

EFFECTIVENESS OF TSUNAMI TEMPORARY EVACUATION SITES (TES) IN PANGANDARAN VILLAGE USING AGENT-BASED MODELING

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ABSTRACT

In 2006, a tsunami triggered by an Mw 7.7 earthquake hit Pangandaran village, causing around 600 fatalities. Subsequently, efforts to improve tsunami preparedness were initiated and have been steadily advanced ever since. At present, Pangandaran is acknowledged as one of the nine villages by UNESCO-IOC for being a tsunami-prepared community in Indonesia, which indicated by having a tsunami evacuation plan, including nine Tsunami Temporary Evacuation Sites (TESs). This research evaluates those nine TESs by determining based on demand (over and under) using the capacity demand index (CDI). Additionally, the streets that are likely to be congested during evacuation were investigated. The CDI was calculated from the result of an agent-based model, which was based on the Tohoku University numerical analysis model for investigation of evacuation no. 1 (TUNAMI-EVAC1), an agent-based tsunami evacuation simulation framework written in NetLogo. A worst-case earthquake with Mw8.7 that occurred in the southern Java subduction zone was considered herein. This model was customized to represent the actual state of Pangandaran village using population data from UNESCO-IOC and questionnaire data from a previous study. The developed model contained an uncertain variable, i.e., population distribution. The model was thus run with 150 repetitions to obtain a reliable conclusion. The corresponding results revealed that an average of two TESs faced over-demand, whereas the other seven experienced under-demand. The highest demand was observed for the Pangandaran Grand Mosque, with an average CDI of 2.78, followed by the *Krisna Beach* hotel with an average CDI of 1.05. Significant congestion was noted on *Parapat* street and *Kidang Pananjung* street located in the center of Pangandaran village.

Keywords: agent-based modeling, tsunami evacuation simulation, NetLogo, Pangandaran.

1. INTRODUCTION

Indonesia is located at the intersections of three significant tectonic plates: the Sunda Block, the Pacific Plate, and the Indo-Australian Plate (Irsyam et al., 2020). The complex interactions among these plates have caused numerous earthquakes in the country, some of which were sufficiently large to trigger destructive tsunamis. Over the past two decades, Indonesia has experienced several catastrophic tsunamis such as the Indian Ocean Tsunami in 2004, the Pangandaran Tsunami in 2006, the Mentawai Tsunami in 2010, and the Palu Tsunami in 2018 (Triyono et al., 2018), leading to substantial loss of life. Thus, it is important to conduct research on this field to minimize the casualties caused by tsunami disaster.

Pangandaran village is situated in the Pangandaran district, part of the Pangandaran Regency in West Java province. It is a peninsula and the main tourist destination on the southern coast of Java Island. It was severely impacted by the 2006 tsunami triggered by an earthquake with Mw7.7 located off the coast (Triyono et al., 2018). The resident population of the Pangandaran district was

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11,274 in 2021 (International Tsunami Information Center, 2021). Pangandaran village is also one of the nine villages or cities in Indonesia that are recognized by UNESCO-IOC as a tsunami-ready community. Historical records indicate that tsunamis struck Pangandaran on September 11, 1921, (M7.5) and July 17, 2006 (M7.7), causing around 600 fatalities (Fritz et al., 2007). Consequently, tsunami preparedness efforts began in 2006 and have been continuously enhanced since then (International Tsunami Information Center, 2021).

2. DATA

Two main systems are used in the agent-based model (ABM): environment and agents. The environment includes a road network represented by a GIS shapefile sourced from OpenStreetMap; TES locations, which consist of a main TESs and alternative TESs as identified by Koswara et al. (2021). The tsunami inundation scenario is based on a worst-case earthquake scenario with a magnitude of Mw8.7, as modeled by Anugrah et al. (2022) using the Cornell Multi-grid Coupled Tsunami model (COMCOT) tool developed by X. Wang (2009).

The agent system simulates a population of 11,274 people residing in Pangandaran village, as recorded by the International Tsunami Information Center (2021). This system includes the destination choice where agents chose the nearest TES using an improved A* algorithm developed by Mas (2012). Evacuee movement speeds vary by mode of travel: adults and young individuals move on foot at speeds of 2.7 m/s, children at 1.2 m/s, and the elderly at 1.05 m/s; those on motorcycles and cars travel at 16 m/s (Wargadalam, 2022). Preparation times before evacuation are categorized into immediate departure, and delays of up to 5, 10, 30, or more than 30 minutes, as noted by Koswara et al. (2021). Casualties are determined by water depth, with thresholds set at ≥ 0.85 meters for pedestrians and ≥ 0.5 meters for vehicles Mas (2012).

