly. People received information via radio, neighbors, police, firemen, and official PR vehicles. Those who thought a large tsunami would come tended to start evacuation immediately, while others moved to see their families, and even tidy up scattered objects, and lost valuable time for evacuation. During evacuation, 60 % used a car. However, traffic congestion halted evacuation processes. Another reason for high fatalilty rate in area 2 is the existence of the Natori River in north of area 2. The river rolled as a channel for ease of tsunami inundation toward the area 2. Therefore the tsunami reached this area fast and inundated the area.

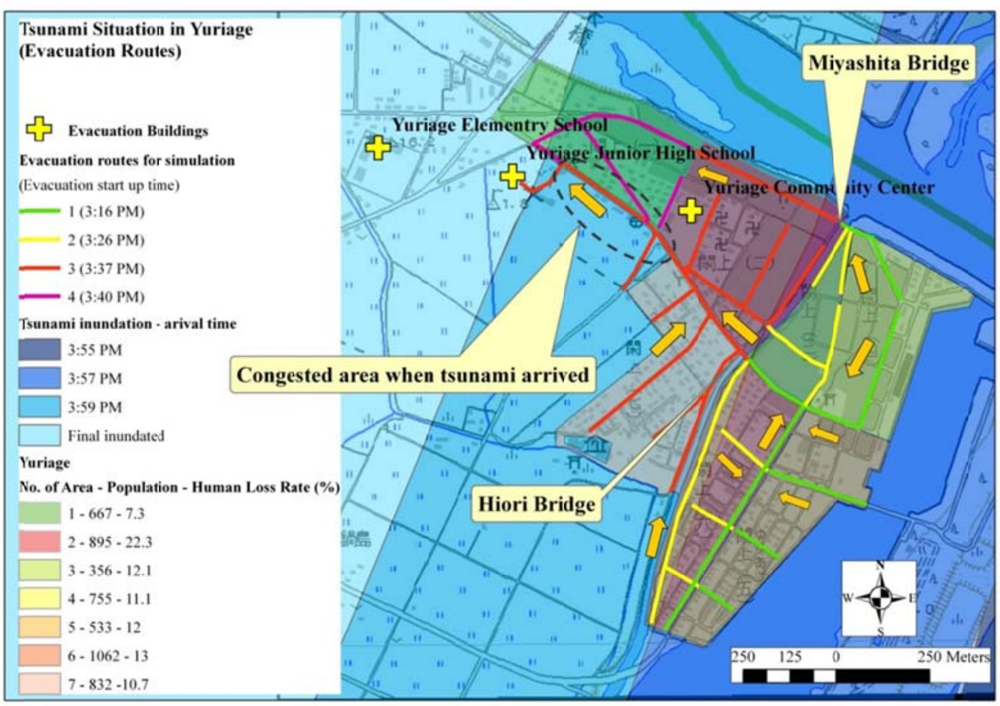

Figure 3. Evacuation behavior in 7 areas of Yuriage due to the 2011 Tohoku Earthquake

According to field surveys conducted among the survivors of the tsunami in other regions, pre-evacuation time for Yamamoto and Minami Sanriku areas was more than 30 minutes. It has also been reported that comparatively less people heard warnings or messages from the local government or the local mitigation centers (Dulam et al. 2012). This pre-evacuation time depends on many factors like perceived importance, uncertainty of the warning, finding family members, gathering valuables, etc. Based on the field survey results and watching the NHK documentary movie (NHK Special, 2011), we have classified the 28 main evacuation routes and assigned an evacuation startup time for each route. Fig. 3 shows these evacuation routes, direction of evacuees flow, and time for starting evacuation.

