Invited Paper

EVALUATION OF TSUNAMI EVACUATION ROUTES AT BENGKULU CITY INDONESIA USING NUMERICAL SIMULATIONS

Radianta Triatmadja[1] and Sultan Sidik Nasution[2]

[1] Department of Civil and Environment Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia, e-mail: radiantatoo@yahoo.com

[2] Department of Civil and Environment Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia

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Abstract

Tsunami may attack Bengkulu City at any time. Although the City has prepared evacuation shelters and signboards at strategic locations to direct people to the shelters, the roads from the tsunami prone inundation areas that lead to the shelters should be evaluated to assure their reliability. A numerical simulation based on multi agents was used to study the routes' capacity for evacuation during tsunami hazard. The approximated time available starting from the earthquake was 20 minutes. The first five minutes up to ten minutes were considered as the time for the government to state whether an evacuation was necessary or for the people to get ready for the evacuation. Five scenarios were tested. These were normal condition where the people were assumed to follow the existing evacuation sign boards, normal condition but with alternative direction of evacuation, a condition with obstacle during peak hour at a market, evacuation during night time, and a normal condition with increasing population. The simulation indicated that under normal condition, most of the people reached the shelter in less than 20 minutes. The alternative evacuation direction performs slightly better. The obstacles due to cars that were parked along the roads slightly increased the number of casualties. Evacuation scenario during the night time increased the casualties due to the limited vision especially along the lanes. The evacuation route should be well prepared especially during tsunami event in the future.

Keywords: Bengkulu, Evacuation, Numerical, Preparedness, Simulation, Tsunami

Introduction

Bengkulu Province on the west side of Sumatera Island Indonesia is prone to tsunami attack. Historically, the province has experienced a number of earthquakes which some of them were tsunamigenic. There were two large earthquakes in 1818 and 1833 at Richter scale of 8.8 [1] whilst a 7.3 Richter scale earthquake struck Bengkulu in the year 2000. Another large earthquake happened in 2007 at 8.4 Richter scale where the center was at 4.517˚ S-101.382˚ E at a depth of 30 km under the boundary between Indo-Australian plate and Eurasian plate which triggered tsunami [2]. Within the last decade, there were 10 tsunami events in Indonesia, in which four of them directly hit Sumatera Island. Table 1 shows the tsunami events along the Sumatra Island including Bengkulu [1]. It can be inferred from Table 1 that Bengkulu is prone to tsunami and that mitigation and preparedness against the hazard is necessary.

Bengkulu City is divided into 3 zones with different risks categories (the high risk zone, the medium risk zone and the low risk zone). The high risk area includes Malabero village and Sumur Meleleh village. These villages are densely populated residential areas bordering the Indian Ocean.

In 2012, the local government of Bengkulu City published a Regional Regulation that regulates urban land use plan. The regulation includes the evacuation routes during natural hazards such as tsunami. The evacuation routes and shelter location for Malabero village and Sumur Meleleh village have been determined. The main routes for the evacuation were through Pendakian road, – Ahmad Yani road, Letkol Barlian road –Sint. Carolus road – Ps. Barukoto II road leading to the Merdeka square (shelter area). The Bengkulu City, Malabero village and Sumur Meleleh village are shown in Figure 1.

Table 1. Tsunami Hazards along the West Sumatera Island

Date	Magnitude (RS)	Epicenter	Arrival time (minutes)	Location	Height (meter)	Casualties
26 -12-2004	9	N-West Sumatera	33	Aceh, Meulaboh	50.9	165.000
28-03-2005	8.7	N-West Sumatera	43	Padang Sidempuan	3	800
12-09-2007	8.4	Bengkulu, Sumatra	35	Bengkulu	0.98	25
25-10-2010	7.2	Mentawai, Sumatera	10	Mentawai	8	413