Table 1. Capacity of TES (Koswara et al., 2021).

Code	Name	Capacity (person)
TES1	Pangandaran Grand Mosque	500
TES2	Pangandaran Shelter	5,000
TES3	Nature Reserve	6,400
TES4	Horison Hotel	3,846
TES5	Laut Biru Hotel	9,077
TES6	d'BILZ Hotel	1,884
TES7	Pantai Indah Hotel	1,317
TES8	Fortuna Hotel	719
TES9	Krisna Beach Hotel	4,448
Total Capacity		33,191

Koswara et al. (2021) reported that the Regional Disaster Management Agency (BPBD) of Pangandaran stated that there are 9 (nine) TES available for tsunami evacuation (Table 1). Table 1 shows points 1–3 and 4–9 that represent the main TESs and hotels that can be used as alternative TESs, respectively. The main TES could accommodate roughly 11,900 people which is enough for the entire Pangandaran village population. Combined with the alternative sites, the TESs could accommodate 33,191 people, almost triple that of the village's population. However, due to the uneven distribution of population and the dynamic nature of humans during tsunami evacuations, some TESs may experience

over-demand and under-demand. This study used a worst-case scenario earthquake on the southern part of Java by Anugrah et al. (2022) with collaboration of Meteorological Climatological and Geophysical Agency (BMKG), National Disaster Management Agency (BNPB), and BPBD.

3. METHODOLOGY

3.1. Research flowchart

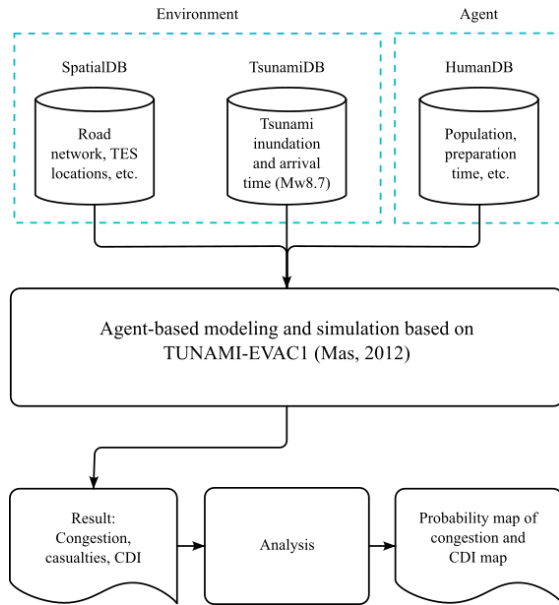


Figure 1. Research flowchart.

Herein, mainly environment and agent data were utilized; the former comprised spatial database (SpatialDB) and tsunami database (TsunamiDB) containing information about the system's environment. SpatialDB includes various spatial data such as road networks, TES locations, buildings, seas, and rivers, whereas TsunamiDB comprises tsunami inundation data with a 1-s temporal resolution, totaling 301 data files in the American Standard Code for Information Interchange (ASCII) format (Anugrah et al., 2022). Lastly, human database (HumanDB) contains the characteristics of the population including population data, preparation time, agent's speed, and age groups. These three datasets were preprocessed and integrated into an agent-based model using the NetLogo software based on the TUNAMI-EVAC1 framework (Mas, 2012). The model was then used for simulation runs, and the obtained results were processed to obtain the

probability map of congestion, the severity of congestion, and the CDI map (Figure 1).

3.2. Metrics

The severity of congestion was calculated by counting how many congestions occurred on certain roads in all repetitions (Eq. 1) where n is the number of repetitions and x_i is the number of congestions on repetition i . CDI (Eq. 2) was used to indicate whether a TES is over-demanded or under-demanded in the form of a probability.

$$SC = \sum_{i=1}^n x_i \quad (1)$$

$$CDI = \frac{Demand}{Capacity} \quad (2)$$

The pedestrians' speeds were adjusted based on the crowd in their area. Goto et al. (2012) reported that if the density of population in a pedestrian's vicinity was 1.0 person/m² or more, their speed will decrease until it reaches zero at 6.0 person/m². The same principle applies to motorcycles but with different criteria, where the maximum speed was 16 m/s at a density of 0–0.17 person/m². Beyond that range, the speed will decrease until the density reaches 0.9 person/m²; at this point, the speed will be the same as that of pedestrians.