4. SIMULATION MODEL

In this research, we have developed a model based on concepts from swarm intelligence known as Particle Swarm Optimization (PSO). The proposed model was originally developed to simulate crowd dynamics and behaviors during evacuation from individual buildings. In this study, we will show its application to analyze tsunami evacuation dynamics. The model can simulate human behaviors such as pre-evacuation times, crowd flow movement, overtaking, dynamic obstacle avoidance and walls avoidance. Human behaviors observed during evacuation can be classified into one of the following categories: 1) Psychological behaviors: These behaviors are based on individual characteristics. Some of the behaviors include making a decision to evacuate, leaving the activities currently engaged in, taking the shortest exit out of the area, overtaking slower moving occupants, swerving away from danger, avoiding obstacles, taking alternate exits in case of overcrowding, etc.; 2) Physiological behaviors: These behaviors are the occupant’s physical response to effects of danger. Some of the examples are poor visibility (in the case of heavy traffic), the effect of flood velocity on the evacuees’ velocity and mobility, etc.; and 3) Social behaviors: These behaviors include the evacuees’ interaction with other occupants. They are among the most difficult behaviors to simulate. PSO was originally developed by Kennedy and Eberhart, 1995 and has previously been applied to solve nonlinear optimization problems (Javanbarg et al. 2012a and Javanbarg et al. 2012b).

PSO can be briefly described as an evolutionary computation technique based on swarm intelligence. Each individual in a swarm is called ‘particle’, and changes its positions over time. Each particle represents a potential solution to the problem. In a PSO system, particles fly around in a search space.
During its flight each particle adjusts its position according to its own experience and the experience of its neighboring particles, making use of the best position which is called ‘particle best’ encountered by itself and its neighbors. The overall effect is that particles tend to move towards most promising solution areas in the search space, while maintaining the ability to search a wide area around the localized solution areas. The performance of each particle is measured according to a pre-defined fitness function, which is related to the problem being solved and indicates how good a candidate solution is. The algorithm of PSO is described as the following:

$$v_{id}(t+1) = v_{id}(t) + c_1 r_1 (p_{id}(t) - x_{id}(t)) + c_2 r_2 (p_{gd}(t) - x_{id}(t)) \tag{4.1}$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1) \times \Delta t \tag{4.2}$$

where $\Delta t = 1$ is iteration (time) and equals 1s, $i = 1,2,...,N$ is the particle's index, $d = 1,2,...,n$ indicates the particle's *d*-th components, c_1 and c_2 are the positive constants referred to as cognitive and social parameters, respectively (c_1 and c_2 are considered 1 in this study), and r_1 and r_2 are random numbers uniformly distributed in $[0,1]$, denoted as $r_1, r_2 \in [0,1]$.
Using PSO tsunami evacuation dynamics can be simulated in the following steps:

- Tsunami arrival time is used as the startup of evacuation. Every iteration in PSO is considered one second (*t*=1 sec).
- The population in each area is known (swarm). For each area depending on evacuation startup time, the PSO loop starts and runs the swarm toward the exit.

- In each iteration every evacuee moves to the new position with a new velocity using Eqs. (4.1) and (4.2), respectively.
- The evacuee behaviors can be considered as the extra terms (modifications) in velocity equation.
- For each swarm, the end of the run of PSO is the tsunami inundated time.
- The number of evacuees who could egress the area are safe and the rest are assumed victims.

5. CASE STUDY OF YURIAGE

The study applied the developed model to the tsunami evacuation analysis of Yuriage. For this study, we have modeled the human behavior during the evacuation process. However, the evacuation using car will be considered for future work. The following data were prepared as the input to the model:

