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Agent-Based Modeling of Vertical Tsunami Evacuation in Enggano Island, Indonesia: Route Dynamics, Shelter Capacity, and Behavioral Performance

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ABSTRACT Enggano Island is situated above the southern segment of the Sunda megathrust, making it highly vulnerable to earthquakes and tsunami hazards. In remote coastal villages, such as Kaana, the lack of adequate evacuation infrastructure presents significant challenges for disaster risk reduction. This study aims to evaluate tsunami evacuation strategies using an agent-based modeling approach implemented in a three-dimensional simulation environment. A purposive sampling survey involving 83 residents was conducted to collect socio-demographic data, tsunami awareness, preparedness levels, and evacuation preferences. These inputs were used to calibrate agent behavior and movement patterns to better reflect realistic community dynamics in the simulation. The model simulates multiple evacuation configurations to examine survival rates and evacuation times under different spatial layouts, building distributions, and shelter capacity assumptions. Results showed that horizontal evacuation via a single inland route leads to severe congestion and low survival outcomes, with only 8.2% of agents reaching safety within ten minutes. In contrast, the addition of vertical evacuation buildings significantly enhanced evacuation performance, yielding survival rates above 90% under all conditions. Even when shelter capacity was limited to 70% of its full design, over 93% of agents were still able to evacuate successfully, although with increased delays. Vertical-only evacuation produced stable performance with average completion times of approximately five minutes. These findings emphasize the importance of integrating vertical shelters in strategic locations, optimizing route accessibility, and adapting building capacity to physical and demographic constraints. This study contributes to tsunami risk mitigation planning by offering empirical insights into evacuation dynamics in isolated island environments such as Enggano Island, Indonesia.

KEYWORDS Disaster mitigation; Agent-based modeling; Tsunami vertical evacuation; Shelter capacity; Evacuation time; Enggano Island

1 INTRODUCTION

Indonesia is located within the Pacific Ring of Fire, a region characterized by high seismic activity. Enggano Island, one of the country's outermost islands in the Indian Ocean, is highly vulnerable to earthquakes and tsunamis due to its proximity to the Sunda subduction zone and major active faults. To the southwest lies the Sunda subduction zone, where the Indo-Australian Plate subducts beneath the Eurasian Plate, while the Sumatra Fault extends to the north and the Mentawai Fault to the south. The western part of Sumatra frequently experiences strong earthquakes associated with this subduction system (Anggraini et al., 2025). Similar tectonic activity occurs throughout the archipelago, reflecting high seismic exposure (Mase and Likitlersuang, 2021; Mase, Fathani and Adi, 2021; Mase et al., 2023; Somantri et al., 2023). This position places Enggano within an active tectonic system capable of generating megathrust earthquakes. Historical records have documented three major earthquakes in this region, namely the Bengkulu–Enggano earthquake (Mw 7.9) in 2000, the Bengkulu–Mentawai earthquake (Mw 8.6) in 2007, and the Mentawai earthquake (Mw 7.7) in 2010 (Mase, Fathani and Adi, 2021; Mase, 2022). Figure 1 illustrates the location of Enggano Island, the subduction zone, active faults, and the epicenters of these major earthquakes, highlighting the island's significant tsunami hazard.)

Recent seismic activity around Enggano has been marked by shallow slow-slip activity and strain accumulation in the Mentawai Forearc Sliver, suggesting the potential for a major earthquake (Mallick et al., 2021; Razi et al., 2023; Heliani et al., 2025). Tsunamis generated by such events could reach Enggano in less than 15 minutes, particularly along coastal areas perpendicular to the fault strike (Triyoso et al., 2024). The island's flat topography and limited road access make horizontal evacuation inadequate, similar to other disaster-prone regions where limited routes hinder timely movement to safety (Hardiansyah et al., 2020). These characteristics, including limited topography and short warning times, make Enggano a criti-

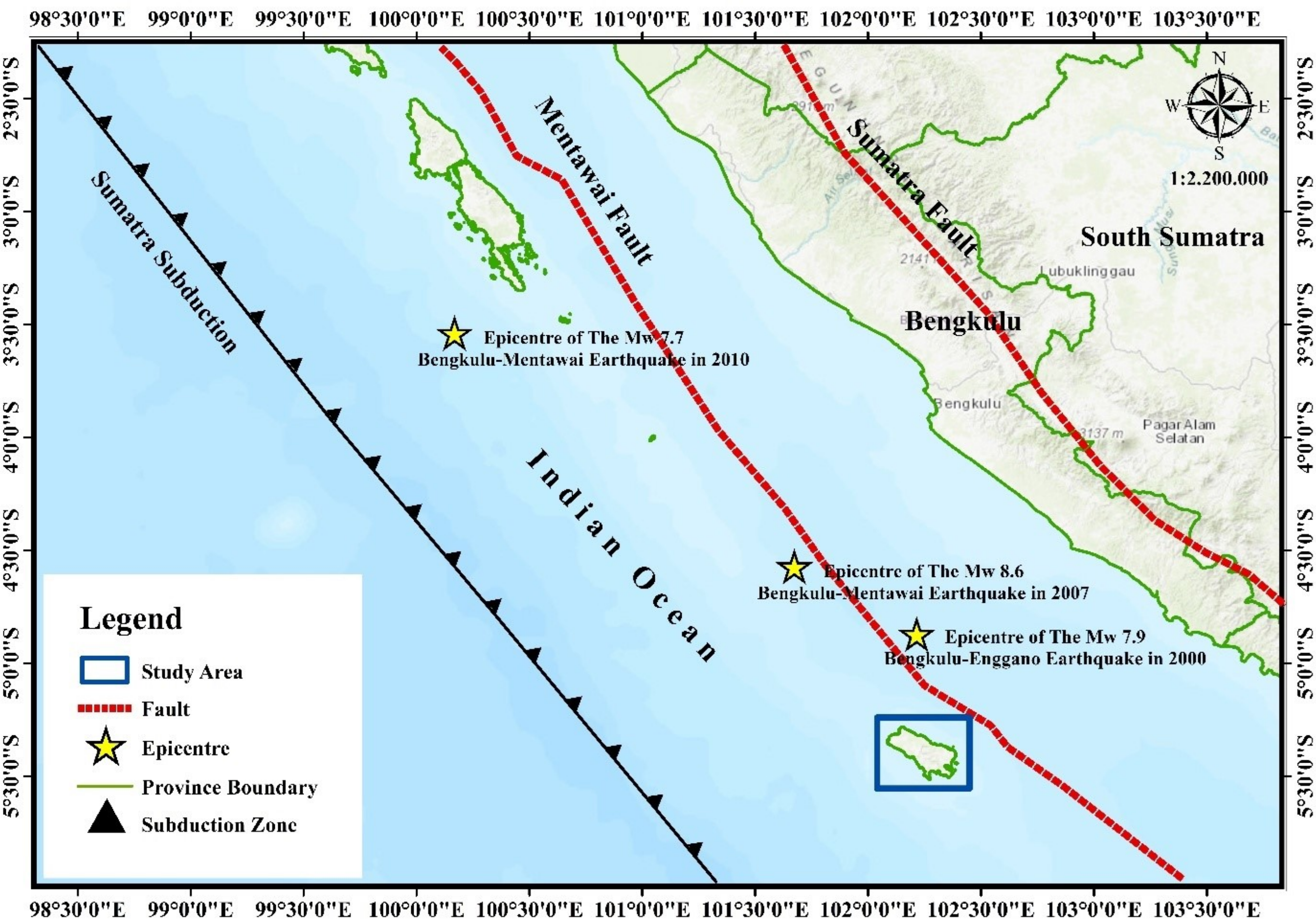


Figure 1. Seismotectonic map of the Enggano region (modified from Mase, Sugianto and Refrizon (2021)).

cal setting for evaluating effective tsunami evacuation strategies.

To overcome these constraints, Tsunami Vertical Evacuation (TVE) buildings have been proposed as an important alternative. Reinforced multi-story structures allow residents to reach safe elevations within a short time (Kim et al., 2022; Ibrahim et al., 2023). This strategy is particularly relevant for small islands with limited topography and infrastructure. TVE buildings function not only as de ignated shelters but also as part of an integrated evacuation strategy within disaster management. Their effectiveness depends on both physical design and human factors. Behavioral and demographic attributes—such as walking speed, stamina, age composition, and response promptness—directly influence how efficiently people can reach these shelters. Understanding these behavioral dynamics is essential for optimizing the design and placement of TVE buildings, ensuring that evacuation strategies are feasible for small-island communities like Enggano. Beyond physical design, collective and social behavior also plays a crucial role in determining how communities respond to evacuation measures. Field observations in Indonesian disaster contexts have shown that collective decision-making and social influence strongly shape how people respond to evacuation warnings (Hardiansyah et al., 2018). These behavioral and social findings highlight the importance of integrating human dynamics into tsunami evacuation planning, complementing the structural and spatial approaches adopted in previous studies.

Previous tsunami evacuation studies have focused on spatial and structural performance, emphasizing shelter capacity and route efficiency (FEMA, 2012; Wood et al., 2023). In Indonesia, Jihad et al. (2023) investigated the use of hills and public buildings as vertical evacuation sites in Aceh, while Vivita et al. (2023) analyzed mosque-based community shelters. Similar approaches in Japan have confirmed that strategically located Tsunami Evacuation Buildings (TEBs) can significantly reduce casualties (Hoshino et al., 2025; Murao et al., 2025). However, these capacity-based frameworks assume uniform evacuee mobility, overlooking behavioral diversity that critically influences evacuation outcomes (Muhammad et al., 2021).