The concept of congestion varies between pedestrians and vehicles. For pedestrians, congestion occurs when the density of people in front reaches 70% of the available space. For vehicles, congestion occurs when the density of vehicles in front reaches 7% of the available space (Mas, 2012). The same concept was applied for calculating the density of pedestrians and vehicles: dividing the number of people or vehicles by the area. However, the definition of area differs for pedestrians and vehicles. For pedestrians, the area is based on a 60° field of view with a maximum distance of 5 m, whereas vehicles use a 60° field of view with a maximum distance of 10 m.

4. RESULTS AND DISCUSSION

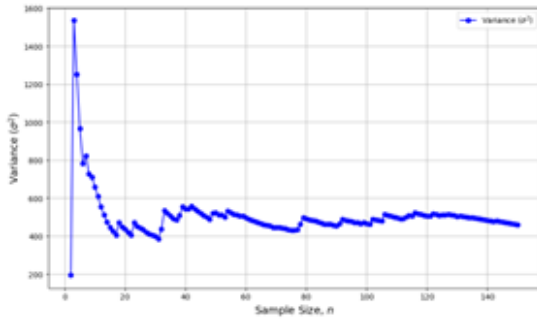


Figure 2. Convergence check.

Table 2. The average, standard deviation (SD), minimum, and maximum values of casualties for type group relative to the total population.

Type	% Casualties relative to total population			
	Avg	SD	Min	Max
Kids	3.65	0.14	3.26	3.97
Young	0.29	0.06	0.16	0.43
Adults	2.27	0.13	1.92	2.56
Elders	1.52	0.09	1.25	1.73
Cars	1.31	0.27	0.53	1.84
Motorcycles	15.59	3.17	4.55	20.43
Total Avg Casualties	24.58			

means 2,771 people died, and conversely, 8,503 or 75.42% survived during the simulation. The highest deaths were contributed by motorcycles, this is due to the congestion that occurred during the simulation and the fact that it is the second most chosen transportation choice with 30.46% choosing to evacuate by motorcycles.



Figure 3. Congestion severity map — indicates how severe the congestion is on a specific road. The higher the number (dark red), the more severe the congestion was.

Multiple simulation iterations of the ABM were performed to consider the uncertainty. The required number of repetitions depends on the number of uncertain variables involved. The higher the number of uncertain variables, the higher the number of repetitions needed. Herein, one uncertain variable, i.e., the initial location of the agent, was used. To determine the required number of repetitions, simulations were conducted repeatedly until convergence was observed on a chart depicting sample size versus variance (Lee et al., 2015). Figure 2 shows that with 150 repetitions, stable and converging aggregated casualties were observed. Based on these findings, 150 repetitions were employed.

Simulating the initial positions of residents is challenging because the population varies across locations at different times. For instance, people are generally at their workplaces during the day and at home during the night. By accepting this uncertainty, we ran 150 repetitions of scenarios with different agent starting points in a stochastic simulation. The average, standard deviation (SD), and minimum and maximum number of casualties were obtained, as shown in Table 2. The percentage of casualties was relative to the total population, i.e., 11,274. Results show that the total casualty on an average was 24.58%, which means 2,771 people died, and conversely, 8,503 or 75.42% survived during the simulation. The highest deaths were contributed by motorcycles, this is due to the congestion that occurred during the simulation and the fact that it is the second most chosen transportation choice with 30.46% choosing to evacuate by motorcycles.

Congestion is a problem that often arises during tsunami evacuation. This condition occurs when the volume of vehicles or pedestrians using the same route exceeds its capacity. In addition, differences in the speed of each individual and vehicle make congestion even more complex. The severity of the congestion can be seen in Figure 3. Severity refers to how often a specific road experiences congestion. This map is valuable for identifying which roads are frequently congested during a tsunami evacuation. Based on Figure 3, it is evident that the most severe congestion and the road that is likely to be congested is the road

located in the center of Pangandaran village, which is the intersection between *Parapat Street* and *Kidang Pananjung Street*.

