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NUMERICAL SIMULATIONS OF AN EVACUATION FROM A TSUNAMI AT PARANGTRITIS BEACH IN INDONESIA

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ABSTRACT

The tsunami disaster in Calang (Aceh, Indonesia) in December 2004 caused traffic jam at a bottleneck on an evacuation road that was fatal, killing most of the evacuees. This tragedy provides an invaluable lesson for evacuation planning in several other locations that are prone to tsunami events. Parangtritis is a local tourism destination that is also prone to tsunami hazard. Although the evacuation routes have been prepared and evacuation direction sign boards have been provided, a study on their capacity and suitability were required. One of the methods was employing mathematical simulations. This paper addresses the development of a mathematical model based on the Dijkstra algorithm and its application to evacuation during a tsunami at Parangtritis Beach, Indonesia. The running speeds of evacuees were derived from world athletes' running records but with significantly lower coefficients to model ordinary people. Trial runs were also carried out to calibrate the value of *f* that represented the ratio between running speed on the certain route and on well paved, horizontal and obstacle free road. The results suggested that the existing evacuation routes were not sufficient and that the direction of evacuation need adjustment. It was found that relatively slower runners that were in front of faster runners would potentially decrease the average evacuation speed. Vertical evacuation routes, such as along steep hills or high buildings, must be wide enough (to ensure a low crowd density) and easily accessible (to ensure a higher evacuation route speed) to avoid traffic jams. The number of people to be evacuated and road condition are vital factors to determine the evacuation routes to the selected shelters.

Keywords: *tsunami; evacuation; simulation; numerical; multi agent; Indonesia; running speed*

1 INTRODUCTION

Tsunamis have been generated several times along the Sunda Trench, the boundary between the Indo-Australian and Eurasian plates to the south of Java Island. Fig. 1 presents five locations of earthquakes relatively near to the study area that triggered tsunamis over the last 155 years based on National Geophysical Data Center/World Data Service (NGDC/WDS) (2014). Damanik et al. (2010) determined that a seismic gap region almost due south of Parangtritis (Fig. 1), may experience earthquakes in the near future. Kongko (2012a) compiled the run-up data and indicated that the 2006 tsunami run-up at Parangtritis and the surrounding area ranged from 2.8 to 5.5 m.

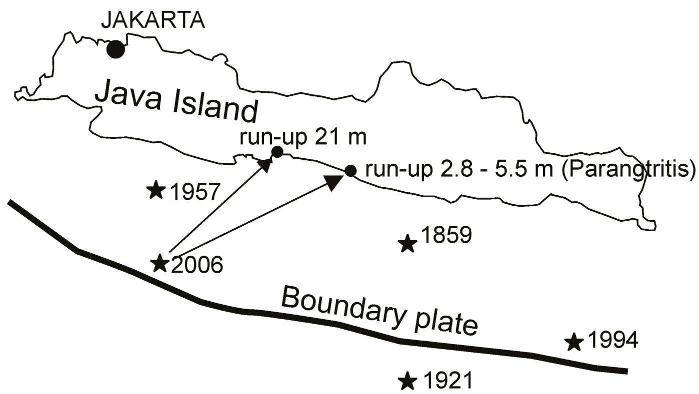

Figure 1. Tsunamigenic earthquakes over the last 155 years (based on NGDC/WDS, 2014)

Kongko (2012b) conducted a more detail numerical model using an M_w 8.2 earthquake with an epicenter located along the boundary between the Indo-Australian and Eurasian plates at approximately 210 km to the south of the beach. The maximum tsunami height at Parangtritis beach was 4.47 m where the tsunami travel time was 33 min. German Indonesian Tsunami Early Warning System (2010) recommended that when the tsunami height is greater than 3 m, the people at Parangtritis Beach should evacuate to Shelter 1, Shelter 2 and Shelter 3 (Fig. 2).

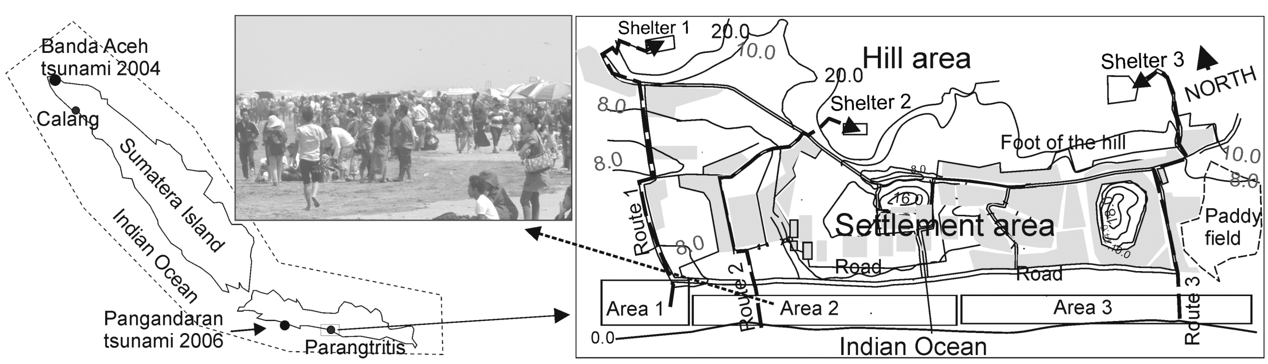

Figure 2. Map of Parangtritis Beach and the crowd during a public holiday.

Parangtritis is a local tourist destination located at the southern coast of Java Island in Indonesia, facing the plate boundary between the Indo-Australian plate and Eurasian plate. Fig. 2 presents the sketch of Parangtritis Beach and the crowd during a public holiday. The detail of the evacuation routes is given in Figure 7. With a nearly vertical hill behind the beach area, a tsunami of 10 m high may run up, be reflected by the hill, and inundate the entire area Triatmadja (2010). Thus, the hill would become the only safe evacuation area during a large scale tsunami event.