- *Map data:* Figs. 1 and 2 show the map used for this study.
- *Distribution of inhabitants:* Table 1 used for population of each area. A total number of 28 routes were considered.
- *Time to start evacuation:* Fig. 3 summarizes the time to start evacuation corresponding to each route. It is assumed that the early evacuation routes corresponding to area 4 & 5 started with a 30 minutes delay after the earthquake.
- *Evacuation speed:* In Yuriage area, there are many narrow roads in which houses stand close together (width of routes are 6 to 12m), and the area is relatively aging society with more than 20%, and 12% of the population being over 65 years old and 75 years old, respectively. In consequence, rapid evacuation activity is not expected. Therefore, in this study, the evacuation speed was divided into two parts. The normal evacuees can have an automated varying velocity which calculated using Eq. (4.1) with a maximum of 1.5 m/s. The aged (over 75 years old) and handicapped evacuees are calculated using a velocity of 0.1 m/s.
- *Evacuation places and routes:* Based on the field survey results, many of the evacuees 15 min before tsunami arrival left the Yuriage Community Center to move to Yuriage Junior High School. Moreover, those who did early evacuation used a car to go to Yuriage Elementary School which is located in the area with inundation height of less than 2m and remained safe (please refer to Kawata, 1997). Therefore, the Yuriage Junior High School was considered as the final evacuation place. Routes mainly used for evacuation are depicted in Fig. 3.
- *Final tsunami inundation time:* Tsunami inundation time shown in Fig. 1 was considered as the end of evacuation. The evacuees remaining in the inundated area at that time were considered as the casualties.

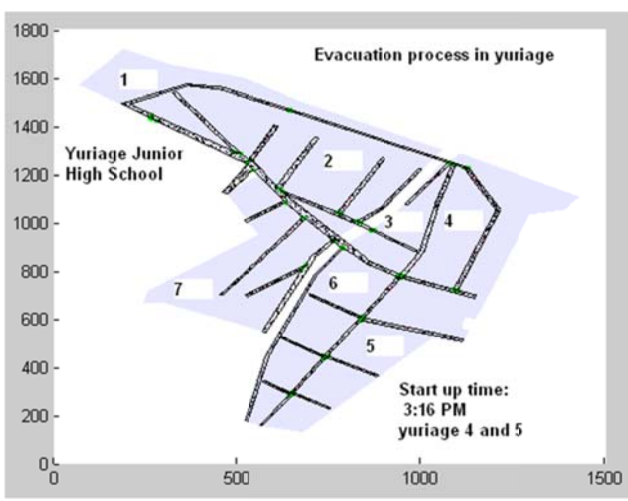

Figure 4. Simulation of evacuation progress starts at 03:16 PM from Yuriage 4 & 5 (axes show coordinates)

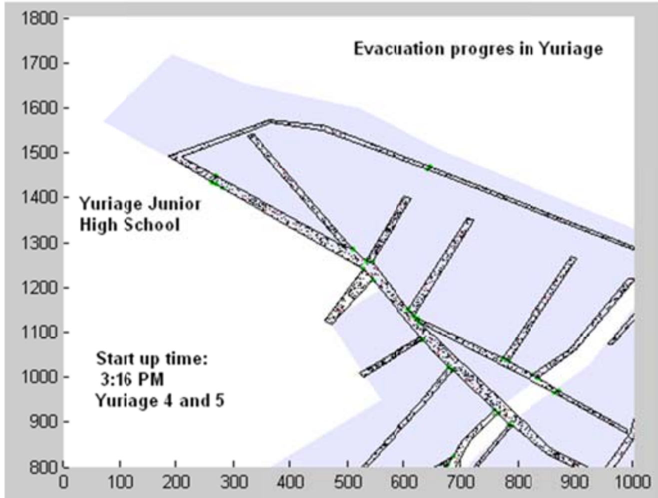

Figure 5. Simulation of evacuation progress starts at 03:16 PM from Yuriage 4 & 5

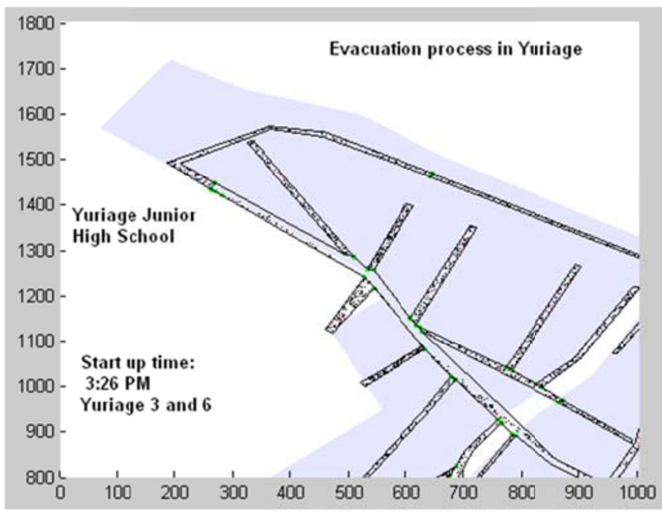

Figure 6. Simulation of evacuation progress starts at 03:26 PM from Yuriage 3 & 6

