Tsunami Evacuation Simulation for Disaster Awareness Education and Mitigation Planning of Banda Aceh

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SUMMARY:
Tsunami evacuation simulation combining tsunami inundation simulation and people evacuation sim0ulation was applied to the tsunami-prone area of Banda Aceh, Nanggroe Aceh Darussalam, Indonesia. People's evacuation was simulated based on multiagent simulation handling over 40,000 agent models, including walking family, motorcycle, and automobile agents. Agent ratios and their basic responses were defined in a survey of mass evacuation in Meulaboh, Nanggroe Aceh Darussalam, triggered by the May 7, 2010, earthquake. Several simulations were developed using different scenarios such as evacuation start timing, automobile evacuation ratios, and evacuee destinations. Simulations were shown to school students and to municipal office personnel. Based on their evaluations, this simulation proved to be effective in disaster education and city planning.

Keywords: tsunami, evacuation, simulation, multiagent model, disaster education

1. INTRODUCTION

The huge tsunami hitting Banda Aceh on December 26, 2004 washed away almost half of the city and killed a quarter -- 60,000 souls -- of the urban population (BRR NAD-Nias 2008). Although most of the city has been reconstructed by the efforts of the Indonesian government and many oversea donors, social measures as well as hardware action are needed to avoid having such a tragedy recur. Actually, Banda Aceh city office conducted a tsunami evacuation drill on November 2, 2008. However, it was expensive to conduct and presented difficulties in enabling many residents to take part.

One solution would be to use the tsunami evacuation simulation which simulates the evacuating only local people. This would easily teach the importance of quick evacuation and provide people with a chance to take part in a drill virtually on a computer. In Japan, tsunami evacuation simulation developed into one of the most effective disaster training tools available (Katada 2004).

We applied such simulation to Banda Aceh fitting local conditions, and studied suitable ways to implement it in community and school disaster awareness training and in urban disaster planning. For the first stage, the simulation targeted the western half of coastal Banda Aceh in order to verify the applicability, and then, it targeted all of the coastal area, which had a population of about 100,000.

2. TSUNAMI INUNDATION SIMULATION

The December 26, 2004, Indian Ocean tsunami was selected for simulation. Professor Shunichi Koshimura of Tohoku University analyzed the tsunami numerically (Oya 2006) and provided the results of his sophisticated tsunami inundation simulation of Banda Aceh for this study. He used a source model based on a seabed fault model of the Sunda trench and a nonlinear long-wave equation differentiated by the leapfrog scheme (Imamura 1995). The simulation was tuned using actual tsunami inundation records and evaluated for adequate accuracy for this study.

3. EVACUATION SIMULATION

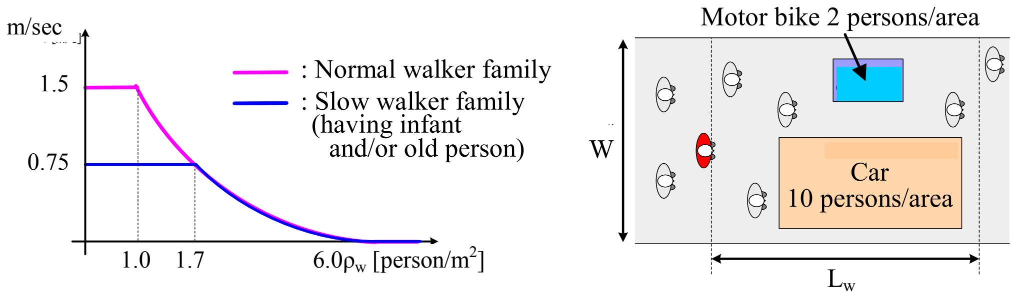
3.1. Methods and Basic Assumptions

The people evacuation simulation is a kind of crowd-flow simulations using multiagents (Helbing 2003), individual agents are modeled to move along a digitized road network following predefined rules:
1) Agents must follow road network data links from their houses to evacuation sites following the shortest possible path in terms of physical length for walking and motorcycle evacuation or the shortest time path in terms of time taken for automobile evacuation. For crowding, agents must slow down, and for traffic jam stoppages, they must wait or search for the second shortest path.
2) If the road is wide enough, faster agents pass slower ones.
3) The speed of an automobile agent is controlled by road width too.