Routes to temporary safe grounds or shelter areas have been prepared at Parangtritis Beach. The final portions of the routes that lead to the hill's top are two narrow stairways to Shelter 1 and Shelter 2 and two paved 7- to 8-m-wide roads to Shelter 3 (Fig. 2). These facilities are expected to save a lot of lives during tsunami hazard and hence evaluation of the capacity and suitability of the evacuation routes should be conducted. One of the methods is using simulations of evacuation. Physical simulations of an evacuation require a significant number of people, resources and funding, good coordination, and preparation time. In contrast, mathematical simulations are considerably less expensive risk free and easier to manage, although they cannot provide evacuation experience and skills to residents. Affan et al. (2010) demonstrated that their mathematical simulation software, which accommodates user input on their preferred routes at Banda Aceh, helps them to justify their evacuation routes. In an area where most of the people are tourists, it is not possible or at least not efficient to educate and provide the experience necessary to tourists regarding evacuation because they only stay for a short duration. For such conditions, the mathematical simulation is a good alternative for evaluating the preparedness of the infrastructures. Many mathematical modeling approaches are available to simulate evacuations, as described by Hamacher and Tjandra (2001) and Gwynne et al. (1999). The spectrum of such mathematical models is broad, with macro- to micro-scale simulations. The latter is extremely detailed with regard to the dynamics of the evacuees and is suitable for the present study. Numerical simulations of an evacuation related to tsunami events have been conducted for a number of cases in Indonesia. Noda et al. (2010) simulated the evacuation of residents during a tsunami event in Meulaboh, Indonesia. The model was capable of simulating the evacuation process in large areas serviced by roads and junctions. Goto et al. (2012) performed another similar simulation with additional types of evacuees, namely, normal walkers, slow walkers, motorcyclists, and automobiles. They suggested that the use of automobiles should be limited, whereas the use of motorcycles to evacuate to certain shelters is necessary. Imamura et al. (2012) demonstrated that even after 45 min, only 37.7% of evacuees managed to escape from the hypothetical tsunami in Padang during the worst-case scenario.

The goal of this research is primarily to evaluate the performance of a relatively simple mathematical model based on the Dijkstra algorithm to evaluate a predefined evacuation routes, such as those in Parangtritis Beach, Indonesia.

2 MATHEMATICAL MODEL ALGORITHM

At the start of the evacuation simulation, all of the evacuees should have their own shortest paths as the primary routes that guide the evacuees toward a safe ground. Evacuees may divert slightly from the shortest path because of obstacles (or other evacuees). The most popular algorithm for determining the shortest path is most likely the A* (A star) algorithm developed by Hart et al. (1968). This algorithm is the core component of most animated games (Pinter 2001). Pinter (2001) improved the algorithm to provide smooth paths and turns. The smooth straight paths are achieved through an additional algorithm that checks whether the points along the line from the original position to the targeted position at typically 1/5 the size of the grid the unit overlap any neighboring blocked nodes. Such an improvement makes the algorithm requires additional computational resources. The Dijkstra algorithm Dijkstra (1959) is similar to the A* algorithm but without the heuristic feature (guessing the more likely shortest path to the target). In certain cases Dijkstra algorithm requires more computational time to check all nodes up to the target. However, when the shortest paths to the shelters from almost the entire nodes in the computational domain are required as in this study, Dijkstra algorithm is as good as A* algorithm and is easier to handle. Both algorithms are more suitable for defining the optimum evacuation routes rather than for simulating evacuations in which people must follow predefined routes. In this study, to be consistent with the goal of the research, it was assumed that the evacuees were obliged to go to a particular shelter based on their original location area along the beach. However, their shortest paths were determined based on Dijkstra algorithm. There were three evacuee areas, as shown in Fig. 2. The assumption appears reasonable when addressing the evacuation of people where most of the evacuees are visitors, such as at Parangtritis Beach. According to Badan Pusat Statistik Kabupaten Bantul (2013), the total number of residents in Parangtritis village was 7,653 people, and only 2,200 people lived in the Parangtritis Beach area. This was a small percentage when compared to the number of tourists during public holidays, which may surpass 20,000 people. These visitors are not familiar with the beach area and hence will largely follow the available evacuation route directions.

The simulation area was divided into square grids and nodes to identify the positions of the evacuees and obstacles in the entire simulation area. A number of models and software packages, such as EGRESS and FlightSim, use a similar technique (Hamacher, and Tjandra, 2001). Based on the average shoulder breadths of Indonesian residents, which are 41.7 and 38.2 cm for male and female adults, respectively (Laboratorium Perancangan Sistem Kerja dan Ergonomi-Teknik Industri -ITB, 2007), a uniform grid size (Δs) of 0.5 m × 0.5 m is selected, this approximately equals the area occupied by one person. The EXODUS software package typically uses the same grid size (Gwynne et al., 1999). In this study, Dijkstra algorithm was used to define the shortest paths of every node to the designated shelters. Along the selected shortest paths, the evacuees may change their directions to avoid the crowd by following the next best choice of paths based on the next smallest cost value of the surrounding nodes. At each node, the evacuees were given five best choices of movement.

3 RUNNING SPEED AND ASSUMPTIONS OF RUNNING BEHAVIOR AND CONSTRAINTS

Steudel-Numbers et al. (2009) argued that taller people run faster. They found that the male volunteers (179.6 cm), who were on average taller than the female volunteers (168.2 cm), ran most efficiently at 3.7 m/s, whereas the female volunteers ran at 2.9 m/s during a 5-min test run. The mean heights of male and female citizens of Indonesia are 158 and 147 cm, respectively (Frankenberg, et. al., 2003). Hence, the average Indonesian resident (healthy but not an athlete should be significantly slower. In fact, Imamura et al. (2012) simulated an evacuation during a tsunami event in Indonesia using a constant average running speed of 1.67 m/s, which was slightly faster than the preferred walking speed of 1.42 m/s (2006). Goto et al. (2012) used an even slower running speed of 1.5 m/s for average people when no other people were within 1 m^2. Several factors may affect the running speed of an individual: the (a) evacuee's physical condition (gender, age, health, disabilities), (b) preparedness (shoes, dress, any items or infant to carry), (c) distance of run, (d) crowd density, and the (e) road condition (soft sand, hard sand, paved road, steep slope, stairs, slippery road, stony road, road with obstacles, visibility).