Fig. 4 shows the situation of evacuation at the beginning of evacuation. Figs. 5 through 8 depict different stages in evacuation processes started from different areas. Fig. 9 shows the area of the main evacuation route between the community center and junior high school where there is traffic congestion in and experienced a high death toll due to tsunami inundation based on the field survey data.

6. RESULTS

The final result of simulation for total human casualties is 685 deaths, which is close to the actual of 667 deaths. The result for simulating the number of casualties in each area due to tsunami inundation is compared with the actual human loss and shown in Fig. 10. As seen, the proposed model could appropriately predict the number of victims in most areas. However, the model needs more modification in terms of input data including more detailed layout of evacuation routes in two areas 6 and 7. Moreover, we have considered an average 12% rate for handicapped and elderly people which could be accurately included in analysis by actual rate for each area (Table 2.1) in the future.

From this study the survey findings by Murakami et al (2012) can be strengthened. Iimportant lessons learned from the tsunami disaster due to the 2011 Tohoku Earthquake that could be considered for further inclusion in the developed model includes:

- Many of handicapped and aged people were not able to move. In several cases, they preferred to go up to the second floor rather than to evacuate their houses. This caused an increase in the rate of casualties for elderly people. Therefore, the behavior of handicapped and elderly people in evacuation during a catastrophe may be separately modeled.
- Younger members of families often went to seek for their families and loved ones. Some could succeed in their efforts, but some of them were washed away with their loved ones. The seeking for loved people during a disaster is an important issue needs to be addressed as opposed to increasing the pre-evacuation time and disrupting the evacuation process because of contra flow problems when one seeks for loved ones instead of rapid evacuation.
- Using cars in evacuation needs to be treated since the traffic jam was among the main reasons for a high rate of fatality in Yuriage. Therefore, the swarm model we proposed should be extended to a multi-swarm model to include the effect of car-traffic flow.

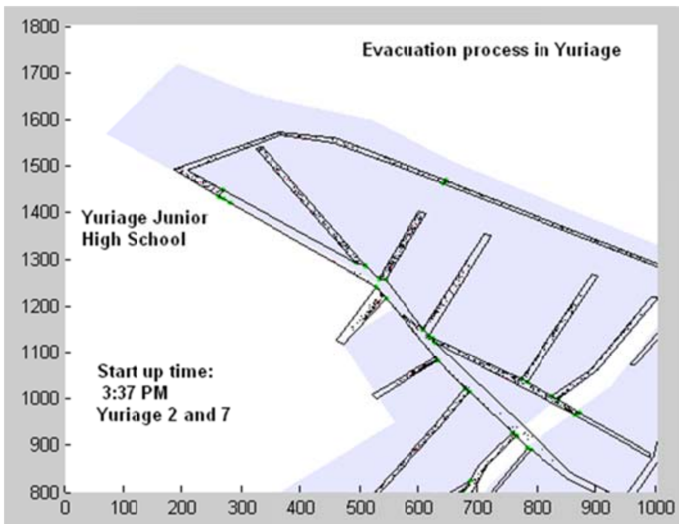

Figure 7. Simulation of evacuation progress starts at 03:37 PM from Yuriage 2 & 7