3.2. Agent Modeling

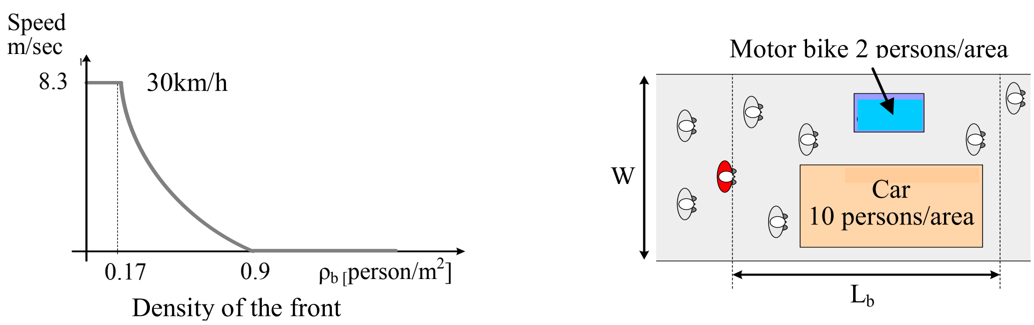
Our study assumed that individual persons belonged to families. Families as such were classified into (i) normal walkers, (ii) slow walkers, (iii) motorcyclists, and (iv) automobile occupants. In walking and automobile evacuations, 1 family was modeled as 1 agent. In motorcycle evacuation, 1 family was broken down into pairs modeling each pair as 1 agent.

3.2.1. Walking evacuation
Normal walkers moved at a maximum of 5.4 kilometers/hour. Slow walkers, representing families with handicapped, older, and infant members moved at a maximum of 2.7 kilometers/hour. The ratio of slow walkers was determined from door-to-door interviews. Figure 3.1. shows the relationship between walking speed and density of agents in front. Speed decreased with increasing density, stopping at a density 6.0 person/m^2. In calculating density of agents in front, an automobile was assumed equivalent to 10 walkers and a motorcycle to 2 walkers.



ρ_w is density of agents in front for a walker defined by ρ_w= n/(Lw×W),
where n: number of persons in L_w×W area, L_w: search length (3 meters), W: road width

Figure 3.1. Walking speed and density of agents in front



ρ_b is density of agents in front for a motorcycle defined by ρ_b= n/(L_b×W),
where n: number of persons in L_b×W area, L_b: search length (16.7 meters), W: road width

Figure 3.2. Motorcycle speed and density of agents in front

3.2.2. Motorcycle evacuation

Figure 3.2. shows the relationship between motorcycle speed and density of agents in front. When the density on a road was less than 0.17 person/m^2, then motorcycle speed was 30 km/h. Speed decreased with increasing the density, becoming the same as a walker's at a density of 0.9 person/m^2.

3.3. Automobile Evacuation

Automobiles took the path taking the shortest time to a destination, assuming an automobile to be 5.7m long -- 4.7m body plus 1m minimum clearance -- and 1.7m wide. In the absence of obstacles, automobiles moved freely for $L_f = V_f \times \Delta t$, where L_f: free run distance (Figure 3.3.), V_f: free movement speed, Δt: time step. The maximum free run speed was 40 km/h when a road was over 4 meters wide, decreasing based on width as shown in Figure 3.4.

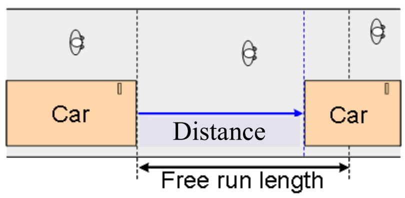


Figure 3.3. Definitions of inter-vehicular distance and free run length

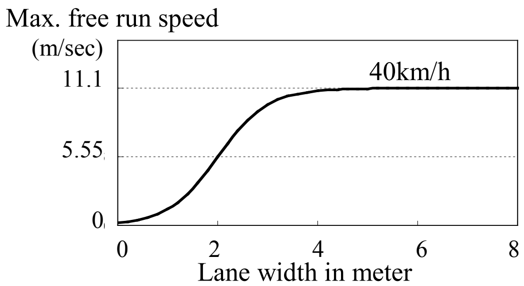
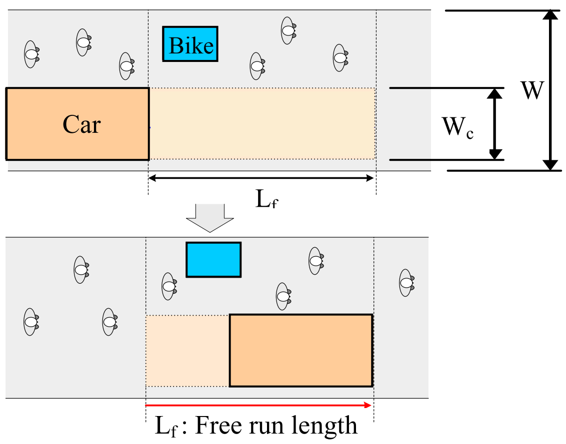


Figure 3.4. Automobile speed and lane width

(1) For 1 lane (5m>road width), with other automobiles at least L_f away and density of agents in front for automobile ρ_c less than 1.0 person/m^2, the automobile moved until L_f.