Recent developments have shifted toward behavioral and Agent-Based Modeling (ABM) approaches, which simulate evacuation as an emergent process shaped by individual decision-making and social interaction (Wilensky, 1999). Mas et al. (2024) incorporated reinforcement learning to improve pedestrian routing, while Choi et al. (2024) showed that social influence and compliance affect crowd movement. Empirical evidence from Indonesian disasters also highlights the importance of social dynamics in shaping evacuation responses (Hardiansyah et al., 2020). Several ABM studies have integrated demographic and infrastructural data for improved local calibration and realism (Ito et al., 2021; Muhammad et al., 2024). Within tsunami contexts, parameters such as walking speed, stamina reduction, and response promptness affect evacuation time, yet most ABM studies remain focused on urban or mainland environments.

Building on these developments, ABM has emerged as a widely used approach for simulating tsunami evacuation dynamics, as it can represent individual interactions and environmental constraints. Wang and Jia (2021) proposed a comprehensive ABM framework for tsunami evacuation that incorporates various movement modes and behavioral variability, providing a foundation for realistic evacuation risk assessment. Harris et al. (2024) applied ABM in Milford Sound, a remote tourist area in New Zealand, and found no scenario where all individuals could reach safety before the tsunami arrival. Fathianpour et al. (2023) reported that vehicle-based evacuation saved only 45% of the population, much lower than pedestrian evacuation, while Hasegawa and Takabatake (2024) highlighted the influence of traffic flow on shelter optimization. Mas et al. (2024) used reinforcement learning to reduce intersection congestion, achieving faster evacuation than shortest-path routing. Choi et al. (2024) emphasized social-behavioral differences between tourists and residents, and Yamada and Yamasaki (2021) showed that evacuation direction–not only distance–affects shelter distribution and travel time. Similar frameworks have also been implemented in Indonesia. Muhammad et al. (2024) developed an ABM-based framework to assess tsunami risk using population and infrastructure data, stressing the importance of local data integration. Ito et al. (2021) applied ABM to identify hard-to-reach areas during evacuation, which is relevant for remote locations. Collectively, these studies demonstrate the versatility of ABM in simulating evacuation processes across diverse contexts.

However, despite these advancements, most frameworks still emphasize physical capacity and shelter distribution, with limited integration of behavioral heterogeneity—particularly in small-island contexts. This study addresses this limitation by incorporating individual behavioral diversity into an ABM framework customized for Enggano Island. The approach offers a novel integration of behavioral, spatial, and structural parameters to enhance the realism and applicability of tsunami evacuation modeling.

To overcome these limitations, modeling individual behavior is essential in tsunami evacuation because evacuees show heterogeneous movement responses during short-warning conditions. Evacuation performance therefore, depends not only on shelter capacity and route connectivity but also on individual decision-making under pressure. Earlier tsunami evacuation research has primarily focused on shelter capacity and route connectivity, providing important insights into infrastructure and spatial planning. However, most of these models assume uniform evacuee behavior, overlooking behavioral diversity that critically affects evacuation efficiency under short-warning conditions. In Enggano Island, where the tsunami arrival time is estimated to be less than fifteen minutes (Triyoso et al., 2024) and road networks are narrow, individual differences—such as walking speed, stamina reduction, and response promptness—strongly influence overall evacuation performance. Incorporating these behavioral parameters into an ABM framework allows a more realistic representation of pedestrian dynamics, congestion formation, and decision-making under pressure. This study, therefore, extends existing capacity-based analyses by emphasizing behavioral heterogeneity as a determinant of evacuation outcomes, particularly in geographically isolated island environments.

The specific context of Enggano Island is crucial, as small-island environments combine limited elevation, constrained infrastructure, and short warning times—factors that amplify the influence of individual decision-making during evacuation. Accordingly, this study uses Enggano as a representative case to analyze how behavioral diversity affects tsunami evacuation performance. While most ABM-based evacuation studies focus on urban or mainland settings, few have explored small-island conditions where infrastructure and evacuation routes are severely limited. To address this gap, the present research develops an agent-based tsunami evacuation model that integrates both horizontal (2D) and vertical (3D) strategies for Kaana Village, Enggano Island. The model evaluates how behavioral parameters—walking speed, stamina reduction, and response promptness—interact with environmental constraints to influence evacuation outcomes. The findings aim to enhance disaster mitigation planning and improve understanding of evacuation behavior in small-island contexts.

Therefore, this study aims to develop a behavioral agent-based model that integrates both horizontal and vertical evacuation strategies to evaluate tsunami evacuation performance in small-island settings. The research addresses three interrelated gaps: (i) a conceptual gap, by incorporating individual behavioral variability—walking speed, stamina reduction, and response promptness—into evacuation anal-

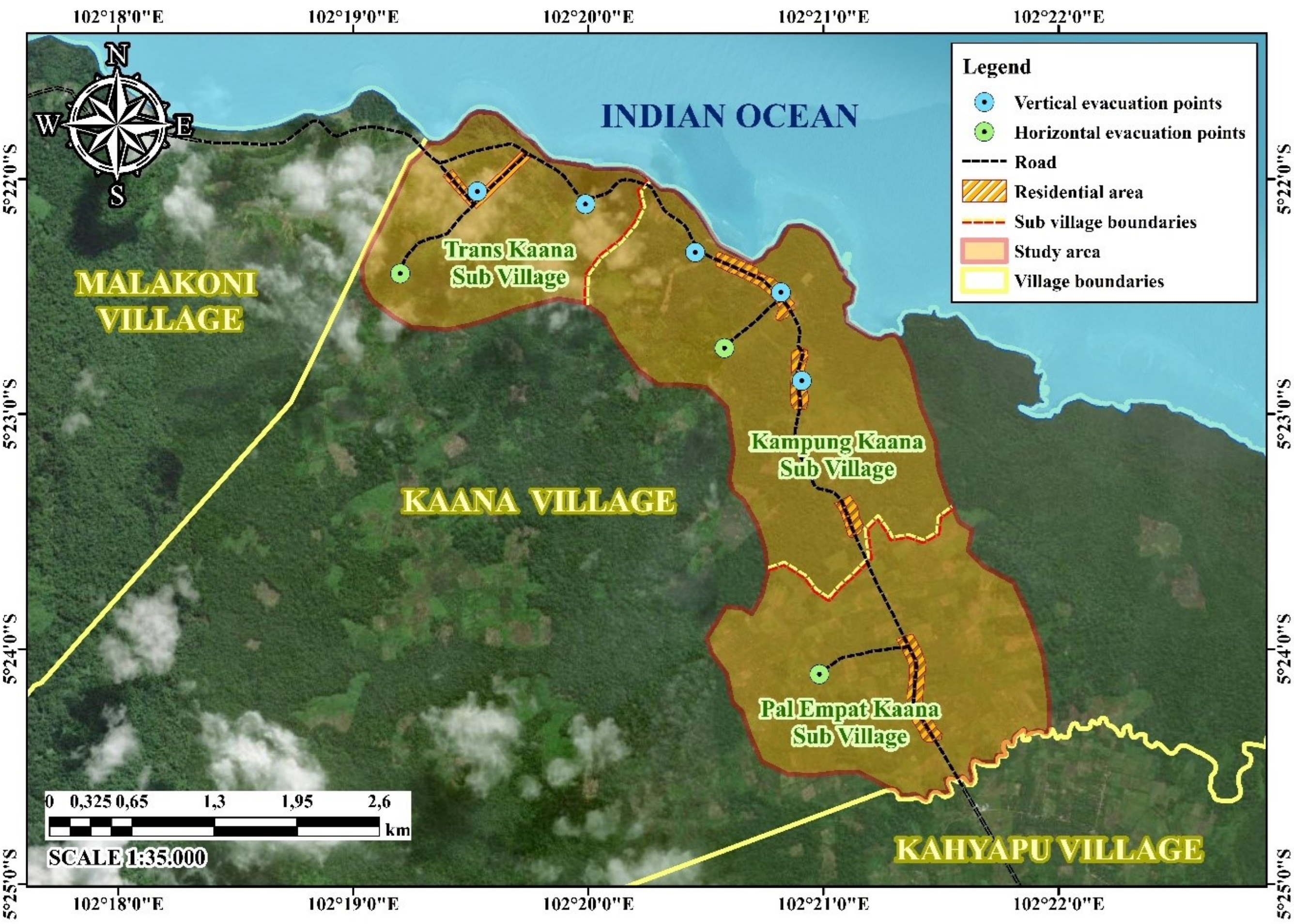


Figure 2. Study Area

ysis; (ii) a methodological gap, by extending previous two-dimensional capacity models into a three-dimensional simulation that combines horizontal and vertical movement; and (iii) an empirical gap, by calibrating the model with locally collected demographic and behavioral data from Enggano Island. By addressing these gaps, the study contributes to enhancing the understanding and application of tsunami evacuation planning in remote coastal communities.

The following section describes the methodology employed in this study, including the development of the behavioral ABM and the simulation design used to evaluate tsunami evacuation performance.

2 METHOD

This section presents the methodological framework and stages of the study. It outlines the overall process, beginning with the justification for using Agent-Based modeling (ABM) in tsunami evacuation, followed by data collection, data analysis, and model development. Each subsection provides detailed explanations of these stages, including the study area, sampling, behavioral parameters, and vertical evacuation modeling, while the research framework at the end of this section integrates all stages into a single conceptual flow.