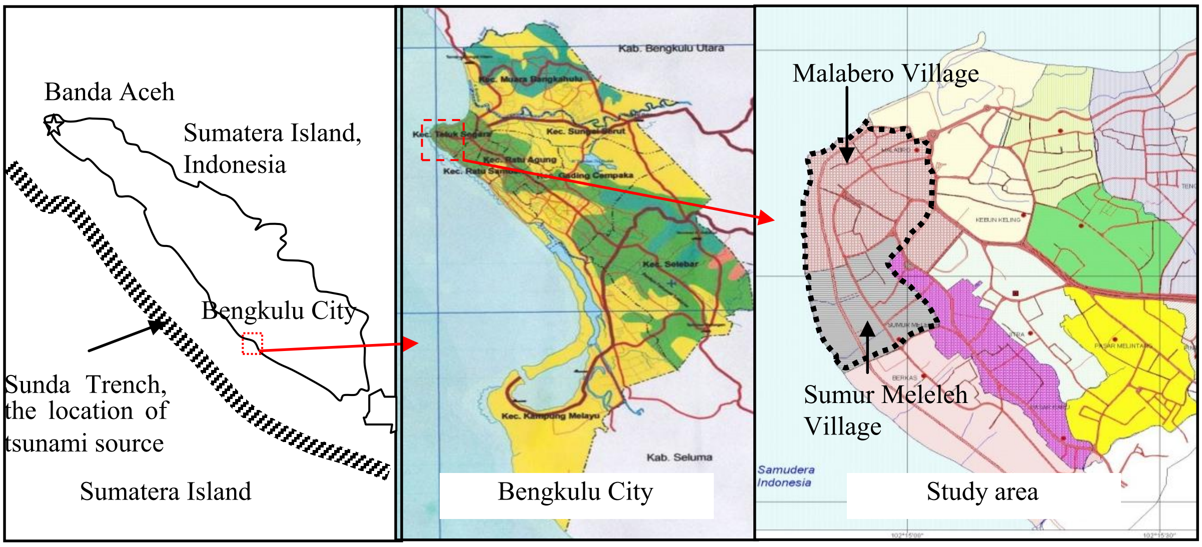

Figure 1. Sumatera Island, Bengkulu City, Malabero and Sumur Meleleh villages

In order to evaluate the capacity of the evacuation routes, two methods of simulation can be employed. The first is the physical simulation where people are employed to simulate the evacuation. This method is very costly, need much longer time to prepare, difficult to control, high risk, and with limited scenarios. However, the simulation may also provide hand on experiences for the people regarding what and how they have to do during the hazard. The second method is the numerical simulation. This method is much simpler, much cheaper and can simulate many scenarios without risk. Numerical simulations however may only be used to evaluate the road capacities and evacuation scenarios without providing hand on skill experiences to the people. With such limitations, the numerical simulation is expected to provide feedback to the local government whether they have to upgrade the evacuation routes for better preparedness. The present study is partly aimed at providing the local government a preliminary evaluation regarding the tsunami evacuation routes capacity.

Numerical Algorithm and Assumptions

Numerical Algorithm

Numerical simulations during tsunami hazard have been utilized by many researchers such as those by [3,4,5,6, and 7]. A number of software for the simulations have also been available with a range of sophistication as can be seen from [8]. Detail numerical simulations that simulate the movements of the people along the evacuation routes normally based on the multi agents method. In this method one person is represented by one agent that acquires a number of properties such as capacity to run, dependency to other agent, and domination against other agent. The agents are placed in certain area prior to the evacuation. The minimum distance or the best routes are then provided for all of the agents. There are a number of methods or algorithms to determine such routes for example Dijktra's algorithm [9] and A* algorithm [10]. The area of study should be divided into grids. The size of the grids is as small as possible to make the movement of the agents accurate. However the smaller is the grid size the more is the number of the grids, the required memory and the time consumption required to run the program. With Dijkstra algorithm, the best route to the shelter should be made available for all the grids that can be occupied by the agents. A* algorithm however is designed to detect a route to the shelter by minimizing the search. Therefore, for a small number of agents A* algorithm is faster than the Dijkstra algorithm. The algorithms basically select the best routes by giving values to all the nodes (grid crossing). The agent will follow the route by moving to the node with the smallest value adjacent to node occupied by the agent until it arrives at the smallest value of the node which is the shelter. In this study however, the algorithm of finding the best path followed that of [11]. Unlike the Dijktra's algorithm or A* algorithm the algorithm described by [11] is based on prior knowledge of known paths or routes. Instead of letting the algorithm to select the entire area for the best routes to the shelter, the algorithm described by [11] required a determined main direction or routes. Such difference is explained in Figure 2.

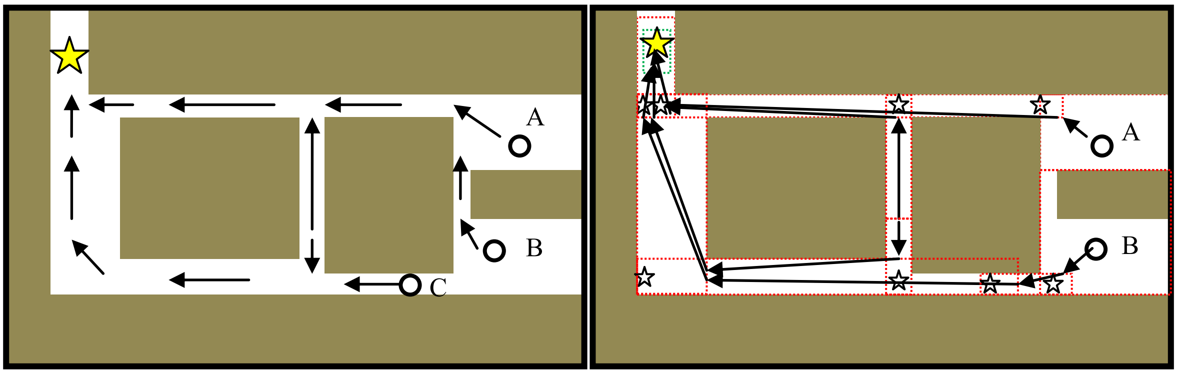

Figure 2. Description of the algorithm. (a) The best routes are defined by Dijkstra's algorithm (b) The routes are determined manually by assigning transitory shelters (small stars symbol) and finally to the shelter (large stars symbol). Only part of the area