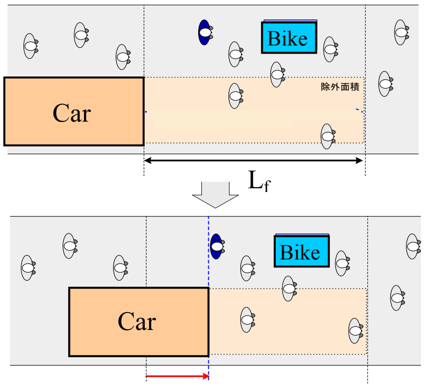


Density of agents in front for automobile : $\rho_c = \dfrac{n}{(W - W_C) \times L_f}$

Where n: number of persons in $L_f \times W$ area
W: Road width
W_c: Car width

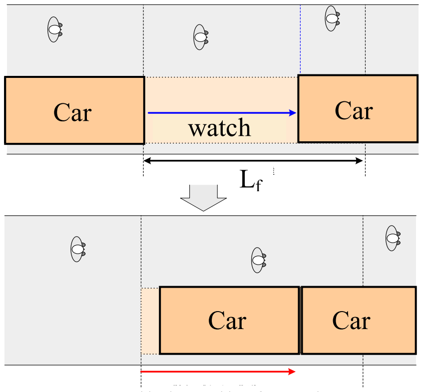
Figure 3.5. No other automobiles and ρ_c<1.0 person/m^2

(2) For 1 lane (5m>road width), with other automobiles at least L_f away and density of agents in front for automobile ρ_c more than 1.0 person/m^2, the automobile could move until meeting the nearest walker or motorcycle, as shown in Figure 3.6.
(3) For 1 lane (5m>road width), with another automobile within L_f and density of agents in front ρ_c in inter-vehicular distance less than 1.0 person/m^2, the automobile could move until meeting the tail of another automobile, as shown in Figure 3.7.
(4) For multiple-lane roads (11m>3-lane road width >8m> 2-lane road width >5m), automobiles could change lanes to a vacant lane as shown in Figure 3.8. Walker and motorcycle agents entered the left end automobile lane first and, if density ρ_w exceeded 1.0 person/m^2, they entered the next left automobile lane.