2.1 Study Area and Data

Enggano Island lies in the southern segment of the Sunda megathrust and is characterized by high seismic activity. This study focuses on Kaana Village, located along the island's eastern coast. The site was selected because of its varied topography and the availability of a verified tsunami evacuation map from the Bengkulu Provincial Disaster Management Agency (BPBD). Kaana Village comprises three sub-villages—Trans Kaana, Kampung Kaana, and Pal Empat Kaana—each representing different elevation levels and evacuation distances. Spatial data, including road networks, residential areas, and designated vertical evacuation sites, were compiled from BPBD, satellite imagery, and field surveys. These datasets were reconstructed in NetLogo 3D to represent the spatial configuration of the study area and serve as the foundation for the simulation modeling (Figure 2).

2.2 NetLogo and Agent-Based Modeling

This study adopts an ABM approach to simulate tsunami evacuation dynamics in Kaana Village, Enggano Island. ABM enables autonomous representation of individual behaviors within a spatial environment and captures dynamic interactions between agents and their surroundings (Bonabeau, 2002). The simulation was developed in NetLogo 3D (Wilensky, 1999), which supports spatial visualization and flexible rule-based agent behavior configuration according to local parameters. A similar approach was implemented by Hardiansyah et al. (2022) in Bengkulu to evaluate vertical evacuation in multi-story buildings, which effectively represented individual movement and bottleneck formation during evacuation. Each agent represents one resident of Kaana Village with predefined demographic and behavioral attributes. The simulation environment consists of road networks, buildings, and vertical evacuation shelters (TVEs). The model operates in discrete time steps (ticks), with one tick equivalent to one second of real time. Formally, the model is structured as a discrete-time dynamic system:

$$S_i^{(t+1)} = f(S_i^{(t)}, N_i^{(t)}, E^{(t)}) \tag{1}$$

where $S_i^{(t)}$ denotes the state of agent i at time t, $N_i^{(t)}$ represents the set of neighboring agents, and $E^{(t)}$ refers to the environmental condition at time t. The function f governs agent behavior—direction choice, movement, and stamina reduction—allowing each agent's state to evolve according to both internal characteristics and external interactions. Agent displacement is calculated based on walking speed and time step duration:

$$\Delta x = v.\Delta t \tag{2}$$

where v is the agent's walking speed (m/s) and Δt is the time interval. This equation determines the linear distance of each agent per simulation tick and provides the basis for calculating movement distance along the road network. When the number of agents on a road segment exceeds its maximum capacity, congestion occurs, and the effective walking speed is reduced. The congestion slowdown coefficient is computed using an exponential function (Harris et al., 2024):

$$\phi_C = e^{-\frac{U}{C}} \tag{3}$$

where ϕ_C is the congestion reduction coefficient (ranging from 0 to 1), U is the number of agents on the segment, and C is the maximum road capacity, assumed to be one agent per meter of road length. This formulation reproduces the exponential decrease in pedestrian speed under crowded conditions. Agent movement direction d_i is determined using a cost-minimization function:

$$d_i = arg \min_{d \in D} \text{Cost}(d, S) \tag{4}$$

where D denotes the set of available local movement options (forward, left, and right on the road patches), and S represents the agent's local state, including road connectivity and the relative position of nearby shelters. Agents select the nearest shelter using Euclidean distance through the NetLogo distance function and move along the road network while avoiding non-road areas. This setup combines distance-based targeting with rule-based navigation, maintaining computational stability while representing movement under Enggano's limited road conditions. Local density naturally arises from agent interactions when several agents occupy the same road segments, without requiring an explicit density parameter.

All agents act rationally within this framework, immediately initiating evacuation upon receiving a warning and adjusting their movement when roads become congested or blocked. The empirical basis for this behavioral assumption is described in the subsequent section. Panic, herding, and bounded-rational behaviors were excluded to isolate the influence of key behavioral parameters—walking speed, stamina, and response promptness—on evacuation outcomes.

All agents act rationally within this rule-based framework, consistently seeking the nearest accessible shelter and adapting their heading when road segments become congested or blocked. Panic, herding, or bounded-rationality behaviors were intentionally excluded to isolate the influence of key behavioral parameters—such as walking speed, stamina, and response promptness—on evacuation performance. This abstraction enables a clearer interpretation of behavioral sensitivity within the simulated environment.

In all scenarios, agents are assumed to evacuate immediately upon receiving the early warning, without any decision delay. Variations in arrival times at shelters arise from differences in location, route choice, walking speed, and congestion effects. These mathematical formulations underpin the agent behavioral system in the NetLogo 3D model and are integrated with local demographic and spatial data to produce a contextually grounded tsunami evacuation simulation.

2.3 Sample and Population

According to data from the North Bengkulu Central Statistics Agency in 2024, Enggano District has a total population of 4,502, with 825 residents living in Kaana Village as of February 2025. These figures serve as the foundation for the agent-based simulation, with each of the 825 agents representing one individual.

The population was divided into three sub-villages: Trans Kaana (29%), Kampung Kaana (41%), and Pal Empat Kaana (30%). These proportions were based on the 2025 population data from the Kaana Village Administration Office and were used to determine the number of agents in each sub-village. Agents were placed randomly within each sub-village boundary to approximate the residential distribution. The simulation environment included the main road network and the location of Tsunami Vertical Evacuation (TVE) shelters, which were adapted from the actual village layout. This setup provides a simplified but realistic representation of Kaana Village for evacuation modeling.

Field data were obtained through a purposive survey involving 83 respondents (about 10% of the total population), focusing on residents in tsunami-prone areas. The sample size followed (Yount, 2006) practical guideline for small populations, which suggests 10–30% as an acceptable range. The lower bound (10%) was adopted to maintain data diversity and field feasibility in a remote-island context. The survey was not intended for statistical inference but to rather obtain behavioral information for model calibration, such as walking speed and response promptness.

Based on the collected field data, respondents comprised 51% males and 49% females. The age composition aligned with the 2025 population recap obtained from the Kaana Village Administration Office, Enggano District, which indicates that approximately 94% of residents are within the productive age group (15–64 years) and 6% are non-productive. These proportions were maintained during respondent selection to ensure that the demographic structure in the field data corresponds with the real population. The same ratios were then used to assign age-related agent attributes in the simulation.

The demographic and behavioral data obtained from the survey were then incorporated into the model to represent population characteristics in the simulation. These demographic settings, combined with behavioral and spatial parameters, formed the basis of the agent initialization process. By incorporating these attributes, the model reflects the actual social and physical characteristics of Kaana Village, enhancing its accuracy in simulating tsunami evacuation dynamics.

2.4 Model Parameters

Each agent in the model represents an individual resident of Kaana Village, Enggano Island, with attributes assigned from field-survey data, including gender, age, mode of transportation (walking or motorcycle), and response promptness during evacuation. The simulation environment includes road networks, shelter locations, and agents, with the road network proportionally scaled to represent the real spatial layout of the study area.

Response promptness represents the behavioral attribute describing how quickly residents initiate evacuation after receiving a tsunami warning. This attribute was obtained from a five-point Likert-scale survey assessing respondents' awareness and understanding of tsunami hazards. The mean score was approximately four, corresponding to the "agree" category, which indicates that most respondents were aware of tsunami threats and recognized the need for immediate evacuation once a warning is received. Accordingly, this empirical finding was used to justify the assumption that all agents immediately evacuate after receiving a tsunami warning with no delay time, which was applied as the behavioral rule in the simulation.

These behavioral parameters were integrated with mobility attributes such as walking speed and stamina. In horizontal evacuation scenarios (Scenarios 1 and 2), walking speeds are differentiated by demographic profile based on survey results: productive males at 3.9–4.6 km/h, productive females at 3.3–3.75 km/h, non-productive males at 3.0–3.5 km/h, and non-productive females at 2.7–3.0 km/h. Motorcycle users travel at a fixed speed of 8.3 m/s, which is directly applied in the model without additional conversion.

These walking speeds were obtained from field measurements in Kaana Village. Respondents were asked to walk a measured distance at their fastest pace, and the time taken was recorded to calculate the average walking speed. This approach was intended to represent faster movement during evacuation conditions. The motorcycle speed of 8.3 m/s was determined from observed average riding speeds along the main village road, representing typical local mobility conditions. These values were used to ensure that the simulated movement parameters accurately reflect local evacuation mobility characteristics.

For vertical evacuation scenarios (Scenarios 3 and 4), stair-climbing speeds are calculated by applying a reduction factor of 60% to the surveyed horizontal walking speeds. This reduction reflects the slower movement observed in empirical studies of stair ascent compared to level walking (NIST, 2014; Chen et al., 2018). The reduced speeds are stored in km/h within the model and then internally converted to m/s for displacement calculations, in accordance with Eq.2.

The model also assigns stamina values to represent endurance during prolonged movement. Agent speeds decrease gradually due to physical fatigue, with more pronounced reductions for individuals with lower stamina, especially during stair climbing. The fatigue factor is set higher for non-productive agents (0.005–

0.010 per tick) and lower for productive agents and motorcycle users (0.002–0.004 per tick), with stamina values categorized as low (7–10), medium (12–15), and high (18–21). These parameters are calibrated so that, during continuous stair climbing, cumulative speed reductions over a 3–5 minutes period fall within the 10–25% range reported in vertical evacuation studies (Halder et al., 2021; Zhu et al., 2021; Pan et al., 2023). All parameters are applied consistently across the four simulation scenarios to ensure comparability of results.