In Figure 2(a), the direction of the evacuation (arrow signs) are automatically provided by the A* and Disjkstra algorithm, whilst in [11] they have to be provided by the user (manually) by defining a series of transitory shelter. Each transitory shelter is provided for certain area. Only agents that are in the area of transitory shelter will be directed to the transitory shelter. A certain value is given for each transitory shelter. The values of the transitory shelters are smaller as they get closer to the shelter. The value of the shelter node is the smallest. When an agent is in two different transitory shelters of different values, the agent will be directed to the transitory shelter with smaller value. Hence, before reaching the shelter, the agents should be given entry to a number of transitory shelters areas with gradually smaller value. The transitory shelters are designed not to contain any obstacle so that all nodes within the transitory shelter area have straight routes to the transitory shelter. The algorithm within the transitory shelter area becomes straight forward. The movements of the agents follow the nodes as described in Figure 3.

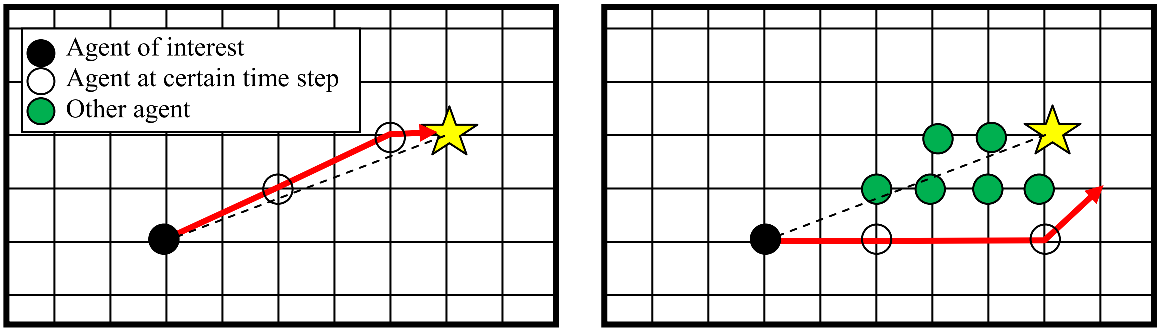

Figure 3. Example of an agent movement (a) without obstacles (other evacuees) and (b) with other evacuee as obstacles

In this algorithm the agent may move Δs to an empty node that is the closest to the straight line connecting the agent with the shelter during one time step. When the node is occupied by another agent, the next node is considered as the new target (Figure 3b). The distance Δs depends on the time step, running capacity of the agent, the road condition, and the number of other agents surrounding the agent of interest. Since the time step and the grids are discrete, there may be a residual distance during one time step. This distance is stored and added for the next move. If due to the surrounding condition (very crowded condition) the agent cannot move the maximum distance (the capacity plus the residual distance) during a one time step, the residual distance is cleared. During one time step the agents move one after another. Smaller time step provides more accurate result as it avoids the situation where one node is used by more than one agent at the same time step.

Assumptions used in the Algorithm and Simulations

There were a number of assumptions used in the simulation. The agents were assumed to be on the roads or outside of the buildings prior to evacuation. This might not be a realistic assumption if the starting time of the evacuation was the same as the earthquake event. Based on the standard operating procedure, it may take some time before the local government issued the evacuation instruction. Many people tend to wait and see the respond of their neighbors before conducting evacuation. Assuming that the first 5 minutes after the shock were used for preparation, it was realistic to assume that all the people were outside the building and ready for evacuation. The number of the people was assumed equals the whole population in the area of study which was 3673. The distribution of their locations at the start of the evacuation was assumed to follow the number of people in the neighborhoods. There were 19 communities or neighborhoods in the study area. The distribution of the population based on age in both villages is given in Table 1. Based on Table 1 and Figure 4, it appears that the density of the population in Malabero village was higher than that at Sumur Meleleh village.

The evacuation was assumed to be conducted by foot. No car and motorcycle were utilized. This might not be a good assumption as in reality people tend to drive their cars for the evacuation. During the chaos, where people are in a hurry, the use of cars may bring about accidents that lead to traffic jam. The use of automobiles should be limited for evacuation in Padang City during tsunami event [7]. Motorcycle is more flexible as they may go easily with the crowd this could be the reason why evacuation to certain shelters need motorcycles [7]. The false issue that the earthquake in Bantul regency Indonesia in 2006 has triggered tsunami made people panic. People that believed in the issue tried to evacuate using their cars and motorcycles and created severe traffic jam with approximately 3 km of line up cars and motorcycles stagnant along the street of Parangtritis-Yogyakarta [12]. In this study, the roads intersections were many as can be seen in Figure 4. Such crossroads could be the origin of traffic jams. In addition, the total average distance of the evacuation was relatively short (less than 1 km). Therefore it was assumed that in this study no cars and motorcycles were utilized for evacuation.