Move until the nearest obstacle

Figure 3.6. No other automobiles but ρ_c>1.0 person/m^2



Move until the tail of another car

Figure 3.7. Another automobile ahead and ρ_c<1.0 person/m^2

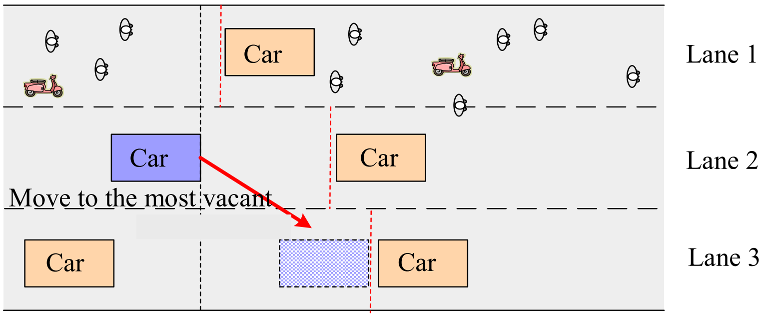


Figure 3.8. Multiple-lane case

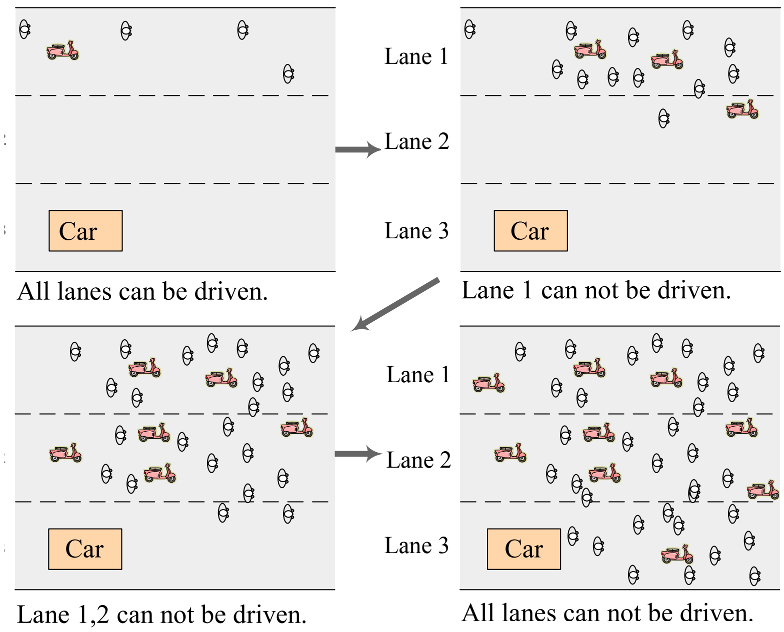


Figure 3.9. Occupation by walkers and motorcycles

4. SUPERIMPOSING TSUNAMI SIMULATION ON EVACUATION SIMULATION

The basic concept for superimposing tsunami inundation simulation on evacuation simulation in the same time-domain originated in a series of studies by Professor Toshitaka Katada (2004, 2006). In our study, we took into account the effect of tsunami inundation on agent mobility. Evacuee location and tsunami depth at the location were calculated step by step linking the 2 simulations into a common time domain. An agent trapped by the tsunami slowed in speed inversely proportionally to tsunami depth and stopped -- "died" -- when depth exceeded 1 meter.

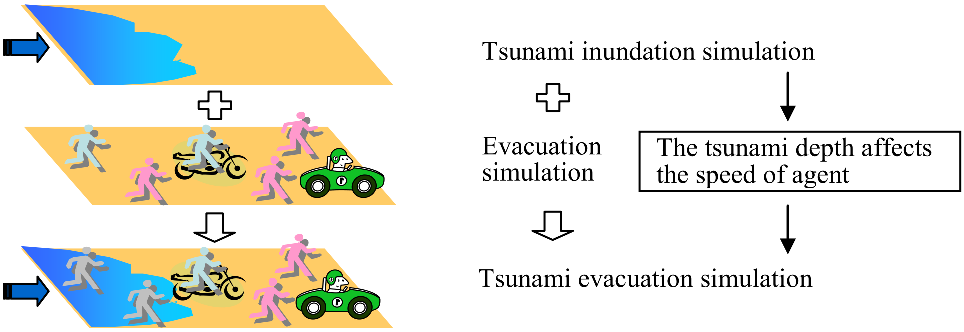


Figure 4.1. Superpositioning concept

5. DATA FOR SIMULATION

5.1. Geography and Population

5.1.1. Road network

Road network data was built from Quickbird satellite images acquired on February 23, 2009 and from field surveys. Data contained origin node data (serial number), terminal node data, and link width (road width) data (Figure 5.1.).

5.1.2. Population

Population data was developed from door-to-door interviews of residents. House-by-house data contained the number of families, ages of family members, and information on handicaps.

5.1.3. Front door

"Front door" data was simulated as the evacuation starting point. The front door was located by identifying the house from Quickbird images and confirmed in house-by-house surveys. Front door data contained building ID and coordinates.

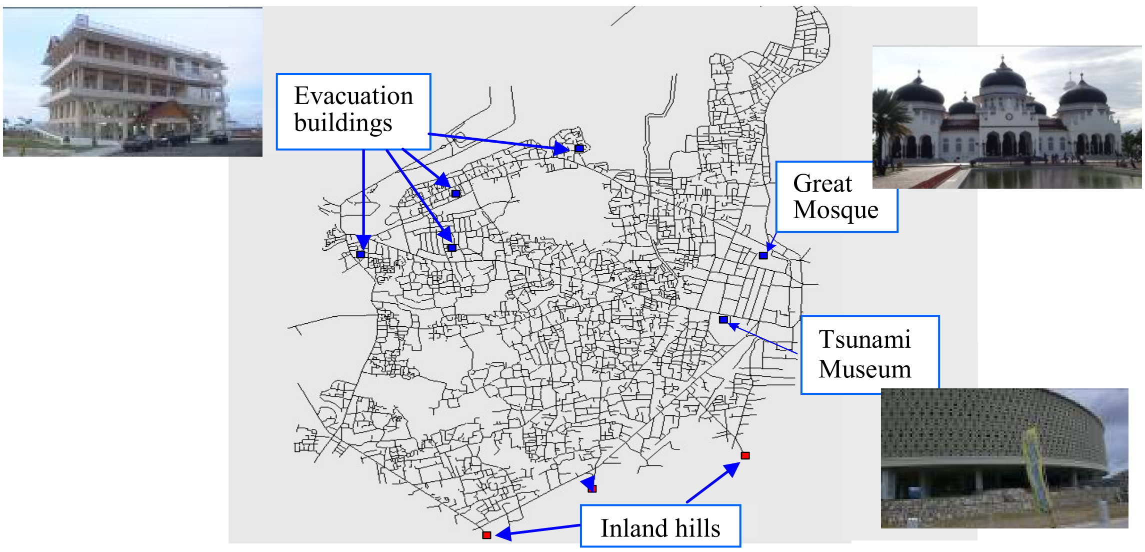


Figure 5.1. Road network and evacuation destinations for modeling the western half of Banda Aceh