The running speed as a function of age and gender may be determined based on the world running records. The following equation is set up to represent the impact of age and gender on running speed:

$$V_C = C(kA/A_0)^k e^{-(kA/A_0)}, \quad (1)$$

where V_c is the individual running speed capacity (running speed with no obstacles on a paved road) for a certain running distance. Both C and k are constants related to gender, age, and running distance. A is the age of the evacuee, and A_o is the optimum age for maximum running speed capacity. Based on Eq. (1), the maximum running speed capacity is $C\,k^k\,e^{-(k)}$ at $A = A_o$. The solid and dashed lines in Fig. 3 demonstrate that the equation is in good agreement with data for the best male and female athletes records based on Eisold (2003), IAAF (2012), and Mastersatheletics

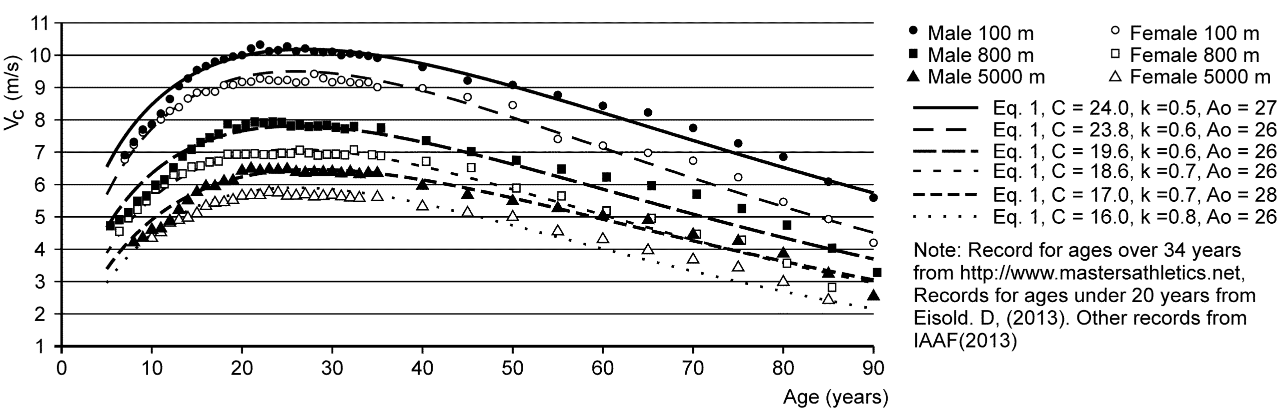

Figure 3. Best running speed capacities of male and female athletes versus age.

(2012) for appropriate *C, k*, and A_o values. Based on this equation, *C* is typically higher for males than females, whereas *k* exhibits the opposite trend. With a slightly higher value of *k*, the performances of female athletes tend to decline more rapidly with age. This conclusion is similar to that of Ransdell et al (2009). A_o is slightly higher for males for short-distance runs (100 m) and long-distance runs (5,000 m). The equation appears to fit the data relatively well until 80 and 90 years of age for females and males, respectively, after which it diverges significantly from the data. Assuming that the effect of age and gender on average people is somewhat similar to the best athletes, Eq. (1) may be expected to also fit average people, although with suitable C, *k*, and A_o values.

Fig. 3 also illustrates that the world running records drop significantly from distances of 100 to 800 m, after which it drops again, although only slightly, for even the 5,000 m distance record. People at Parangtritis Beach must run distances ranging from 500 to 1,500 m. Their running speed capacities during the evacuation based on the above discussion can be estimated based on a distance of 800 m. For a more realistic simulation of an evacuation, the running speed should be varied depending on the road condition by applying a speed factor *f* that represented the ratio between running speed on the certain roads and on well paved, horizontal and obstacle free road. When running closely with others, people may slow down slightly to avoid bumping into others. The inclusion of crowd density into the running speed equation is expected to simulate such behavior. Because discrete space is employed in the present algorithm, the crowd density is determined by the existence of evacuees at adjacent grid points either in front of or beside the evacuee of interest. Fig. 4 presents a possible situation surrounding an evacuee.

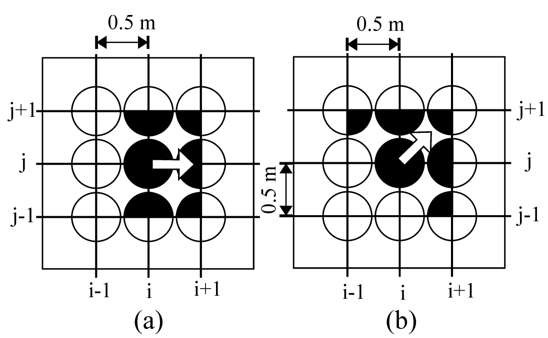

Figure 4. An evacuee at grid point (i,j) surrounded by eight evacuees at surrounding grid points. (a) Evacuee moving in the *X* direction and (b) evacuee moving 45^o to the *X* direction.

Fig. 4 (a) illustrates evacuees moving to the right (east), and Fig. 4 (b) illustrates evacuees moving to the north east. The crowd density (*D*) for an evacuee at grid point (*i,j*) is assumed to follow Eq. (2):

$$D = \sum_{i=1}^{6} m , \qquad (2)$$

where m has a certain value at a grid point that is occupied by an evacuee; otherwise, $m = 0$. The maximum number of evacuees in Eq. 2 is six because the people behind the evacuee of interest are not considered, as in the case of Fig. 4. The values of m at one grid in front of or beside the grid point *(i,j)* is assumed to be 0.5 if the distance to the grid point (*i,j*) is Δs, $m = 0.25$ if the distance to the grid point (*i,j*) is $\Delta s\sqrt{2}$ and $m = 1$ at grid point *(i,j)*, as indicated by the percentage area that is filled with black in Fig. 4. Hence, based on Eq. (2), the values of D for an evacuee at grid point *(i,j)* are 3 and 2.75 for Fig. 4 (a) and Fig. 4 (b), respectively. The minimum value of D is 1, where there are no other people within 1 m^2 surrounding the evacuee of interest.