Table 2. Population in the Study Area

Age	Malabero Village (people)	Sumur MelelehVillage (People)	Total (People)
00 - <4	188	65	253
≥ 4 - <10	155	113	268
≥ 10 - <20	333	215	548
≥ 20 - <30	767	181	948
≥ 30 - <50	655	345	1000
≥ 50 - <70	421	157	578
≥ 70	47	31	78
Total (all ages)	2566	1107	3673

Source : Respective village offices (2013)

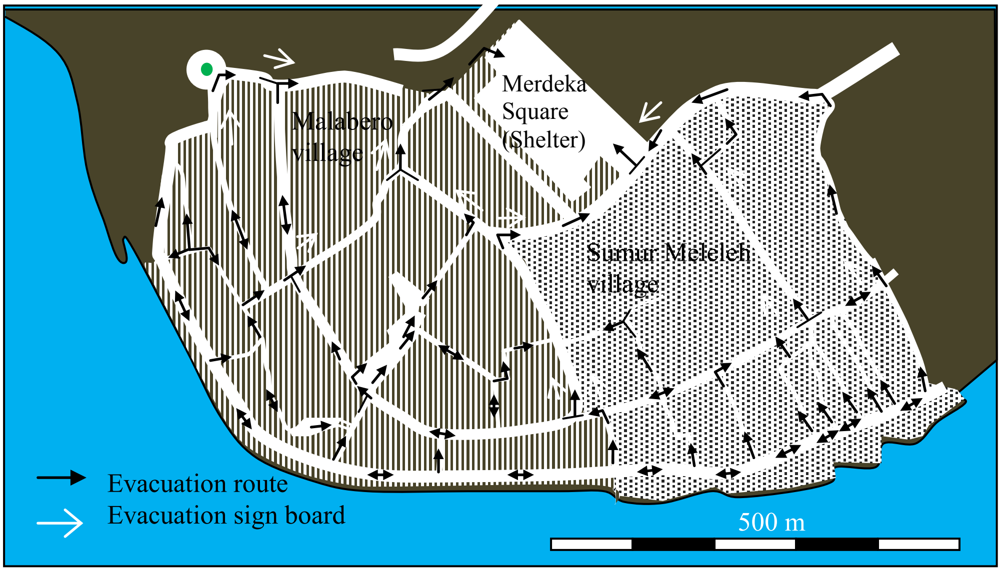

Figure 4. Map of Malabero and Sumur Meleleh villages and evacuation routes

The road condition along the evacuation routes were assumed as follows. The night light conditions, unpaved roads, and sloping roads were considered to affect the performance of the road and hence the running speeds of the agents. The assumption for the reduction of the running speed is given in Equation 1.

$$V = C_R C_v V_c \qquad [1]$$

where V is the running speed, V_C is the maximum speed of the agent, C_R is the coefficient due to road condition, C_S is the coefficient due to slope and C_V is the coefficient due to the visibility. C_S is assumed as follows

$$C_S = e^{-\tan(1.5\alpha)} \text{ ; for } \alpha < 40^o \qquad [2]$$

where α is the road slope in degree. The assumption (Equations 2) suggests that the running speed reduces to 75% and 6% for a road slope of 10^o and 40^o respectively. Significantly higher reduction due to slope was employed by [13], where at 10^o for instant, the speed reduces to 40%. The total distance of evacuation in the present study is significantly shorter than those of [13] which partly explain the less reduction due to slope. In this study the slope of the roads for certain sections (for example between intersections) were averaged and the coefficient due to the slope was approximated based on Equation 2.

Night visibility depends on the street light. Under a bright light such as during the day, the visibility is enough for people to run at running capacity and hence C_V =1. The C_V coefficient was determined using a simple method based on digital camera light metering as follow. The digital camera DSLR (*Digital Single-Lens Reflex*) Canon EOS 650 D was set at constant F6.3 and ISO 400. A dark condition with limited light was metered and the camera speed showed 15 s. In such condition it was approximated that the running speed reduced to 50%. A condition with certain lighting when visibility was assumed to be unaffected was metered. The camera speed showed 1 s. The value of the light meter between them was interpolated for C_V value. The camera was then used to approximate the C_V of the evacuation routes during the night. The value was averaged for a certain distance of the road. Examples of the road condition during the day and night are given in Figure 5. The time in seconds on the figures indicate the shutter speed. It can be seen in the figure that lamps along the road may affect the average light measured by the camera. The method of determining C_V value was an approximation and has not been tested with physical experiment. The result of the survey is given in Table 3. Comparing Figure 5a with Figure 5b and Figure 5c with Figure 5d, it can be deduced that the reduction of visibility at night was more significant along the lanes. This was because lighting was normally not provided along the lanes and only depends on the lighting from the residential houses (Figure 5c). In general the condition of lighting at Malabero village was slightly better than that at Sumur Meleleh village.