5.2. Evacuation Destinations and Capacity

We set 9 evacuation destinations -- 4 evacuation buildings, the Grand Mosque, the Tsunami Museum, and 3 inland hills. Automobile agents were assumed to go to the nearest inland hill among 3. Motorcycle agents were assumed to go to the nearest destination among Grand Mosque, Tsunami Museum, and 3 inland hills. Walker agents were assumed to go to the nearest destination among the 9.

Table 5.1. shows the assumed capacity and entry speed of evacuation sites. The Grand Mosque could house up to 7,600 evacuees and had no entry speed limits due to its open-walled architecture. Other Evacuation buildings and the Tsunami Museum had limited housing capacity and limited entry of 20 persons/second based on entrance gates, which were 10 meters wide.

Table 5.1. Evacuation destination capacity

Destination	Housing capacity (persons)	Entry speed (persons/second)
Inland hill	Unlimited	Unlimited
Evacuation buildings	1,000	20/second
Grand Mosque	7,600	Unlimited
Tsunami Museum	4,000	20/second

5.3. Agent Behavior

To get data on people's behavior, we surveyed people in Meulaboh, the third large city in Nanggroe Aceh Darussalam. A M7.2 earthquake at 50 kilometers south of Meulaboh (Figure 5.2) on May 9, 2010 resulted in massive disorder evacuation (Nurdin 2011). Meulaboh was also one of the cities worst affected by the December 2004 tsunami, which left 15,000 dead from among a population of 80,000. The May 9 earthquake did not generate a tsunami, but was large enough to raise tsunami fears in the minds of residents, who created huge jams in their hurried attempts to evacuate.

We interviewed 250 residents in Meulaboh's tsunami risk area using questionnaires and analyzed the following (Figure 5.3.-5.6.) from data:

Figure 5.2. Earthquakes on March 7 and May 9, 2010

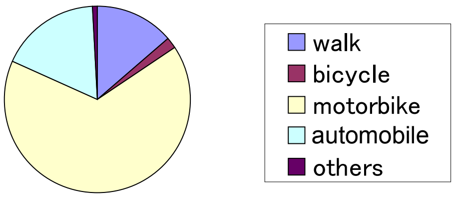


Figure 5.3. Method of evacuation

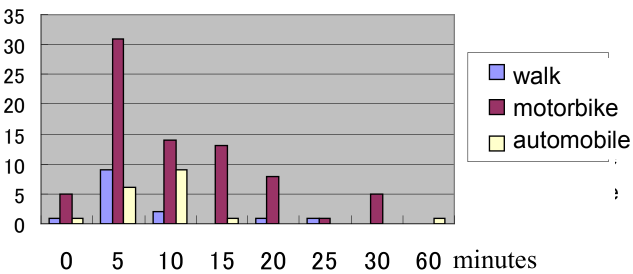


Figure 5.4. Time needed to start evacuating

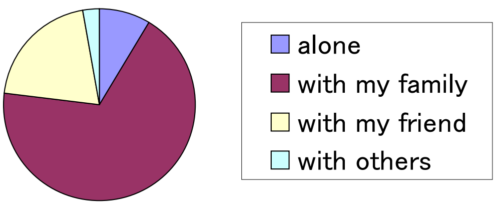
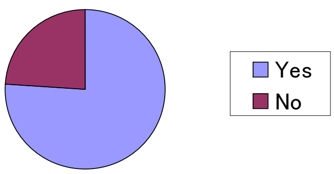


Figure 5.5. With whom evacuated?



Figur 5.6. Trapped in traffic jam?

6. SIMULATION CASES AND SCENARIOS

6.1. Cases

Five cases were simulated under different evacuation scenario methods and timing.

Case 1: Standard. People started evacuating after hearing sirens. The ratio of evacuation methods was evaluated from the survey in Meulaboh (Figure 5.3.).

Case 2: Ratio of automobile evacuation increase

Case 3: Automobile evacuation was inhibited.