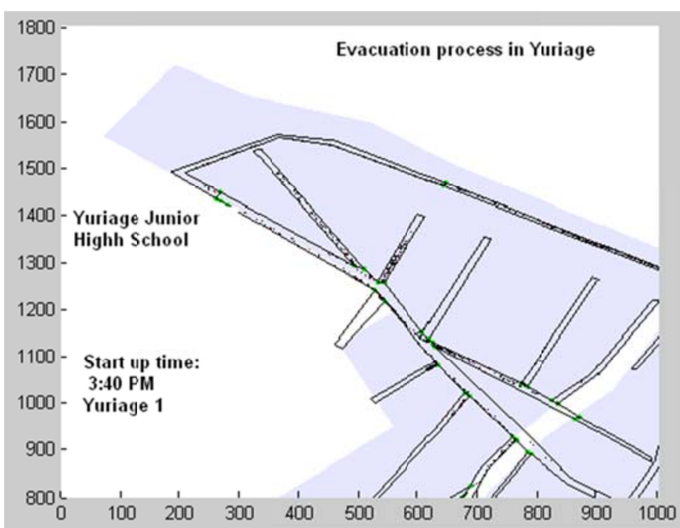

Figure 8. Simulation of evacuation progress starts at 03:40 PM from Yuriage 1

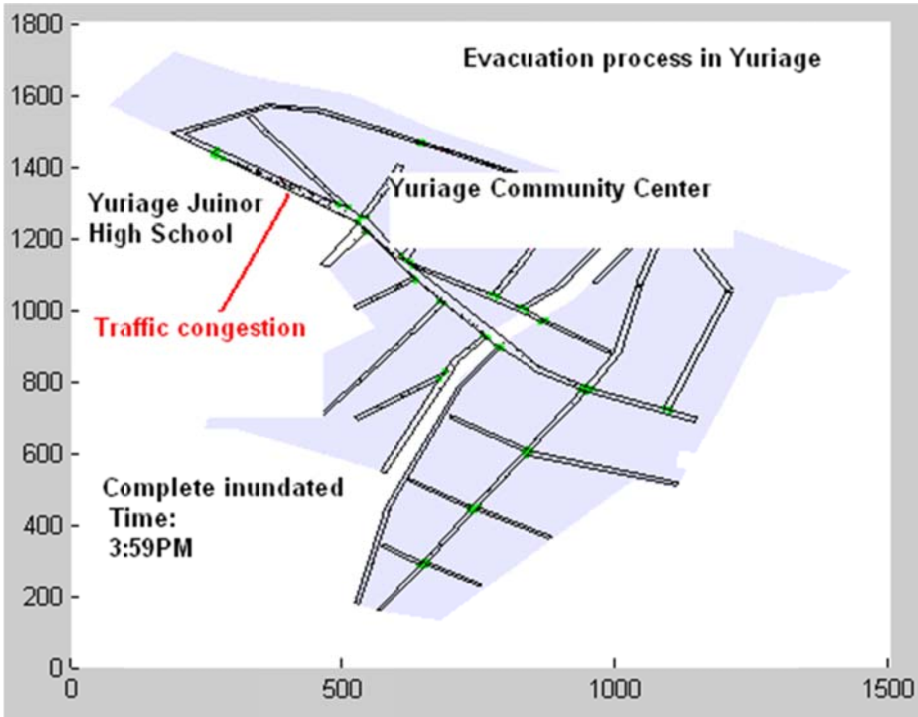

Figure 9. Simulation of evacuation progress starts at 03:59 PM
(The congested area had the most casualties when area inundated by tsunami at 04:00 PM)