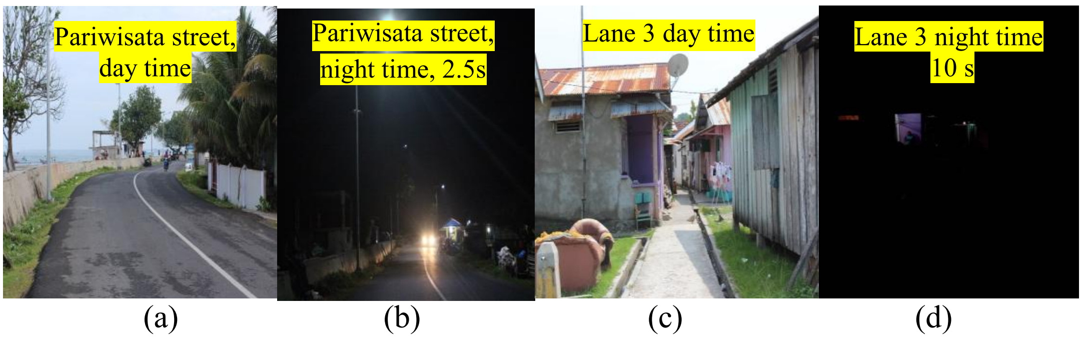

Figure 5. Examples of road condition and visibility during day time and night time

The capacity of running speed or maximum running speed of an agent is naturally depend on age, gender, health and disability. In this study, the average running capacities were assumed to vary between 1.3 to 2 m/s for male and 1.0 to 1.5 m/s for female agents. An average of a normal walker of 1.7 m/s and a slower walker of 0.75 m/s were used by [7]. The average running capacities in the present study were approximated as 1.6 m/s and 1.4 m/s for male and female respectively. With such speed, it was expected that the evacuation can be completed within 20 minutes which was the approximated available time for evacuation [14].

Table 3. Streets and Lanes Coefficients during the Night

	Malabero village		Sumur Meleleh village	
	Average	**Minimum**	**Average**	**Minimum**
Streets	0.84	0.70	0.82	0.64
Lanes	0.76	0.68	0.72	0.63

Table 4. Number of Population Assumed in Scenario 5

Year	Percent growth	Total Population
2020	25	4592
2027	50	5510
2033	75	6428
2040	100	7346

Based on approximated population growth at Teluk Segara District (2010-2013) Bengkulu City Agency

Numerical Simulations

The map of Malabero and Sumur Meleleh villages are given in Figure 4. The evacuation routes are given in the figure based on the available evacuation sign boards along the routes that lead to Merdeka Square. There were five scenarios of simulations that were tested in this study.

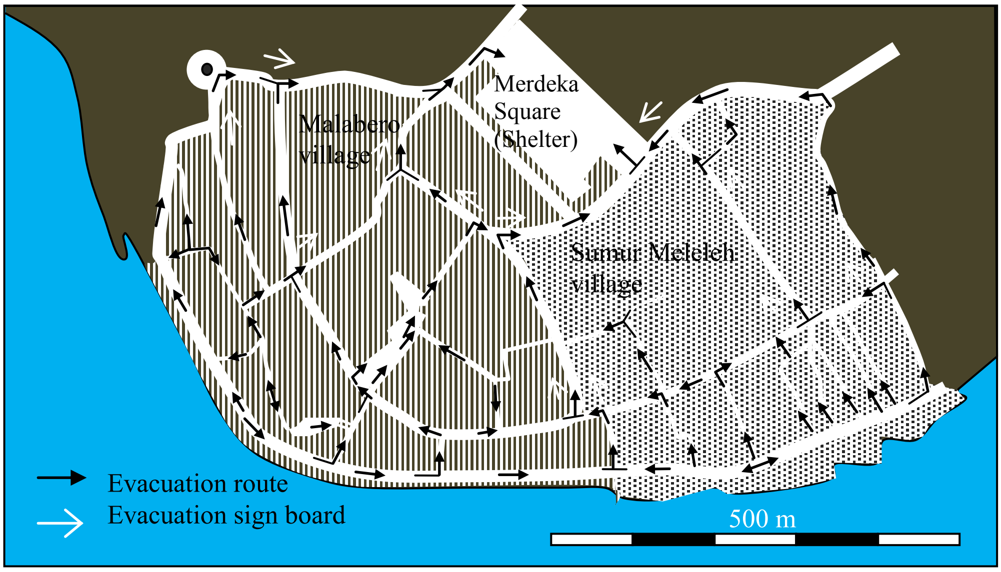

Figure 6. An alternative evacuation routes (alternative direction scenario)

These were 1) normal condition where the people were assumed to follow the existing evacuation signboards as given in Figure 4, 2) normal condition but with alternative direction of evacuation, 3) condition with obstacles during peak hour at a market and along the evacuation roads, 4) evacuation during night time, and 5) normal condition with increasing population. The alternative directions of evacuation are given in Figure 6, whilst the obstacles during scenario 3 are given in Figure 7.