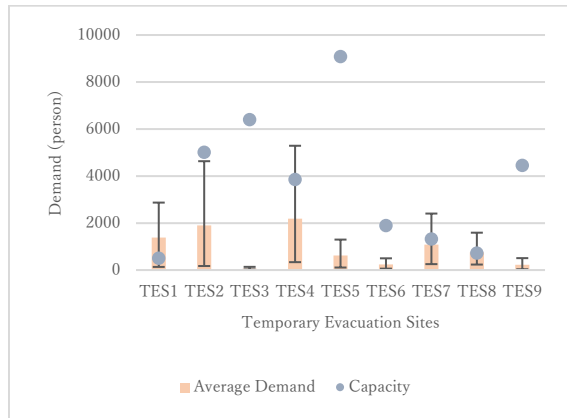


Figure 4. TES capacity vs. average demand. On average, TES1 and TES8 are over-demanded, whereas other TES are under-demanded.

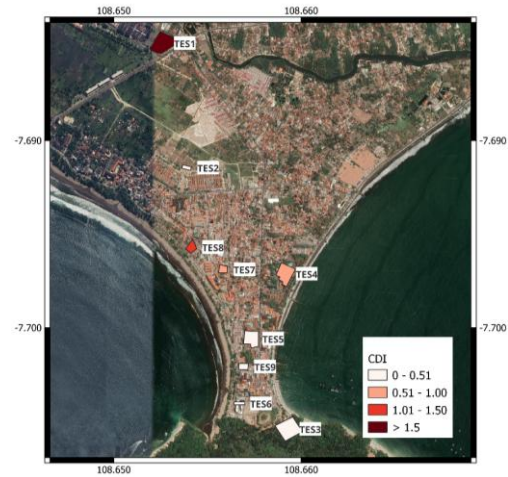


Figure 5. Capacity demand index map of TES in Pangandaran.

Based on the result in Figure 4, TES1 or Pangandaran Grand Mosque and TES8 or *Krisna Beach* hotel are over-demanded, whereas on an average, TES7 is adequately utilized, and the remaining TESs are under-demanded.

As shown in Figure 5, local stakeholders and laypersons can easily understand which TESs are over and under demanded. The value of this map is based on the average demand derived from Table 2. A value from 0.0 to 0.5 signifies that less than 50% of the capacity is utilized, whereas a value from 0.5 to 1.0 indicates most capacity is in use. Notably, a value exceeding 1.0 highlights that the TES is in a state of over-demand.

5. CONCLUSIONS

In this study, the tsunami evacuation model in Pangandaran village was simulated with an Mw8.7 earthquake using agent-based modeling method. The earthquake source was three segments in subduction located in the southern part of Java Island. The tsunami was expected to arrive at Pangandaran village 40 minutes after the earthquake occurred. The aim is to evaluate the nine TESs by determining their CDI based on demand (over and under) and investigates the streets that are likely to be congested during a tsunami evacuation. The tsunami event was simulated to get the tsunami inundation data, which is ASCII data with 1-second temporal resolution and incorporated into the model. The tsunami inundation data was used to define the casualties. Casualties were defined when the inundation depth was ≥ 0.85 m for pedestrians and ≥ 0.5 m for cars and motorcycles.

The tsunami evacuation model was based on TUNAMI-EVAC1 with road network data, data of preparation time, age group, TES locations, and mode of transportation, speed of agent type, and speed adjustment. The pathfinding algorithm used in this model is an improved A* (A-star) algorithm. We ran the model for 150 repetitions to consider the uncertain variable in the model, i.e., population distribution.

The findings of convergence check revealed that 150 repetitions were convergent and stable among the examined instances, indicating reliability in the results. The simulation results showed that on an average, 24.58% of the population were casualties, which translates to 2,771 fatalities, whereas 75.42%, or 8,503 people, survived. The simulation also indicated congestion, with the most congested streets being the intersection of *Parapat street* and *Kidang Pananjung street* located in the center of Pangandaran village. Moreover, congestion mostly occurred in areas where people used

vehicles to evacuate. One practical approach to address this issue is to assign police officer to manage traffic flow and encourage people to evacuate to less congested streets.

The simulation results also revealed an additional problem with two TESs being over-demanded, one of which, Pangandaran Grand Mosque, had a CDI of 2.78; this indicated that it was occupied by nearly three times over its designed capacity. *Krisna Beach* hotel was another overly occupied TES with a CDI of 1.05. The remaining seven TESs experienced under-demand. This situation underscores a significant challenge in uneven distribution demand across all available TESs. This issue can be addressed by either building new TES near the over-demanded TESs or assigning people to evacuate to specific TES.

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