Each agent's behavior during simulation is determined by the interaction between demographic and behavioral attributes. Walking speed and stamina values define individual mobility capacity, directly influencing travel time and fatigue effects during evacuation. Response promptness determines whether an agent immediately begins evacuation or delays movement, affecting congestion dynamics near residential clusters. Meanwhile, transportation mode (walking or motorcycle) modifies both speed and route choice behavior, as motorcycle users are limited to accessible road segments. These parameters collectively shape the emergent evacuation patterns observed in the simulation results, allowing the model to represent heterogeneous responses across the population.

The model was validated using walking-speed data collected from the field survey, which provided empirical measurements of pedestrian movement along evacuation routes. These observed data were compared with simulated walking speeds generated under the same environmental conditions to ensure behavioral consistency. Behavioral and demographic attributes—such as response promptness, stamina reduction, and transportation mode—were used for parameter calibration, while walking speed served as the primary reference for validation.

Statistical reliability was ensured through repeated simulation runs in NetLogo's Behavior Space tool. Pilot simulations were conducted to estimate output variability by calculating the mean and standard deviation of survivors in each scenario. The number of repetitions for each scenario was determined based on the observed variance, ensuring that fluctuations remained within an acceptable range. These consistent repetition settings minimized stochastic bias and produced stable, comparable results across all scenarios.

2.5 Vertical Evacuation Modeling

The Tsunami Vertical Evacuation (TVE) buildings used in this simulation follow the guidelines of the Federal Emergency Management Agency (FEMA, 2012), which provide recommended criteria for the design and evaluation of tsunami vertical evacuation structures. These guidelines require structures to resist tsunami and earthquake forces, have adequate stiffness and ductility, and provide enough capacity for the target population. Internal evacuation routes, such as stairs, must allow smooth flow and avoid bottlenecks.

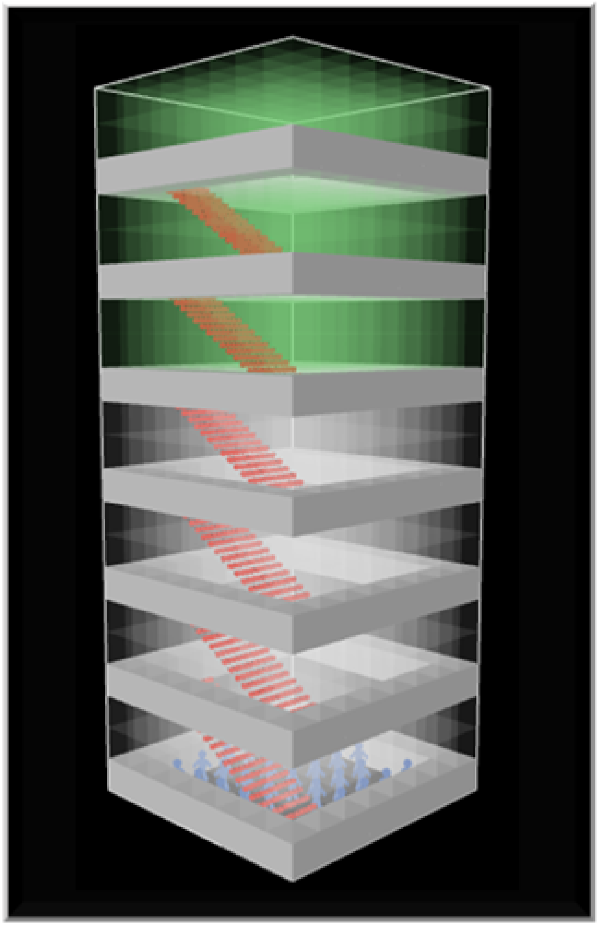


Figure 3. Three-dimensional (3D) model of a Tsunami Vertical Evacuation (TVE) building.

The design is adapted to Enggano Island's geography and logistics, which are remote and have limited access. Each TVE is a modular steel frame building with seven floors, an 8×8 meter footprint, and a total height of 21 meters. Stairs are placed inside to fit the spatial layout in NetLogo 3D and reduce interference with agent flow. Floors 5 to 7 are designated as safe zones based on a 12-meter tsunami height assumption, supported by studies of western Sumatra's coastal run-up (Ibrahim et al., 2023; Triyoso et al., 2024).

Capacity is calculated using the Effective Shelter Building Capacity (ESBC) formula, adapted from (Mayasari et al., 2021):

$$ESBC = \frac{CS \times BA \times NrF}{SpP} \tag{5}$$

where CS = 1.0, BA = 64 m^2, NrF = 3 floors, and SpP = 1 m^2/person. This yields a capacity of 192 people per building, rounded to 195 for simulation purposes.

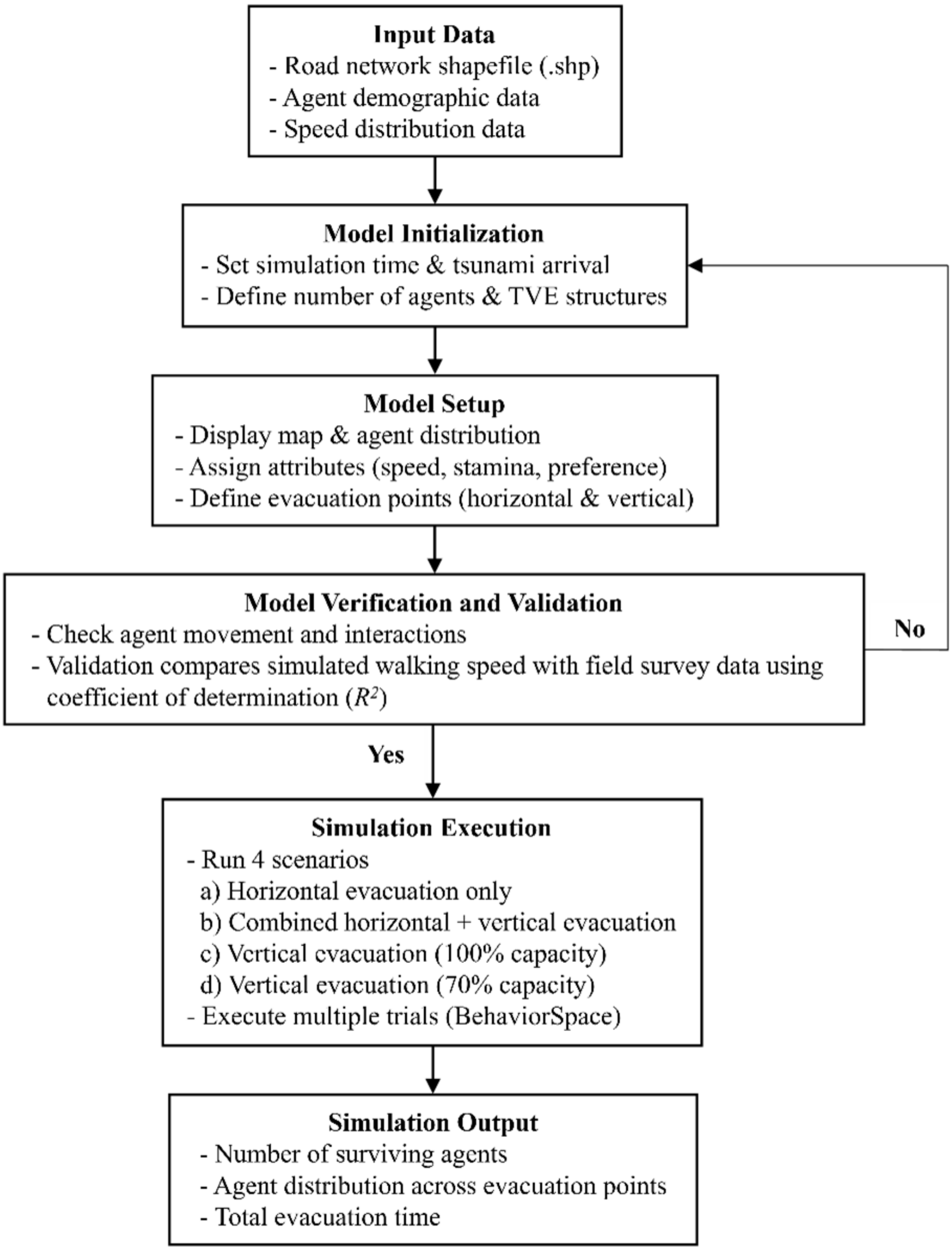


Figure 4. Agent-based simulation workflow for tsunami evacuation modeling.

TVE locations in the model are chosen based on bottleneck analysis from Scenario 1. Points with high population movement and evacuation delay risks were selected, considering FEMA (2012) recommendations on maximum walking distance, road connectivity, terrain obstacles, and proximity to main residential clusters.

With a 195-person capacity per unit, five buildings total 975 spaces, exceeding the 825 agents in the simulation. This ensures all agents can be accommodated if they reach the safe floors before the tsunami arrives. In NetLogo 3D (Figure 3), each TVE is modeled with specific floor dimensions, stair locations, and floor heights. Agents opting for vertical evacuation move toward the building entrance and ascend the stairs step by step to reach floors 5–7. Stairway congestion is explicitly modeled, influencing climbing speed and total evacuation time.