The running speed can then be calculated using Eq. (3):

$$V = C_D f V_C. \tag{3}$$

The value of f depends on the road condition, varying from nearly zero for very steep and narrow steps to 1.0 for well paved horizontal roads. The maximum value of C_D is unity, which is when nobody is around the evacuee. Assuming that C_D decreases exponentially with an increasing crowd density near the evacuee, C_D may be written as a function of D in Eq. (4) to yield the minimum value of $C_D = 0.2$. Goto et al. (2012) used a similar approach with a nonlinear function to represent the effect of the number of people per square meter on the running speed.

$$C_D = D^{-D/2} \tag{4}$$

The use of a square grid requires that the movement of the evacuee be conducted every Δl, which may equal either Δs or $\Delta s\sqrt{2}$, depending on the directions of the movement. The time step used in the simulation was 0.1 s to ensure that each evacuee travels a distance of less than Δs. This distance is stored and added up to the previous acquired distance. When the accumulated distance reaches Δl or greater, the evacuee may move to the adjacent node, and the residual distance is stored. However, if all the nodes of the best selection are occupied, the evacuee does not move, and the accumulated distance is void (Fig. 4b). This approach ensures that no evacuee jumps over another or simultaneously occupies the same node with another evacuee.

During one time step, the evacuees move in sequence until all of the evacuees obtain their opportunity. When an evacuee has completed the move for one time step or does not move because of a lack of acquired distance, the next evacuee gets a turn. This arrangement is realistic when everyone may run freely along the selected paths. However, in a crowded area, to make the movement realistic, the evacuees are assumed to be classified into five groups of different domination levels from 1 (most dominant) to 5 (inferior), which are assumed to depend on age. The most dominant evacuees are selected from those between 25 to 40 years of age for up to 20% of the total evacuees. When the number of evacuees within the specified range is not sufficient, additional evacuees of the maximum domination are selected from the population using a broader range of 20 to 50, 15 to 60, 10 to 70, and from less than 10 or higher than 70 years of age until the required number is fulfilled. Subsequent levels of domination are then similarly assigned to evacuees starting from the age range from 25 to 40 years and following ranges until reaching 20% of the total number of evacuees. The selection method assumes that the number of evacuees at each level is the same. The group with the highest level of domination is given the first opportunity to move, followed by subsequent domination level groups. A similar variation of domination, but with additional complexities, is used by a number of professional software package to reflect the evacuee's attitudes during an evacuation (for example, by the Pathfinder software (Thunderhead Engineering, 2013). Kuligowski et al. (2010) reviewed 26 software packages dedicated to evacuation simulation in buildings, with 23 models including evacuee behavior.

4 PHYSICAL EXPERIMENTS

To determine an appropriate running speed of average people, experiments were carried out using a number of volunteers of different ages and gender. The experimental setting was as follows. First, the volunteers were asked to run a medium distance of 800 m as this represents the average distance of evacuation routes at Parangtritis Beach. The experiment was conducted at Universitas Gadjah Mada, where the volunteers ran 100 m back and forth eight times on flat paved ground. The health of each volunteer was not checked medically, but they declared that they were in good physical condition and capable of running. Therefore, the time of the experiment depended on the availability of the volunteers. When they were sufficiently rested, the volunteers had to run a short distance on the same paved ground and a type of stair to measure the effects on running speed. Another running experiment was carried out at Parangtritis Beach. The volunteers ran for a distance of 50 m on hard sand and another 50 m on soft sand. After sufficient rest, selected volunteers ran a complete path that was from the beach to the location of the safe ground. There were three complete paths, as given in Fig. 2 that represent possible running paths of the evacuees during a tsunami event. We returned to Parangtritis Beach once again to perform a test run for the last part of the evacuation route from the base of the hill to the safe ground. Only selected volunteers were tested. They had to run on a paved road of the same distance, and the results were used to calibrate *f* for the last part of the routes.

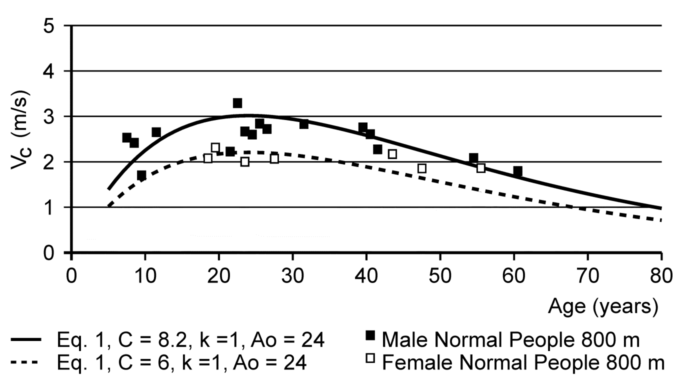

Figure 5. Running speed capacities of average Indonesian residents at 800 m distance.

Fig. 5 presents the results of the medium-running-distance tests on the paved road. In contrast to

Fig. 3, the data in Fig. 5 are more scattered along the line of Eq. (1) because the volunteers were selected randomly, whereas only the best were recorded in Fig. 3. C was expected to be significantly lower for average people than for the professional athletes. Fig. 5 indicates that Eq. (1), with $C = 8.2$, $k = 1$, and $A_o = 24$ for males and $C = 6$, $k = 1$, and $A_o = 24$ for females, may be used to represent the running speed capacities of average people. The simulation assumed that all of the evacuees follow the above coefficients.