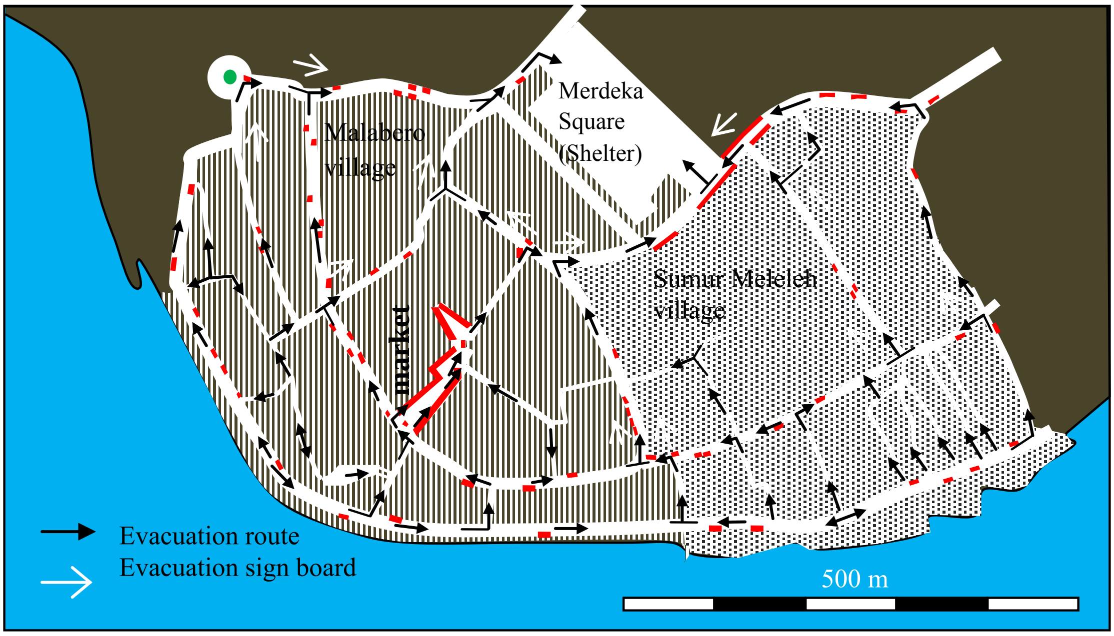

Figure 7. Evacuation routes with obstacles

Results and Discussion

The first scenario suggested that the evacuation routes were quite sufficient to accommodate the two villages to evacuate within 20 minutes. All the people were able to reach the Merdeka Square in less than 20 minutes as indicated by Figure 8.

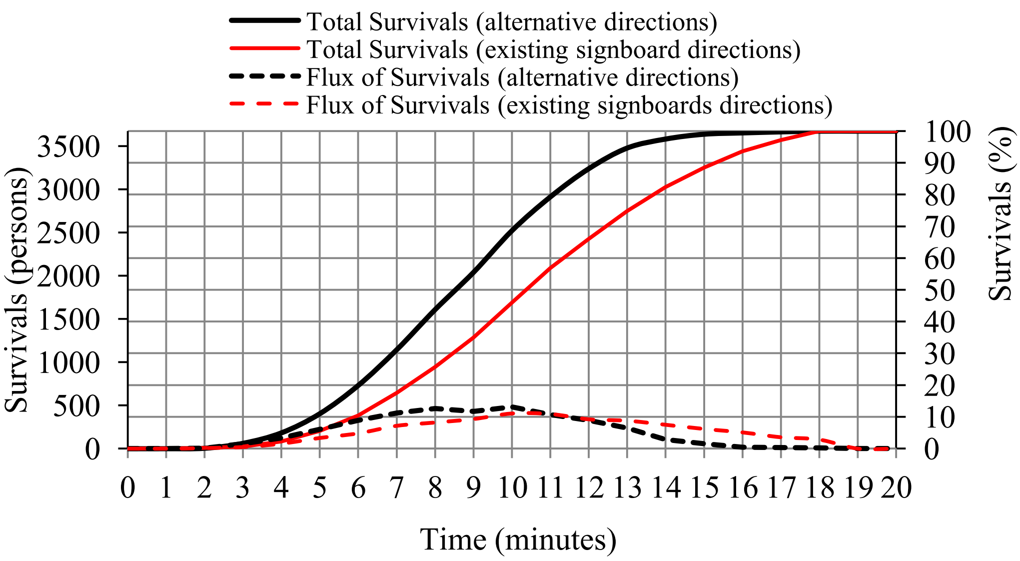

Figure 8. The survivals time history simulated based on the original routes and based on the second alternative directions

The second alternative of route directions performed better where the required total time for evacuation reduced by approximately 3 minutes. The difference between the original route based on signboards and the second alternatives is indicated in Figure 8. It can be seen in the figure that the alternative directions avoid the possibility of congestion along small roads. Although the alternative direction is better, it is important to explain to the residence why such directions will work better since naturally people tend to directly run away from the coastal area.