2.6 Research Framework

The simulation workflow, from data processing to output analysis, is shown in Figure 4. This framework serves as the conceptual and operational basis of the agent-based tsunami evacuation model, linking data collection, behavioral parameterization, and simulation outputs in a structured manner. The agent-based

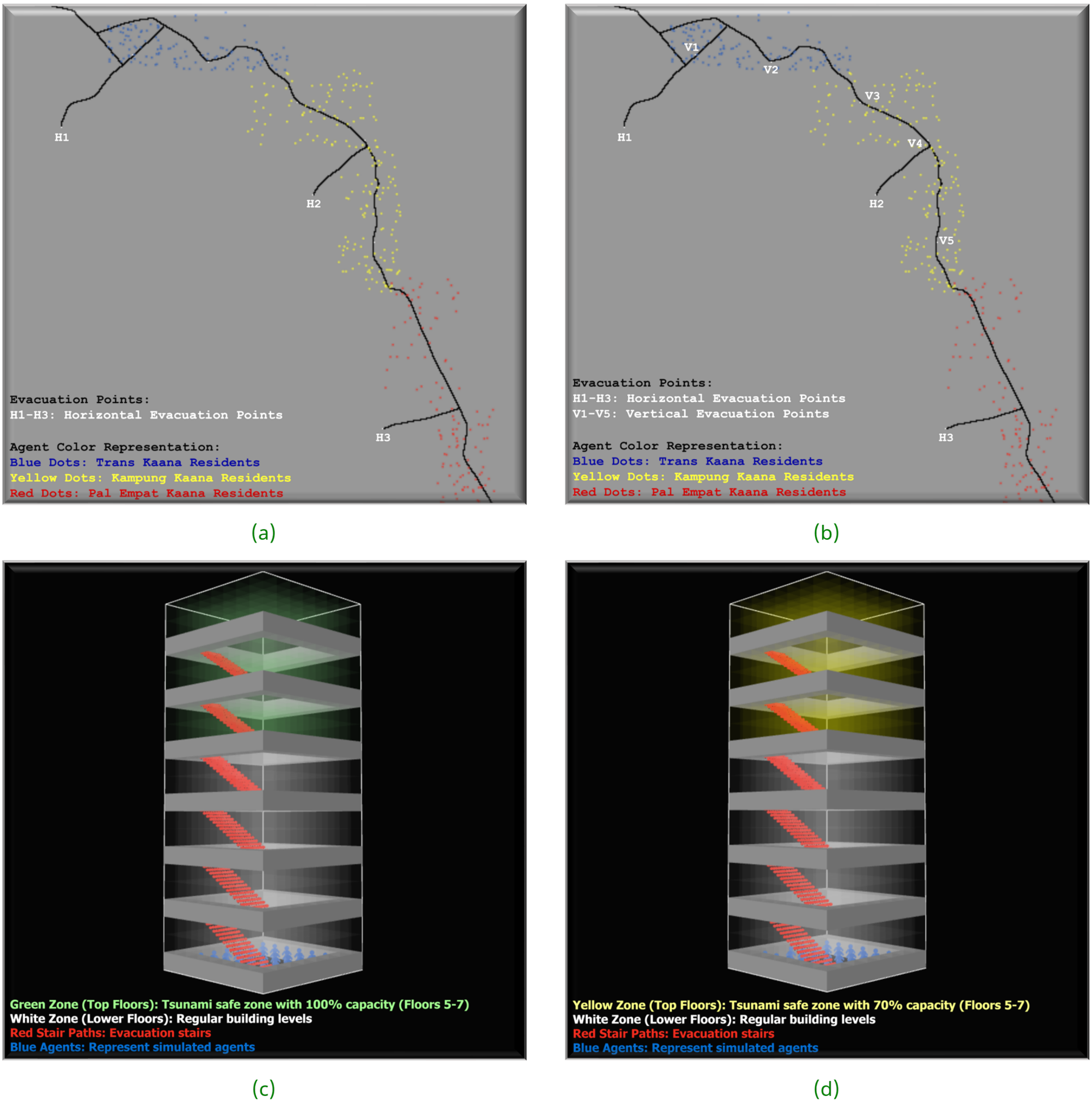


Figure 5. Simulation interface for all evacuation scenarios in NetLogo: (a) Scenario 1 – Horizontal evacuation only, (b) Scenario 2 – Combination of horizontal and vertical evacuation, (c) Scenario 3 – Vertical evacuation using TVE buildings (100% capacity), (d) Scenario 4 – Vertical evacuation with reduced TVE capacity (70%).

tsunami evacuation model was built in NetLogo 3D to simulate evacuee behavior in a realistic 3D environment. The model reflects the spatial layout of Kaana Village, Enggano Island, including topography, road networks, residential clusters, and evacuation buildings. For efficiency, only the road network is visually rendered during simulation. The model runs in discrete time steps (ticks), with one tick equal to one second. A total of 825 agents, matching the actual village population, are distributed across three residential clusters: Trans Kaana, Kampung Kaana, and Pal Empat Kaana. Agent attributes—walking speed, stamina decay, transport mode, and decision logic—are assigned based on field survey demographics. About 18.8% of agents use motorcycles; the rest evacuate on foot.

Tsunami waves are estimated to reach Sumatra's west coast within 10–20 minutes, influenced by local tectonic and bathymetric factors (Dang et al., 2023; Felix et al., 2024; Triyoso et al., 2024). The model simulates tsunami arrival times at 10, 20, and 30 minutes (600, 1200, and 1800 ticks) to cover this range, with the 30-minute case included as a sensitivity scenario to examine the effect of longer warning conditions. Agents follow goal-directed behavior, choosing the nearest shelter based on distance and road connectivity. Paths update dynamically in response to crowding, blocked routes or shelter availability. Movement speed declines over time due to stamina loss, especially for older or less mobile agents. Model validation was performed by comparing the simulated walking speeds of agents with the measured walking speeds obtained from field surveys. The goodness-of-fit between simulated and observed values was evaluated using the coefficient of determination (R^2). A high R^2 value indicates that the model closely replicates real-world walking speed patterns, thereby increasing confidence in its behavioral realism.

The model was run under four scenarios:

a) Scenario 1 – Horizontal Evacuation Only: All agents evacuate via roads to inland safe zones (h1, h2, h3) (Figure 5a).
b) Scenario 2 – Combined Horizontal and Vertical Evacuation: Five Tsunami Vertical Evacuation (TVE) buildings are added. Agents choose horizontal or vertical routes based on proximity and crowding (Figure 5b).
c) Scenario 3 – Vertical Evacuation (100% Capacity): All agents evacuate to TVEs, each with a 195-person capacity on floors 5–7 (Figure 5c).
d) Scenario 4 – Vertical Evacuation (70% Capacity): TVEs operate at reduced capacity (136 people), simulating damage or blockage (Figure 5d).

Each scenario was run multiple times to capture randomness. Key outputs include evacuation time, shelter occupancy, and the number of agents reaching safety.

3 RESULTS AND DISCUSSION

3.1 Results of the Questionnaire Analysis

A survey in Kaana Village involved 83 respondents (51% male, 49% female; 94% in the productive age group). A total of 89% preferred walking for evacuation, while 11% chose motorcycles. This pattern is consistent with Fathianpour et al. (2023) in Napier, New Zealand, where small coastal communities rely on walking due to limited vehicles and road capacity. Such conditions reduce congestion risk but slow evacuation for vulnerable groups.

Seventy-one percent of respondents selected the nearest evacuation site, while 29% chose what they perceived as safer locations. This aligns with Yamada and Yamasaki (2021) in Takanabe, Japan, where residents tended to choose the shortest route even if it did not lead inland. In Kaana, this behavior can increase risk if the nearest route passes through hazard zones.

Tsunami awareness was in the medium category (average Likert score 2.00–2.99), consistent with Yulianto et al. (2023) in Mentawai and Amri et al. (2024) in Bantul, who reported limited understanding of natural warning signs and early warning systems.

Although the survey shows limited understanding, the simulation assumes agents respond immediately to warnings. This is because the study focuses on evaluating routes and shelter capacity, so initial response delays were not modeled. This immediate-departure approach is common in evacuation simulations, emphasizing spatial and capacity aspects, such as Ito et al. (2021); Yamada and Yamasaki (2021); Fathianpour et al. (2023); Muhammad et al. (2024), which model agents moving as soon as the event begins without decision-making delays. Initial response delays are recommended for inclusion in future studies.

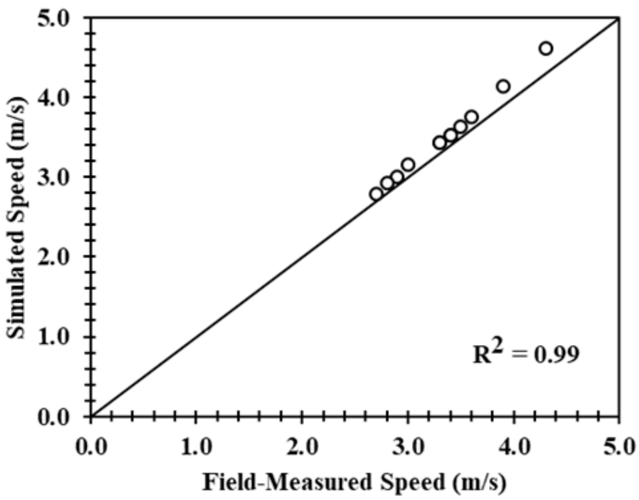


Figure 6. Validation of agent speed simulation with coefficient of determination (R^2 = 0.99).

3.2 Model Validation

The validation process ensured that agent walking speeds in the NetLogo simulation matched real-world conditions. Field measurements were conducted along a 120-meter road segment in Kampung Kaana. Twelve participants represented four demographic groups: productive males, productive females, non-productive males, and non-productive females. Walking speeds were calculated from travel times and converted to meters per tick to match the simulation scale.

Comparison with the simulation results produced an R^2 value of 0.99 (Figure 6), indicating that the field data explained 99% of the variance in simulated speeds and validated the model's mobility parameters.