The data of the running experiment are given in Table 1. The table illustrates that f equals 0.91 and 0.86 for hard sand and soft sand, respectively. For a mixture of steep and mild stairs leading to Shelter 2 (vertical to horizontal slopes of approximately 1:2 to 1:5) and mild stairs (average slope of 1:5) leading to Shelter 1 of Parangtritis Beach, the values of f were 0.19 and 0.27, respectively. The speed factor is significantly higher ($f = 0.40$ to 0.42) on a mildly sloping road (1:6 to 1:8), such as those leading to Shelter 3a at Parangtritis.

Table 1. Results of running experiment

Road condition	Number of Volunteers	Distance (m)	Average Speed (m/s)	Average Speed on Pave Road (m/s)	Speed factor
Hard Sand	15	50	5.26	5.76	0.91
Soft Sand	15	50	4.93	5.76	0.86
Stairs Route 1	2	220	1.38	5.20	0.27
Stairs Route 2	2	150	0.71	3.76	0.19
Steep Road Route 3	3	280	1.95	4.86	0.40
Complete path Route 1	3	1070	1.33	2.32	0.57
Complete path Route 2	3	850	1.81	2.68	0.67
Complete path Route 3	3	840	2.33	2.75	0.85

The running simulation along the complete paths of the evacuation routes at Parangtritis Beach was carried out using the same volunteers. Nine volunteers from 18 to 38 years of age were selected for the experiment. The average speed ratio may be deduced from the calibration results, which yield approximately 0.61, 0.80, and 0.80 for Routes 1, 2, and 3, respectively, whereas the experiment yielded average speed factors 0.57, 0.67, and 0.85, respectively (Table 1).

5 NUMERICAL MODEL PERFORMANCE

The model was tested using a number of male and female evacuees that were assumed to be normally distributed from 6 to 60 years of age with a mean and standard deviation equal to 30 and

12.5 years, respectively. The evacuees were placed randomly along narrow lanes of 3 m wide and 200 m long. The numbers of evacuees in the area were 150, 300, 600, 1,200, 1,800, and 2,400, yielding initial evacuee densities of 0.25, 0.5, 1, 2, 3, and 4 per square meter, respectively. Narrower crowd lanes of 1 m wide and 200 m long with the same initial numbers of evacuees per square meter as above were also tested for comparison. The evacuees had to reach a destination 700 m from the nearest evacuee or approximately 900 m from the furthest (Fig. 6).

A ratio (W) of the average running speeds to the average running speed capacities for a certain distance for all evacuees may be used as the evacuation route speed indicator measuring the effect of D and f on the running speed, as given in Eq. (5).

$$W = \sum_{i=1}^{n} \left(\frac{L_i / T_i}{V_{Ci}} \right), \qquad (5)$$

where n is the number of evacuees, L_i is the running distance of evacuee i to the shelter, T_i is the time required by evacuee i to reach the shelter, and V_{ci} is the running speed capacity of evacuee i for a certain distance.

For the numerical performance test, the people were assumed to run at their running speed capacities ($f = 1$) for the 800 m distance but were dependent on the surrounding evacuees. Based on Eq. (1) with $C = 8.2$ for males and $C = 6$ for females and $k = 1$ and $A_o = 24$ for both males and females, the running speed capacities ranged from 1.6 to 3.02 m/s.

Each scenario was run five times, and the average results are given in Fig. 6. The variation of the results of each scenario was relatively small (less than 10% of the average, not shown in Fig. 6). The figure indicates that W increases as D decreases and becomes nears unity as D becomes approximately 1, where an evacuee may run freely without being affected by other evacuees. During the simulations, the lanes became wider as the faster runners tried to escape from the crowd. The lanes also became longer as the crowd dispersed because of running speed variations as well as the opportunity to run presenting itself. The 1 m lanes expanded up to approximately 6.5 times the initial width, whereas the 3-m-wide lanes expanded only up to 3.5 times. It took less than 5% of the total time of the evacuation for the crowd to expand completely during the test with the highest D value. This indicates that the effect of the initial D value is short lived. With a lower D value caused by a relatively more extensive lane expansion, the 1-m-wide lanes produce slightly higher values of W than the 3-m-wide lanes. The effect of age distribution is not significant on W for evacuees running in open spaces, as indicated by Fig. 6. The crowd of uniform age (30 years old) produces only slightly higher W, especially for low values of D. However, with even the same value of W, the total evacuation time of the uniform age crowd is reduced because the running capacity of the 30-year-old evacuees is higher.

To simulate the effect of fixed width lanes as if on a road with buildings as the boundaries, similar simulations of the above were carried out with walls along the boundaries of the lanes. With such walls, the only way for the faster runners to run to the shelter is behind the slower runners while waiting for available space to overtake the slower runners so that they could run at their running capacities. The results demonstrated that the values of W are reduced significantly because of the wall boundaries (Fig. 6). For 1-m-wide lanes with wall boundaries, it becomes more difficult for the faster runners to overtake the slower runners as the availability of space becomes limited.

Based on Eq. (3), for $f = 1$ and assuming that all of the evacuees run at a uniform, constant speed, D and C_D are constant and equal to their initial value. In this case, W is equivalent to the initial C_D value, which is plotted in Fig. 6 as a dashed line. The figure indicates that all of the lanes without boundary walls resulted in higher values of W, indicated by the dashed line, because of the expansion and elongation of the crowd that led to lower crowd densities. The resulting W is close to the dashed line because the walls were included and because only elongation was possible. When D is relatively large, W becomes slightly higher than the dashed line as the elongation of the crowd becomes more significant. By using a normal age distribution, the blockages caused by slower runners produced significantly lower values of W, especially along narrow lanes. During the test condition for the 1-m-wide lane with boundary walls and normally distributed evacuee ages, slower runners in front slowed down the elongation of the crowd and resulted in an even lower value of W than the initial C_D value for a small D. At a large initial D, the elongation led to higher crowd density coefficients. The variation of W for each scenario may actually be larger than previously indicated for only five runs with random evacuee placements. This variation depends on whether the slower runners are in front of or behind the faster runners. Further experiments where the evacuees were arranged so that the faster runners were initially in front of the slower runners yielded significantly higher values of W, as shown in Fig. 6. Similarly, lower values of W were produced by arranging all of the faster runners behind the slower runners instead of placing them randomly. The difference between the results of placing the faster runners in front of and behind the slower runners indicates the approximate maximum variation due to random placement. Thus, the numerical model performs realistically.