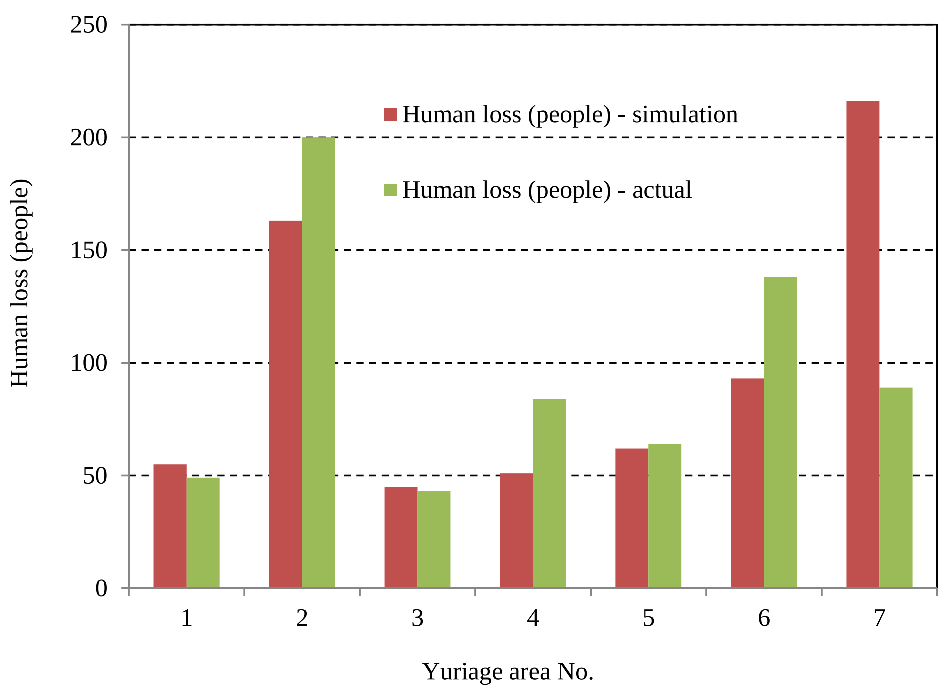

Figure 10. Comparison between results of simulation and actual for human casualties

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REFERENCES

Dulam, R.I., Maddegedara L., Muneo, H., Ichimura, T. and Tanaka, S. (2012). A study on effectiveness of using officials for reducing pre-evacuation time in a large area, based on multi agent simulations. *International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan.

Goto, Y. (2012). Fact-finding about evacuation from the unexpectedly large tsunami. *International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, Tokyo, Japan.

Javanbarg, M.B., Takada, S. and Scawthorn, C. (2012a). Multicriteria Prioritization Model for Earthquake Mitigation of Pipeline Networks, *Earthquake Spectra (2012 forthcoming)*.

Javanbarg, M.B., Scawthorn, C., Kiyono, J. and Shahbodaghkhan, B. (2012b). Fuzzy AHP-based multicriteria decision making systems using particle swarm optimization. *Expert Systems with Applications*, **39:** 960-966.

Kawata, Y.: 1997, Prediction of loss of human lives due to catastrophic earthquake disaster, *J. Nat. Dis. Sci.* **16:1**, 3-13.

Kennedy, J. and Eberhart, R.C. (1995). Particle swarm optimization. *IEEE international.*

Mikami, T., Shibayama, T., Esteban, M., and Matsumaru, R. (2012). Field survey of the 2011 Tohoku earthquake and tsunami in Miyagi and Fukushima prefectures, Coastal Engineering Journal, Vol. 54, No. 1, 1250011, pp. 1-26.

Murakami, H., Takimoto, K. and Pomonis, A. (2012). Tsunami Evacuation Process and Human Loss Distribution in the 2011 Great East Japan Earthquake- A Case Study of Natori City, Miyagi Prefecture. *15WCEE*, Lisbon Portugal.

Murakami, H. and Kashiwabara, K. (2011). Travel means for tsunami evacuation in the 2011 Tohoku Pacific Ocean earthquake – Questionnaire survey in Natori city. *Annual Conf. of the Institute of Social Safety Science*, No.**29**, pp.67-70.

Natori City Office (2011): Tentative proposal for Natori city earthquake disaster restoration, document 1, 21 August 2011, 55p. Available at: http://www.city.natori.miyagi.jp/fukkoukeikaku/node_13257/node_13487 [Accessed 2 February 2012].

NHK Special. (2011). *How to evacuate at huge tsunami disaster?*. Available at: http://www.nhk.or.jp/special/onair/111002.html.

Statistics Bureau (2011). *Statistics data of the Pacific coast in East Japan region related to damages*. Available at: http://www.stat.go.jp/info/shinsai/. [Accessed 20 December 2011].