Using local data to calibrate walking speed parameters is common in agent-based evacuation studies. Chen et al. (2023) developed a tsunami evacuation model for coastal communities in the Cascadia region, USA. Agent walking speeds were calibrated using locally measured data, which were then applied to simulate evacuation travel times and evaluate route effectiveness. Similarly, Santos et al. (2023) conducted a tsunami evacuation study at Figueirinha Beach, Portugal. They measured visitor walking speeds (1 m/s) on-site and incorporated these values into their ABM to assess whether evacuation could be completed before wave arrival.

These findings are consistent with Hardiansyah et al. (2018); Ito et al. (2021); Yamada and Yamasaki (2021); Muhammad et al. (2024), who emphasize the importance of local parameters in improving the realism of evacuation simulations. Thus, validating walking speed in Kampung Kaana aligns with recommended practices in agent-based evacuation studies.

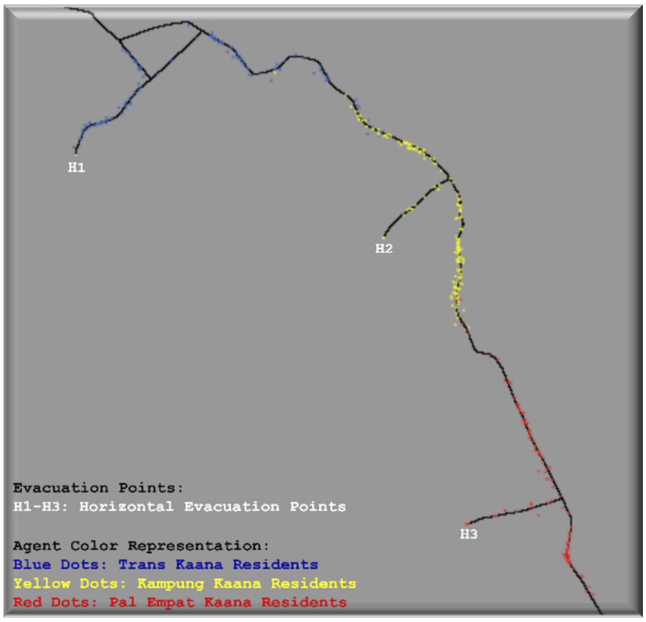


Figure 7. Bottleneck points in Scenario 1 (10-minute tsunami arrival) were used to determine TVE placement in Scenario 2.

3.3 Simulation Results and Scenario-Based Analysis

The simulation produced four scenarios categorized into two analytical groups. Scenarios 1 and 2 compare the effectiveness of horizontal-only evacuation with a combined horizontal and vertical evacuation strategy. Scenarios 3 and 4 evaluate the performance of Tsunami Vertical Evacuation (TVE) buildings under full-capacity and limited-capacity conditions.

The evaluation considered the number of agents reaching shelters, travel times, congestion, and the distribution of agent categories (motorcycle users, productive pedestrians, and non-productive pedestrians) across three tsunami arrival times (10, 20, and 30 minutes). The following discussion highlights key differences between scenarios, the main factors driving these outcomes, and their implications for evacuation planning.

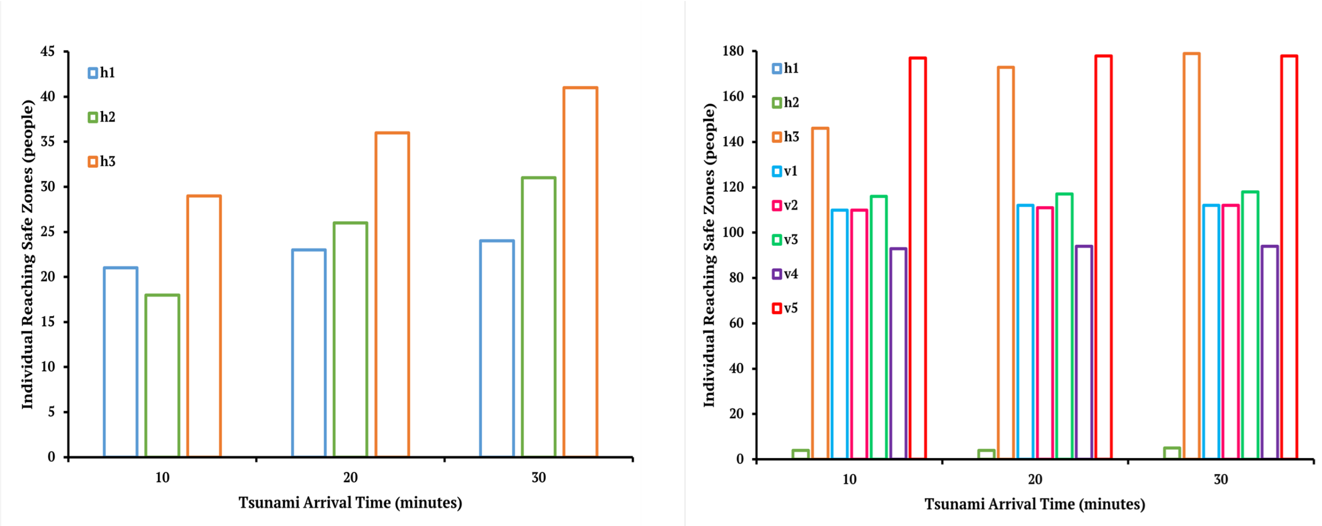
3.3.1 Evacuation Route Scenarios (Scenario 1 & Scenario 2)

Scenario 1 simulates a full horizontal evacuation to three inland shelters (h1, h2, h3) via a single main route. With a tsunami arrival time of 10 minutes, 68 people reached the shelters (21 to h1, 18 to h2, 29 to h3). At 20 minutes, the total increased to 85 people (23 to h1, 26 to h2, 36 to h3), and at 30 minutes, to 96 people (24 to h1, 31 to h2, 41 to h3). The additional time from 10 to 30 minutes resulted in only 28 people reaching safety, indicating that the horizontal route's capacity was the main limiting factor. This finding is consistent with the study by Wood et al. (2023) in the United States, which reported that single, low-capacity routes constrain survival rates even when warning times are extended.

The spatial distribution map for the 10-minute scenario revealed bottlenecks in narrow road segments near dense residential areas (Figure 7). This is similar to the findings of the study by Ito et al. (2021) in Japan, which identified zones with high evacuation impediments. In this study, these bottleneck locations were used as the basis for placing Tsunami Vertical Evacuation (TVE) buildings in Scenario 2 to shorten travel distances and reduce congestion.

Scenario 2 added five TVEs located at the bottleneck points, connected to main roads, and at least 200 m from the shoreline. This minimum distance follows the study by León et al. (2022) in Chile, which reported that 72% of houses within 200 m of the coast suffered severe damage during past tsunami events.

The results of Scenario 2 show significant improvement. With a tsunami arrival time of 10 minutes, 756 people reached safety: horizontal routes accounted for 150 (0 to h1, 4 to h2, 146 to h3) and vertical routes for 606 (v1 110, v2 110, v3 116, v4 93, v5 177). At 20 minutes, the total rose to 789 people (horizontal 177, vertical 612), and at 30 minutes to 799 people (horizontal 185, vertical 614). Over 75% of survivors chose the nearest TVE. v5 consistently had the largest load (177–178 people) because it is the farthest TVE from the shoreline and is located in the center of the main residential area, giving it a large coverage area within a short travel distance. This aligns with the study by Hoshino et al. (2025) in Okinawa, which found that the



(a) (b)

Figure 8. Number of evacuees reaching safety by shelter in Scenario 1 (a) and Scenario 2 (b) for three tsunami arrival times.

proximity of shelters to population centers increases survival chances, especially for low-mobility groups. The comparison of Scenario 1 and Scenario 2 across tsunami arrival times is presented in Figure 8.

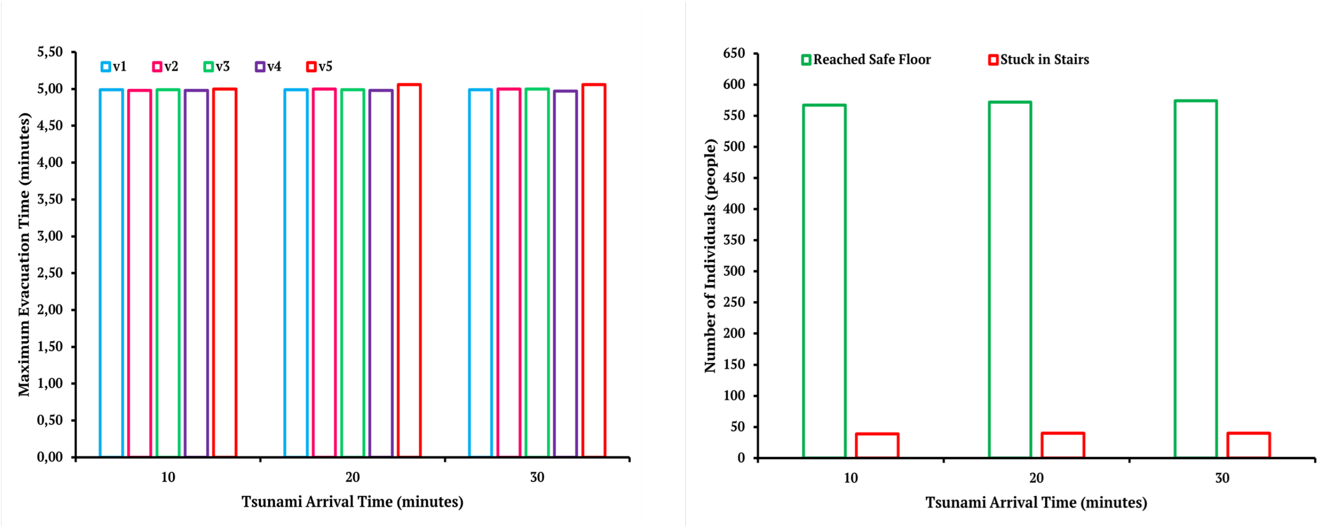
Compared to Scenario 1, Scenario 2 increased the number of survivors significantly. In Scenario 1 (Figure 8a), h3 consistently received the highest number of evacuees at all tsunami arrival times, suggesting a behavioral tendency to select destinations perceived as safer, even if farther inland. A similar phenomenon was reported by Yamada and Yamasaki (2021) in Japan, who found that evacuees often traveled farther than necessary due to perceptions of higher safety. Moreover, non-productive agents in Scenario 1 almost never reached a shelter (4–5 people across all time settings). This illustrates the ineffectiveness of horizontal-only routes with relatively long distances for low-mobility populations. Kim et al. (2022), in a study of Waikiki, Hawaii, also observed that such groups have very low survival probabilities when safe destinations are located too far to reach within the warning time.