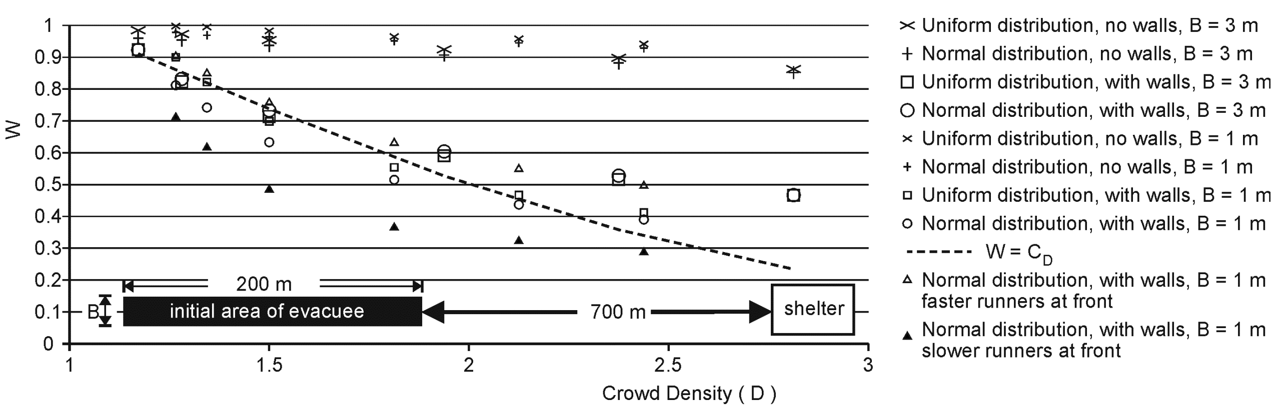

Figure 6. Effect of crowd densities and boundary walls on running speed.

6 SIMULATIONS OF AN EVACUATION AT PARANGTRITIS BEACH

The simulations were simplified by assuming that the people were ready to run after the shock. Such assumption represents the best situation for maximum survivals. In reality people may not evacuate immediately after the shock which may result in more casualties.

The beach area was divided into Areas 1, 2, and 3 with their respective evacuation routes, as depicted in Fig.7, to enable the investigation of *W* at each route for different crowd densities. First, the routes were tested using various numbers of evacuees without considering the effect of road conditions ($f = 1$) to evaluate the effect of *D* on *W*. The evacuees were assumed to be distributed randomly along the beach from the shoreline to approximately 50 m landward from the beach prior to evacuation (Fig. 7).