The peak hours of incoming survivals (people entering the shelter was between 8 to 10 minutes after the start of the evacuation during which the flux of survivals was nearly 500 agents per minute. With that in mind and since there were two relatively large entrances to the shelter, it may be said that the entrance of the shelter was more than sufficient.

When there were obstacles, it was observed that there were traffic jams especially in front of the market. In reality the situation however could be even worse than the simulated due for instance to a chaos within the market which may bring about more serious traffic jams. Cars that were parked along the road did not significantly slow down the traffic as long as there was enough space for the people to evacuate. The traffic jam reduced the peak flux of survivals as indicated by Figure 9.

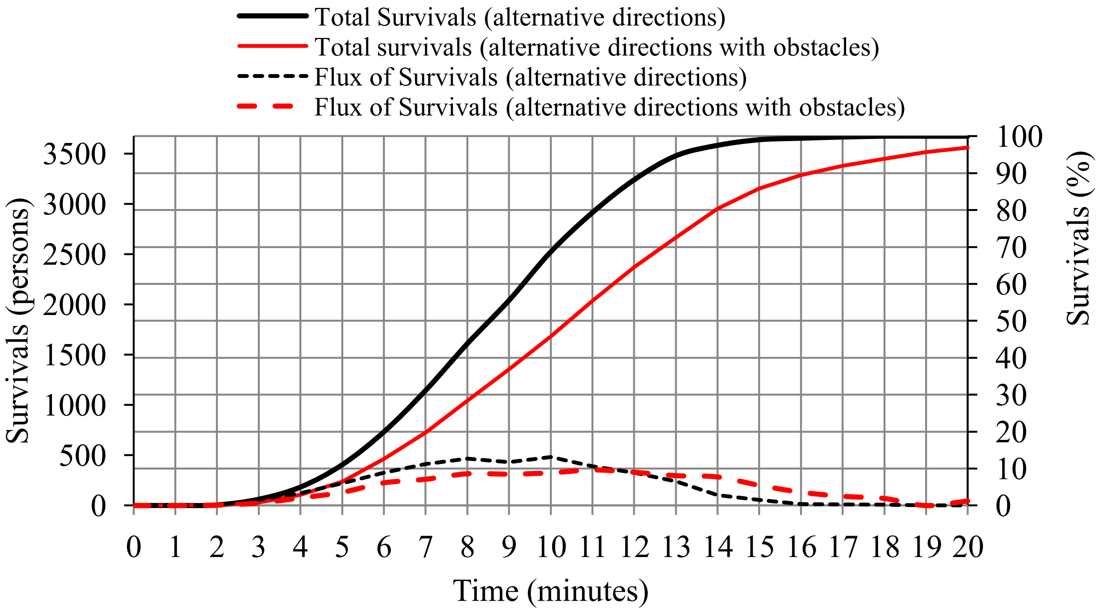

Figure 9. The survivals time history simulated based on the second alternative direction with and without obstacles

The night time evacuation proved to perform the worst. The reduction of the number of survivors was significant. Although the number of the survivals after 20 minutes of evacuation was almost the same with that of scenario 3 (evacuation with obstacles), the number of survivals within less than 15 minutes was significantly less as can be seen in Figure 10. Such situation should be anticipated. The infrastructures and lighting facilities should be improved along the lanes.