In contrast, Scenario 2 (Figure 8b) increased the number of survivors by nearly eight times compared to Scenario 1 and reduced sensitivity to tsunami arrival times. The difference between 10 and 30 minutes in Scenario 2 was only 5.6%, compared to 41% in Scenario 1. This stability supports Choi et al. (2024) in Japan, who concluded that shelter accessibility and proximity matter more than the duration of the warning.

However, the results differ from Zhong et al. (2022) in China, who reported a more balanced load distribution among shelters when locations and capacities were spatially optimized. The difference can be explained by Enggano's settlement layout, which concentrates movement toward the area around v5, making it the most attractive site despite the availability of other TVEs. This highlights the need for flow management strategies to prevent overcrowding at a single central shelter. Mas et al. (2024), who explored machine-learning-based evacuation route optimization, demonstrated that adaptive guidance can redirect evacuees in real time toward less congested shelters, ensuring a more efficient distribution of loads. Such adaptive systems could be further investigated in future tsunami evacuation research for Enggano.

3.3.2 Vertical Shelter Scenarios (Scenario 3 & Scenario 4)

Scenarios 3 and 4 assess the performance of vertical evacuation in five Tsunami Vertical Evacuation (TVE) buildings under two capacity settings: full (100%) and reduced (70%). The three population groups—10-minute, 20-minute, and 30-minute—represent agents who reached each TVE in Scenario 2. Differences in outcomes are due to variations in the number and distribution of agents, not actual tsunami arrival times. Both scenarios apply fatigue effects and random arrival times. Fatigue reduces climbing speed progressively, with greater impact on agents with lower stamina (e.g., non-productive agents with stamina 7–10 and fatigue-factor 0.005–0.010). This approach follows vertical evacuation experiments (Halder et al., 2021; Zhu et al., 2021; Pan et al., 2023), which report 10–25% speed loss during prolonged ascent and queuing. Random arrival times spread the inflow over the simulation period, avoiding large early surges and maintaining smoother queues, consistent with Mas et al. (2024).



(a) (b)

Figure 9. (a) Maximum evacuation time per TVE in Scenario 3 (full capacity). (b) Agents reach safe floors and are held in stairwells in Scenario 4 (70% capacity). Labels "10–30 min" indicate population groups from Scenario 2.

Figure 9a shows the maximum time for the last agent to reach a safe floor in Scenario 3 (full capacity). Times were consistent across all groups, ranging from 4.95 to 5.05 minutes. TVE v5 recorded the highest times for the 20-minute and 30-minute groups (5.05 minutes) due to higher agent loads. No significant congestion occurred because stair capacity matched incoming flow and arrivals were evenly distributed. Fatigue was present but had minimal effect because agents moved continuously without long delays.

In contrast, Figure 9b for Scenario 4 (70% capacity) shows that most agents reached safe floors, but some were held in stairwells—exclusively in v5. In the 10-minute group, 567 agents (93.5%) reached safety while 39 (6.4%) were delayed; similar results occurred for the 20-minute group (572 and 40) and the 30-minute group (574 and 40). Delays occurred because arrivals at v5 exceeded its operational capacity, set to 70% of design capacity. TVEs v1–v4 stayed below their limits and had no congestion. This difference is visible in Figure 10, where v5 shows agents concentrated in stairwells due to overcapacity (Figure 10a), while v1–v4 display unobstructed movement to the safe floors (Figure 10b). Fatigue, negligible in Scenario 3, became more pronounced in Scenario 4 due to extended queues in v5, particularly affecting agents with lower stamina, consistent with Halder et al. (2021) and Zhu et al. (2021), who found greater speed loss among less-fit evacuees during long stair climbs. This is in line with Hardiansyah et al. (2022), who also identified staircases as the most critical bottleneck points in vertical evacuation simulations, highlighting their sensitivity to load concentration. Figure 11 illustrates Scenario 3 under full capacity, where all agents reached the safe floors efficiently. The consistent evacuation times in Scenario 3 indicate that although all agents experienced fatigue, adequate stair capacity meant the slowdown did not significantly affect total evacuation time. Random arrival patterns helped avoid early clustering at stair entrances.

This finding aligns with Jarzyna (2023), who emphasized the importance of matching stair capacity to evacuee volume, and with Zhou et al. (2020), who stressed that staircase design in accordance with standards can minimize fatigue-related slowdowns. It also supports Hoshino et al. (2025), who found that TVEs located in densely populated zones can effectively serve large populations if capacity is sufficient.

Capacity was reduced to 70% to simulate operational constraints caused by structural damage or access limitations. Congestion in v5 occurred because the number of arriving agents exceeded its operational capacity, which in this scenario was set to 70% of the building's design capacity. In contrast, v1–v4 received agent numbers below their respective 70% thresholds, enabling all agents to reach safe floors without obstruction. Under these conditions, the fatigue effect became more pronounced than in Scenario 3, as agents waiting in long queues moved more slowly when their turn came. This phenomenon is consistent with Murao et al. (2025), who documented overcapacity issues in central-city shelters in Banda Aceh, while other shelters remained underutilized.

These results reinforce Nakai et al. (2021), who argue that evacuee allocation should account for actual operational capacity rather than design capacity to avoid

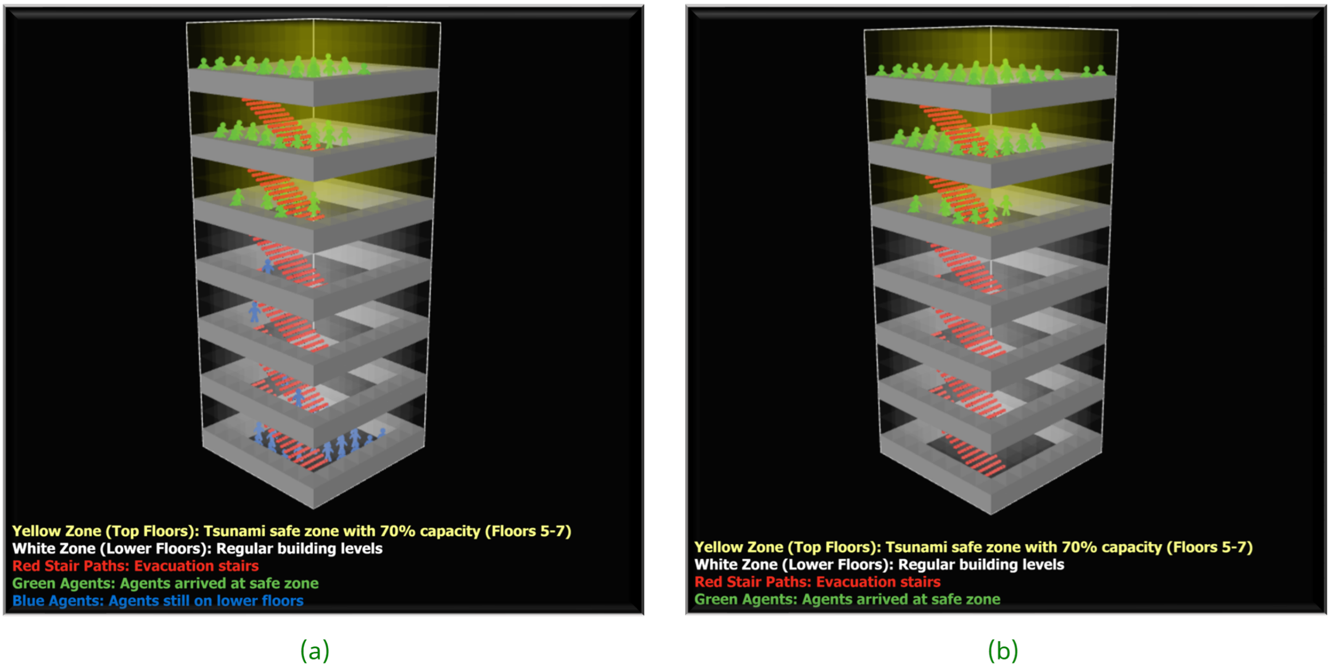


Figure 10. Scenario 4 (70% capacity) in NetLogo 3D: (a) TVE v5 with stairwell queues; (b) TVEs v1–v4 with all agents reaching safe floors.