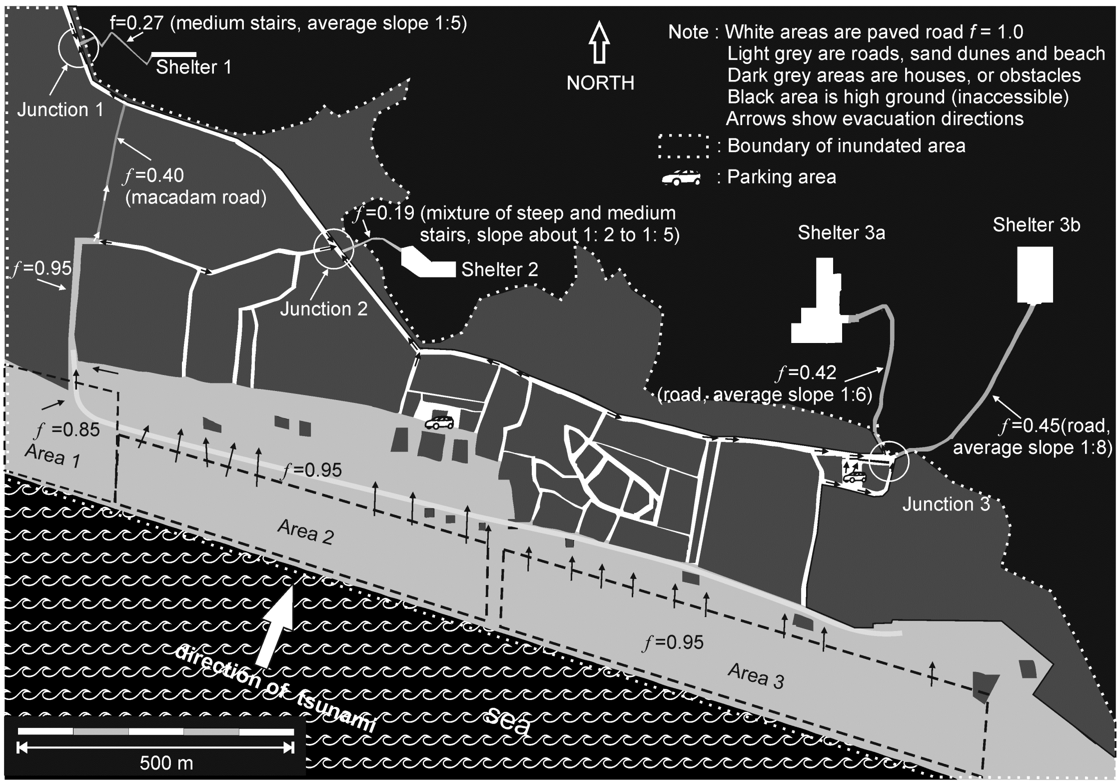

Figure 7. Parangtritis Beach and its evacuation routes

The simulations should be run many times with different positions of evacuees to observe the effect of random placement of evacuees. This would be very time consuming. Therefore, in addition to a simulation using random placement of evacuees, two extreme conditions were considered. These were placing faster runners in front of slower runners and vice versa as previously conducted during numerical performance tests. Such situations are very rare but may yield either the approximate maximum or minimum values of *W* or the number of survivals. The method may be considered as an alternative approach for statistical assessment of evacuation. The results are shown in Fig. 8, where W decreases significantly with an increasing number of evacuees. The dashed lines represent the two extreme conditions. W decreases more rapidly along Route 2 compared to the other routes, suggesting the lower capacity of this route. Unlike Routes 1 and 2, which consist of narrow stairs at the end of the routes, Route 3 has four feeder routes and two main wide sloping roads leading to Shelters 3a which make the evacuation capacity considerably larger, as indicated by the significantly higher value of W in Fig. 8. No evacuation sign board is directed to this direction and hence Shelter 3b was not included in the simulation.

The inclusion of the speed factor f based on the road conditions into the simulation resulted in severe traffic jams, especially at Junction 2 of Route 2. The values of W decreased significantly for all of the routes, especially Route 2. When evacuating 2,000 people, the value of W for Route 2 was 0.25, indicating a highly inefficient evacuation route.

During special public holidays where 10,000 people were distributed evenly in Area 2 and 3 the values of W of Route 2 and 3 were reduced to 0.15 and 0.4 respectively (Fig.8b and 8c). This resulted in the survivals of merely 16% and 90% from Area 2 and Area 3 respectively after 33 minutes (Fig.9b and 9c). Figure 9 indicates that the percentage of survivals after 33 minutes were very low from Areas 1, and 2. In fact, Route 1 and Route 2 can accommodate only 800 people each, whilst Route 3 can accommodate up to 4500 people. These numbers of survivals were consistence for higher number of evacuee. With 2,000 evacuees in each Area, approximately 40% of the evacuees from Area 1 and 40% of evacuees from Area 2 survived. The survivals of Area 3 were slightly less than 50% when the number of visitors in that area was 10000 people. When the number of visitors at Area 2 is 5000 or more the traffic jam at Junction 2 was similar to that at Calang, Aceh in 2004.

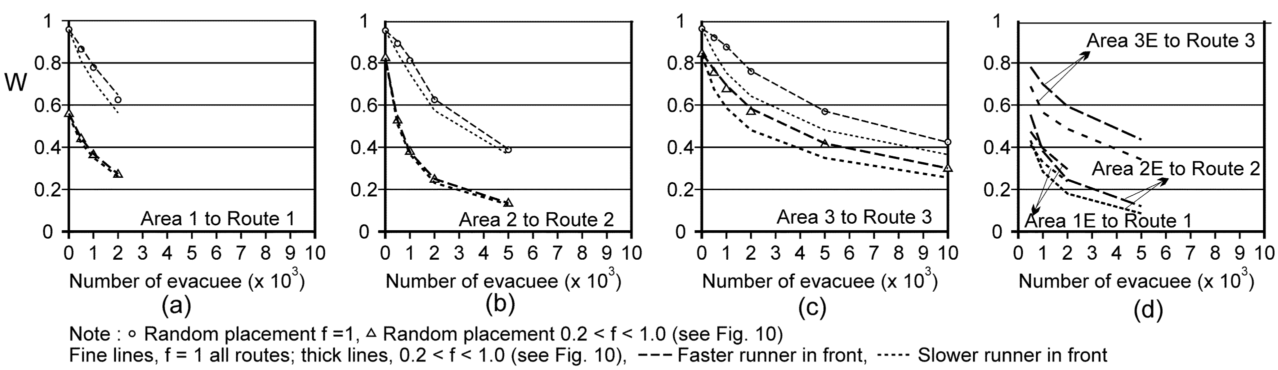

Figure 8. Performance of evacuation routes at Parangtritis Beach for various numbers of evacuees. (a), (b) and (c) evacuee from Area 1, 2 and 3 respectively. (d) evacuees from Area 1E,2E, 3E respectively.

Additional simulations were performed to observe the effect of the initial evacuees' positions. Areas 1, 2 and 3 were expanded to the north until the road along the base of the hill. These are referred to Areas 1E, 2E and 3E, respectively. The simulation indicated that W and the maximum numbers of survivors of Areas 1E, 2E and 3E were only marginally higher than if the evacuees were contained in Area 1, 2 and 3 respectively (Fig. 9 and Fig. 10). However the effect of placing slower runners in front of the faster runners decreased the survival significantly for Area 1E and 2E. The spreading of the evacuees in larger area (Area 3E) increased the chance of survival. Apparently, the slower runners in the case of Area 1E and 2E arrived sooner at the stairs to the hill than the faster runners that were positioned far behind the slower runners and resulted in more blockage of the route.

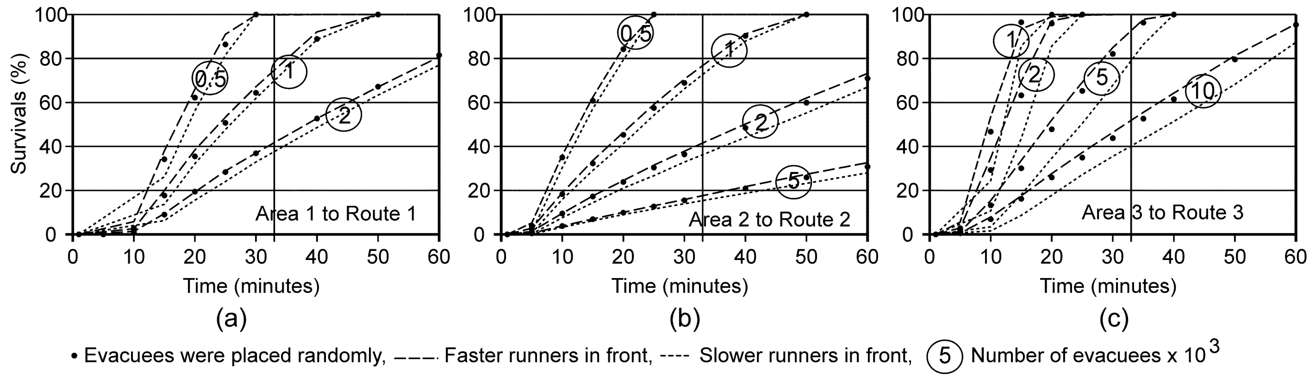

Figure 9. Survivals versus time (a) Evacuees from area 1 to Shelter 1 (b) Evacuees from Area 2 to Shelter 2 and (c) Evacuees from Area 3 to Shelter 3