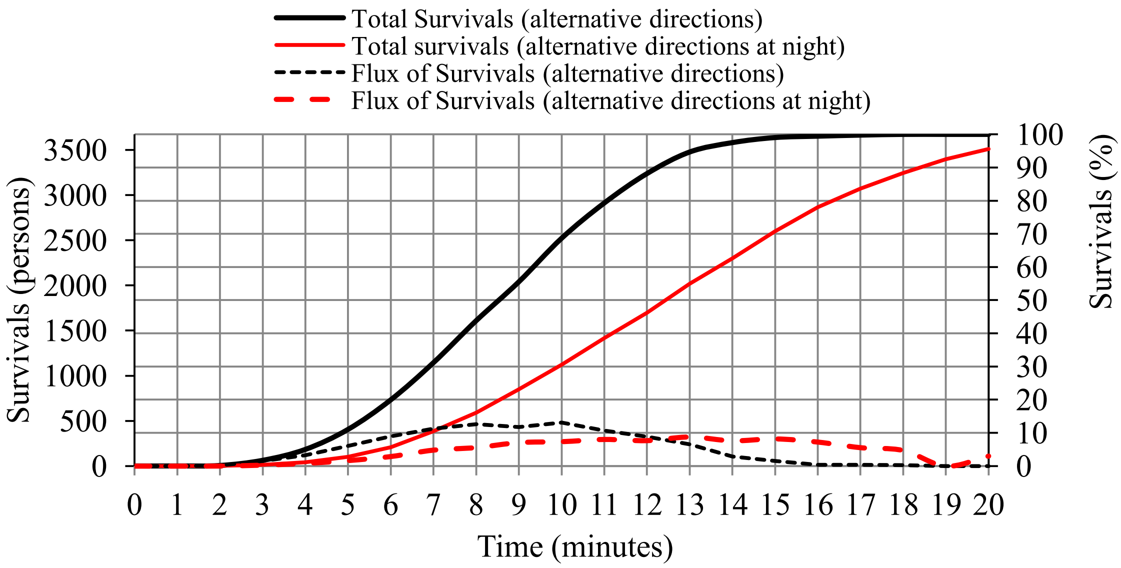

Figure 10. The performances difference between the second alternative and during the night time evacuations

The growth of the population is another situation that the local government should be aware of related to the evacuation routes capacity. Assuming that the routes do not change with time, the population growth effect on the evacuation is provided in Figure 10. In reality as the population grows, there will be more obstacles such as cars that are parked along the routes. This can make the situation even worse during the evacuation.

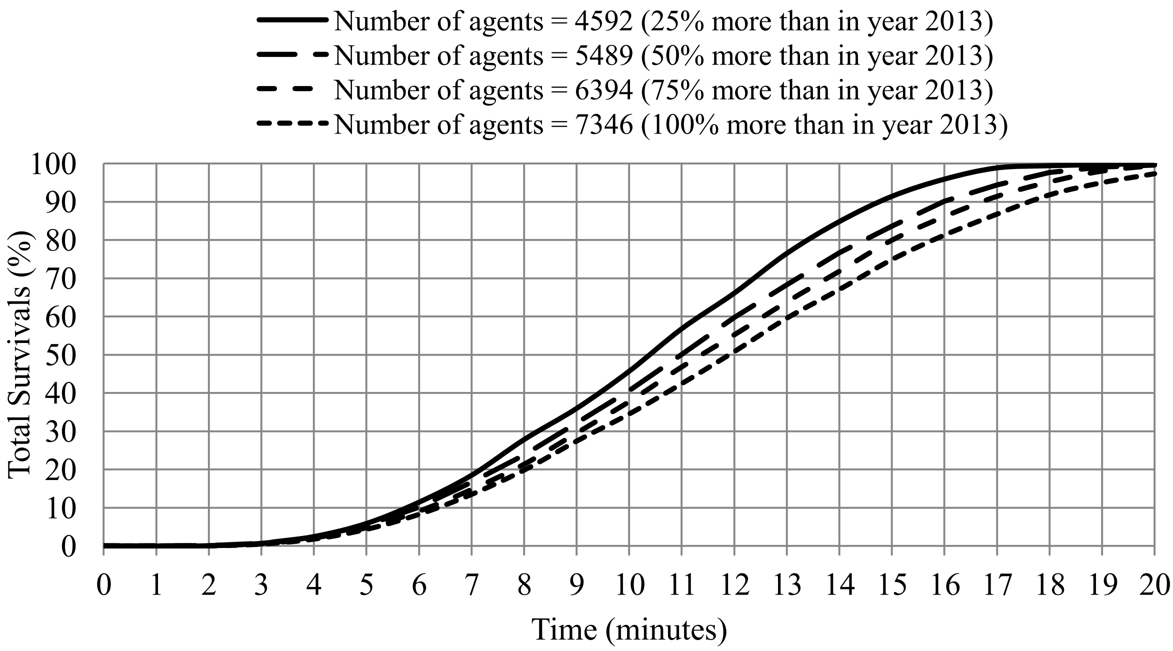

Figure 11. The performance of the evacuations for different number of population inMalabero and Sumur Meleleh villages

Conclusions

The numerical algorithm has been applied to simulate the movement of agents along the evacuation routes. The obstacles especially around the market reduced the capacity of the evacuation routes. Better arrangement of car parks surrounding the market is needed. Higher number of population slowed down the evacuation speed yielding in more casualties.

It may also be concluded that at present the evacuation routes are sufficient to accommodate the evacuation of the people in Malabero and Sumur Meleleh villages especially during the day. At night, limited visibility reduces the evacuation speed especially along the lanes which caused significant number of casualties. Further details survey and experiment regarding the running capacity under different light conditions should be conducted to accurately define the visibility coefficient.

In the future as the number of population increases, the infrastructures need to be upgraded if no casualty is expected. This can be done for example by providing vertical evacuation shelters for the people near the beach.

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