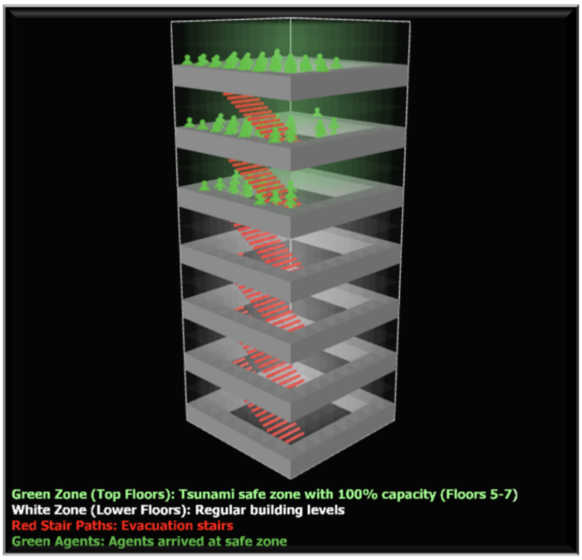


Figure 11. Scenario 3 (100% capacity) in NetLogo 3D, showing all agents reaching safe floors without crowding.

overloading specific locations. Potential solutions include the redistribution of shelter locations, as suggested by Hasegawa and Takabatake (2024), to reduce pressure on a single central shelter, and adaptive routing systems, as proposed by Mas et al. (2024), to redirect agents in real time toward shelters with available capacity.

These findings indicate that under full capacity, fatigue has little impact because stair capacity is sufficient and inflow is controlled. Under reduced capacity, however, fatigue exacerbates delays in overcapacity shelters. In Enggano's context, flow management strategies and the placement of additional shelters in densely populated zones are needed to reduce reliance on the central TVE. This approach is in line with Ibrahim et al. (2023), who recommend planning based on the lowest operational capacity to ensure system reliability during emergencies.

3.3.3 Comparative Evaluation Across Scenarios

This subsection compares the results of all four simulated scenarios to evaluate survival rates, total evacuation times, and the trade-offs between route type, shelter accessibility, and capacity.

Scenario 1 serves as the baseline, where all agents evacuated horizontally toward three inland shelters via a single main road. Limited route capacity and severe congestion produced low survival rates: only 8.2% (68 people) in the 10-minute group, 10.3% (85 people) in the 20-minute group, and 11.6% (96 people) in the 30-minute group. These outcomes confirm that purely horizontal evacuation is inefficient in dense, low-lying areas with restricted road access.

Scenario 2 introduced five Tsunami Vertical Evacuation (TVE) shelters, strategically placed based on bottleneck analysis from Scenario 1. This approach substantially improved survival rates to 91.9% (758 people) for 10 minutes, 95.4% (787 people) for 20 minutes, and 96.5% (796 people) for 30 minutes. The majority of evacuees

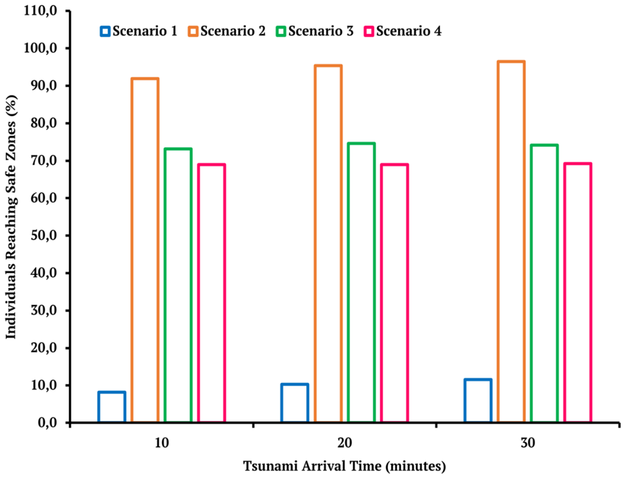


Figure 12. Percentage of agents reaching safety across scenarios and time groups.

Table 1. Total evacuation time (horizontal + vertical) for each group

Group	Horizontal (min)	Vertical (min)	Total Evacuation Time (min)
10-minutes	10.00	4.99	≈ 14.99
20-minutes	20.00	5.05	≈ 25.05
30-minutes	30.00	5.05	≈ 35.05

used vertical shelters, highlighting their critical role for slower or mobility-limited populations.

Scenario 3 isolated the vertical component by measuring ascent times for agents who reached TVEs in Scenario 2, under full capacity. Maximum evacuation times were stable: 4 minutes 59 seconds for the 10-minute group, and 5 minutes 03 seconds for the 20-minute and 30-minute groups.

Scenario 4 simulated a 70% capacity limit to reflect potential structural damage or partial inaccessibility. While overall survival rates remained high (93–94%), congestion occurred in v5—Enggano's most centrally located and heavily loaded shelter—resulting in 39–40 agents being held in stairwells. No such delays occurred in v1–v4, which remained below their operational limits.

The comparative results of all four scenarios are summarized in Figure 12, which shows the percentage of agents reaching safety across different tsunami arrival time groups. The figure highlights the substantial performance gap between Scenario 1 and the other three, as well as the marginal differences between full-capacity and reduced-capacity vertical evacuation.

When horizontal travel times from Scenario 2 are combined with vertical ascent times from Scenario 3, the total evacuation times are as shown in Table 1.

These results show that while vertical ascent times are consistent and relatively short, horizontal travel is the dominant factor in total evacuation time. Under ideal capacity (Scenario 3), fatigue effects are minimal; however, under reduced capacity (Scenario 4), congestion and prolonged queuing increase fatigue impact, especially in overburdened shelters. In practice, balanced shelter distribution and adaptive routing are necessary to maintain system performance during real tsunami events.

The variations observed across all scenarios are primarily influenced by the demographic and behavioral attributes incorporated into the model. Agents with higher walking speeds and lower stamina-reduction rates—representing younger and more physically capable residents—achieved shorter evacuation times and experienced less congestion. In contrast, older or less mobile agents with higher fatigue factors showed slower movement and were more likely to face delays on crowded routes and stairwells. Agents with lower response promptness delayed movement and clustered around nearby shelters, resulting in uneven shelter occupancy. These findings demonstrate that demographic and behavioral variability strongly governs evacuation efficiency, reinforcing the model's ability to represent realistic small-island evacuation dynamics.

3.4 Discussion and Implications for Disaster Planning

The simulation results show that integrating vertical evacuation (TVE) into tsunami response plans greatly improves safety, particularly in densely populated zones with limited horizontal routes. TVEs reduce congestion and shorten travel times compared to horizontal-only strategies.

Implementing TVEs requires careful planning. Key considerations include selecting optimal locations, ensuring capacity matches population distribution, and accounting for local topography. As Zhong et al. (2022) emphasize, shelter design should prioritize accessibility, coverage, and service efficiency under disaster conditions.

The 70% capacity scenario highlights the risk of overloading specific shelters, particularly central facilities such as v5, while others remain underutilized. Oh et al. (2021) note that insufficient operational capacity can create bottlenecks even if overall capacity is adequate. These findings suggest that planning should be based on the lowest expected operational capacity, not only on design specifications.

Behavioral factors also influence effectiveness. This study assumed immediate compliance with evacuation orders, but Cienfuegos et al. (2024) show that delays are common, especially in near-field events. Without addressing human behavior through education and drills, infrastructure alone cannot ensure success. Ibrahim et al. (2023) stress aligning physical infrastructure with community preparedness and early warning systems.

Across all scenarios, the combination of vertical and horizontal strategies outperformed horizontal-only evacuation. The v5 bottleneck under reduced capacity indicates a need for shelter redistribution, adaptive routing, and possibly additional TVEs in high-density areas. Such measures can balance load and maintain performance even when the infrastructure is partially degraded.

Future studies could integrate real-time routing systems, explore phased evacuation strategies, and test scenarios with varying compliance rates to better reflect realistic conditions. These approaches would refine both structural and non-structural measures, ensuring that evacuation planning remains adaptive and resilient in diverse disaster contexts.

4 CONCLUSION

This study set out to evaluate tsunami evacuation strategies in Enggano Island using an agent-based modeling approach, with a particular focus on the role of Tsunami Vertical Evacuation (TVE) shelters in complementing limited horizontal routes. The objectives outlined in the Introduction were achieved by quantifying how behavioral and spatial factors jointly influence evacuation performance in a small-island setting. The results across four scenarios demonstrate that integrating TVEs significantly enhances evacuation effectiveness compared to purely horizontal approaches, reducing bottlenecks, improving the spatial distribution of evacuees, and ensuring survival rates above 90% under most conditions. Vertical ascent itself was not a major limiting factor, typically requiring less than five minutes, whereas horizontal travel time remained the dominant contributor to total evacuation duration. Strategically locating TVEs near residential clusters was found to be crucial in streamlining evacuation flows and improving outcomes for low-mobility groups vulnerable to fatigue effects. Even under a reduced operational capacity (70%), the system remained functional for most of the current population, though delays and congestion emerged in heavily loaded shelters such as v5. These findings contribute to the literature by providing quantitative evidence on vertical evacuation in small island settings and emphasize the importance of planning based on operational rather than design capacity. Nonetheless, the model has limitations, particularly in not incorporating stair slope effects and in simplifying behavioral responses, which may affect the realism of fatigue representation. Additionally, distance in the model is represented through two-dimensional road network geometry without incorporating local elevation, surface characteristics, or off-road movement, which may influence evacuation time estimation in uneven terrain. Overall, the study fulfills its aim of linking behavioral sensitivity with vertical-evacuation modeling and contributes both methodologically and practically to tsunami-risk planning for remote-island communities. Future research should address these limitations by integrating detailed human factors, adaptive routing, and elevation data to strengthen the reliability of evacuation modeling under diverse tsunami scenarios.

DISCLAIMER

The authors declare no conflict of interest.

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