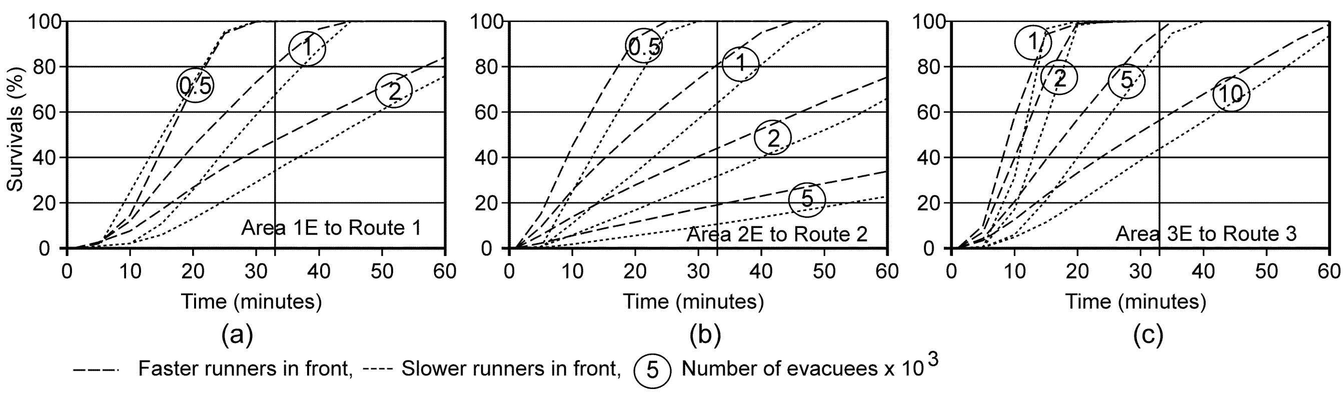

Figure 10. Survivals versus time (a) Evacuees from area 1E to Shelter 1 (b) Evacuees from Area 2E to Shelter 2 and (c) Evacuees from Area 3E to Shelter 3

The distance between Junctions 2 and 3 is approximately 1,150 m, or approximately 7 to 10 min travel time of evacuee. To decrease the severity of the jam at Junction 2, directing the evacuees at all of the junctions between Junctions 2 and 3 to Shelters 3a along the main road is worth considering. With this scenario, an evacuation simulation with 2,000 people in Area 2 and 2,000 people in Area 3 was conducted. After 33 minutes 78% (3174 people) and 22% (826 people) survived at Shelter 3 and Shelter 2 respectively. Comparing to Fig. 9(b), the result indicated an increase survival rate of 60% (corresponding to 1200 survivors) from Area 2. However, when 2,000 people were in Area 2 and 4,000 people were in Area 3, the total survivals were 5522 people in which 874 people were at Shelter 2 and 4648 people were at Shelter 3. Therefore directing the evacuees between Junctions 2 and 3 to Shelters 3 along the main road should be conducted when the people in Area 3 is less than 4000. This suggests that the number of evacuees should be considered when determining evacuation routes. Redirecting evacuees from Junction 2 to Shelter 1 should not be considered even though Junction 2 is closer to Shelter 1 than to Shelter 3 because the capacity of Route 1 is limited.

The use of cars and motorcycles for the evacuation was not considered in this paper. However, as the main roads connecting Junctions 1, 2, and 3 were relatively dense with people during the simulations with 5,000 people or more, the use of cars could endanger the evacuees and even cause traffic jams that hinder evacuation. In addition, Junction 2 was completely packed with people after approximately 7 min, and thus, no cars or even motorcycles could pass through. Furthermore, when the evacuees at all of the junctions between Junctions 2 and 3 were directed to Shelter 3, the main road from Junction 2 to Shelter 3 became more crowded, which might block the cars and motorcycles that move in the opposite direction. The best way for buses, cars, and motorcycles to evacuate is to Shelter 3b. However, their effort to escape from the parking area to Junction 3 may hinder the evacuation because the routes to the main road and along the main road to Junction 3 were crowded during the evacuation.

7 CONCLUSION

A numerical model based on Dijkstra algorithm performs realistically and was successfully applied in simulating the evacuation of people through several routes during a tsunami event at a large beach area, where the running speed of the evacuees varied based on age, gender, crowd density, and road condition. An evacuation route speed indicator (*W*) may be used to measure the effectiveness of the route for different scenarios of evacuation. Placing the slower runners in front of the faster runners significantly reduced the value of *W* and the number of survivors. This result indicates that during an evacuation, people should run at their running capacity to decrease the total number of casualties. It also suggests that confused people or people who run slowly in front of others because of a number of reasons, such as looking for family members while running, helping slower runners, and bringing possessions, may hinder other evacuees and thus result in a reduced total number of survivals. Placing the slower runners in front of the faster runners or vice versa may be used to approximate the worst or the best possible evacuation scenarios respectively. The method may reduce the number of simulation runs.

The simulations showed that evacuation routes should be determined based on the number of evacuees as demonstrated by the simulation that during a crowded public holiday, the evacuees that arrived at all of the junctions between Junctions 2 and 3 should be directed to Shelters 3a to decrease the number of casualties. The evacuation routes of Parangtritis beach area should be improved especially Route 1 and Route 2.

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