Case 4: People changed their destination when they noticed the first destination was filled by others.

Case 5: People started to evacuate after seeing tsunami coming.

Table 6.1. Ratio of those evacuating by walking, motorcycle and automobile

Transport/Case	Walking	Motorcycle	Automobile
Case 1	1/6	2/3	1/6
Case 2	1/6	1/2	1/3
Case 3	1/4	3/4	0
Case 4	1/6	2/3	1/6
Case 5	1/6	2/3	1/6

6.2. Common Basic Scenarios of All Cases

1) Evacuees needed time to prepare after noticing the emergency. The time to prepare and deviation were introduced based on data from Meulaboh (Figure 5.4. and Table 6.2.).
2) Motorcycle and automobile agents were created in random sequence from all families up to a preset number.
3) All families were assumed to be at home when the tsunami occurred and to start from their front doors. They were to become casualties when surrounded by tsunami waters over 1 meter deep.
4) Sirens were assumed to have sounded 10 minutes after the earthquake.

Table 6.2. Time to prepare for evacuation and evacuation trigger

Case	Walking (min)	Motorcycle (min)	Automobile (min)	Evacuation-decision trigger
Case 1-4	5.0, σ=1	7.5, σ=2.5	8.3, σ=1	Hearing siren 10 minutes after earthquake
Case 5	3.3, σ=0.67	5.0, σ=0.67	5.5, σ=0.67	Seeing tsunami 35 minutes after earthquake

Case 5 Time to prepare was made shorter because people evacuated right after seeing the tsunami itself.

7. RESULTS FROM SIMULATION ABOUT THE WESTERN HALF OF BANDA ACEH

7.1. Understandability

We monitored understandability through trial disaster education in schools. After showing simulation together with a short lecture, questionnaires were given to 220 elementary (fourth to sixth grade), middle, and high schools in Banda Aceh. Typical results are shown in the figures below. The right answer is second column in each figure. The question about timing was easy to answer (Figure 7.1.). But that about destination was tricky (Figure 7.2.), because evacuation building capacities were limited and only families having handicapped members should go there and others were encouraged to go to other evacuation places. Most students, even in elementary school, selected “right” answers.

7.2. Typical Disaster Education Results

Figure 7.3. shows Case 3 to be the most favorable because people did not use automobiles. Case 5 was considered the worst because people started evacuating after seeing the tsunami itself and had too little time to reach safe destinations.

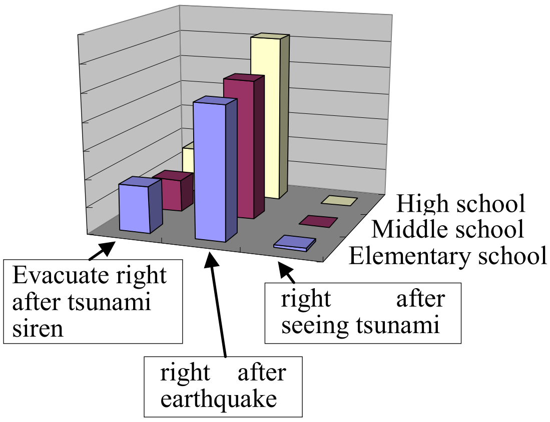


Figure 7. 1. Evacuation timing

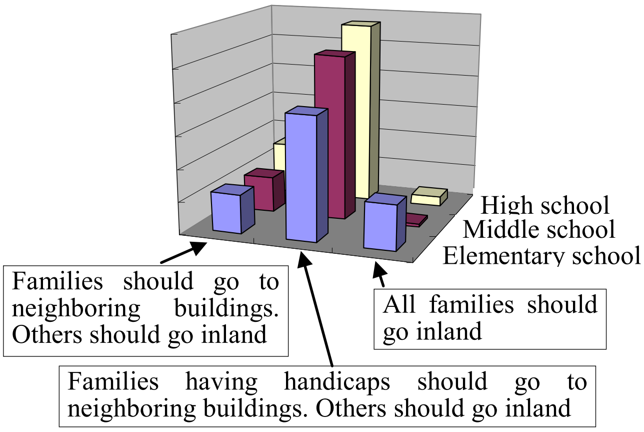


Figure 7.2. Evacuation destination

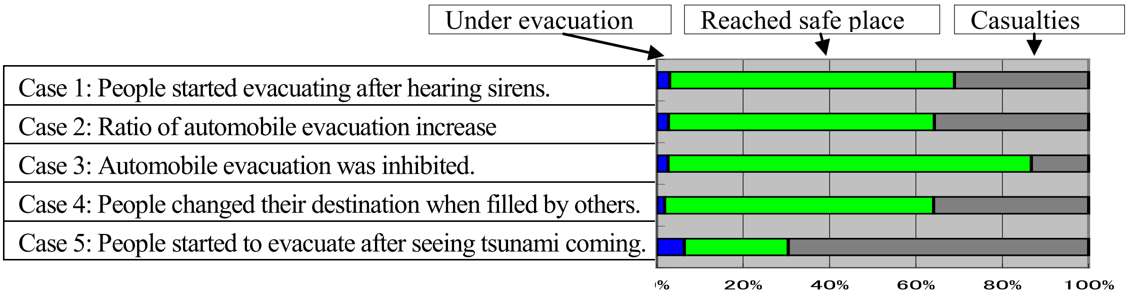


Figure 7.3. Results of 5 cases 1 hour after earthquake

7.3. Typical Evacuation Control Results

Table 7.1. shows evacuation destination occupancy. For Cases 3 and 4, the Grand Mosque and Tsunami Museum were 100% occupied by evacuees, most of whom had used motorcycles to get there. In contrast, buildings designated for evacuation were all relatively empty – a result of the scenario in which all motorcycle evacuees were conducted inland to leave building space for those walking. Some of the motorcycle evacuees should have been conducted to buildings designated for evacuation.

Table 7.1. Evacuation destination occupancy

	Great Mosque	Tsunami Museum	Evac. Bld. A	Evac. Bld. B	Evac. Bld. C	Evac. Bld. D
Capacity (persons)	7,600	4,000	1,000	1,000	1,000	1,000
Case 1 (%)	100	96	16	16	20	14
Case 2 (%)	94	86	17	19	19	13
Case 3 (%)	100	100	30	23	28	19
Case 4 (%)	100	100	16	16	20	14
Case 5 (%)	47	22	7	1	6	5

7.4. Typical City Planning Results

Starting points of individual evacuees are known from the simulation data. Red dots in Figure 7.4. are places where casualties started evacuating. Even in best case 3, some casualties had no effective way to survive. In areas (a) and (c) in Figure 7.4. new evacuation buildings should be constructed to save those who could not reach existing destinations. Especially in area (c), casualties were due to the limited capacities of the Grand Mosque and Tsunami Museum. Existing roads toward inland hills from area (c) should also be widened. In area (b) near buildings designated for evacuation, many casualties occurred because motorcycle evacuees trying to reach the Grand Mosque, the Tsunami Museum, or inland hills were trapped in traffic jams. Some motorcycle evacuees should therefore be encouraged to go to the nearest evacuation building as shown by arrows in area (b) in Figure 7.4.

8. SIMULATION OF ALL COASTAL AREA

As the actual usage, the eastern half area of Banda Aceh was also modeled and the evacuation of all coastal area (west + east halves) was simulated. The total number of agents was 40,000 and the usage of a vector method (network method) instead of a mesh method enabled computation by standard PC.

On demand simulation function was added in order to respond the request from the teachers and the city personnel who monitored the applicability of the simulation. As the result, a user can input his/her own evacuation route and method to the computer and try its adequacy through executing simulation by his/her demand, by knowing with little waiting time whether his/her agent can evacuate safely among congested other agents. Figure 8.1. shows a trace of the moving of the agent evacuating by motorbike, and Figure 8.2. shows the agent being trapped in a traffic jam.

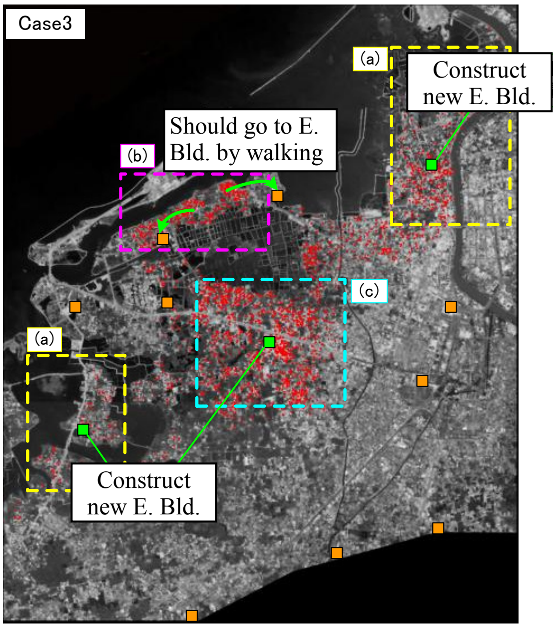


Figure 7.4. Casualties' starting point distribution from case 3 simulation results

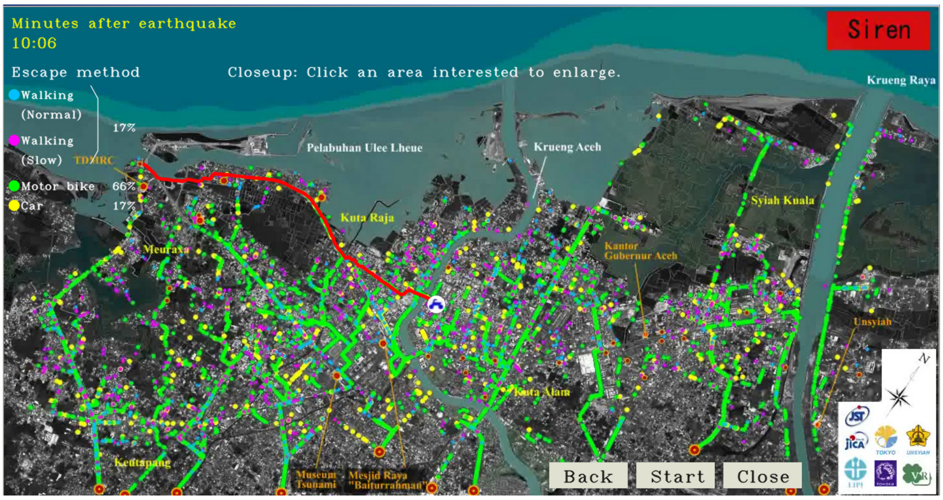


Figure. 8.1. The red line is the trace of the user input agent moving by a motorbike

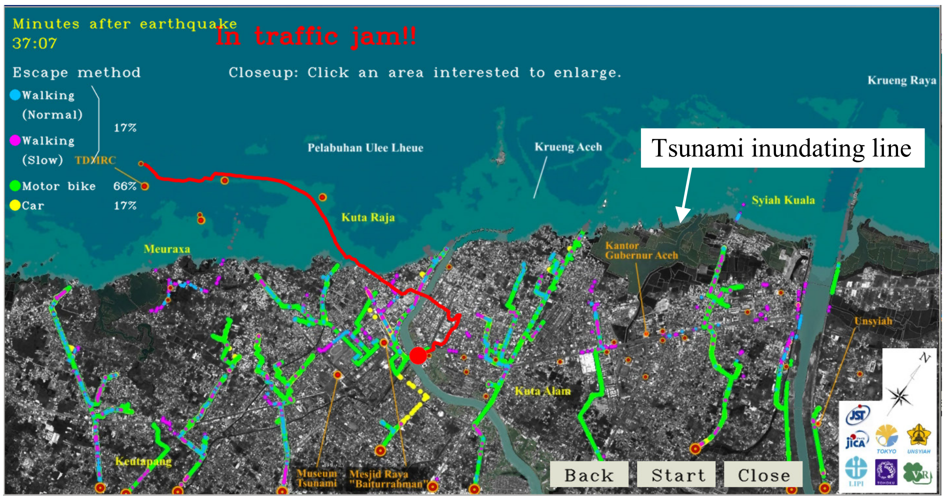


Figure 8.2. Tsunami is coming, but the agent is trapped in a traffic jam

9. CONCLUSIONS

(1) Questionnaires given to elementary, middle, and high school students confirmed that tsunami evacuation simulation was easily understood. The simulation also proved substantially effective for personnel such as city planning office and disaster operation organization workers dealing with disaster management.

(2) Based on simulation results, local authorities should heed the following recommendations:

(i) Automobile evacuation should be limited, and some evacuation using motorcycles should be conducted toward buildings designated for evacuation.

(ii) Several more buildings designated for evacuation should be constructed in air pocket areas.

(iii) The capacity of the Great Mosque and Tsunami Museum is limited, and more effective guidance should be established for evacuees.

(iv) Some evacuation routes to the inland hills should be improved.

(3) We developed simulations of the whole Banda Aceh coast for actual use and an on-demand simulator in which users can enter their own evacuation routes and check their adequacy by executing simulations.

(i) The simulation of the whole coast area clearly identified the bottle necks of escape roads from the coastal area to the inland. There is a main road running from northeast to southwest in Banda Aceh central area. All of the escape roads have to pass across this main load. The crossings originating traffic jams should be improved.

(ii) The on demand simulation displayed by a touch panel computer was easily operated by children as far as they could read words on the display. High efficiency of the on demand simulation to disaster education could be expected.

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