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Tsunami pedestrian evacuation simulation for Camaná, Peru: Perspectives for improving evacuation performance

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Abstract. Optimizing pedestrian evacuation in the face of a tsunami remains a critical challenge for safeguarding human lives. Agent-based models combined with reinforcement learning techniques offer a powerful framework to simulate complex evacuation scenarios, where agents learn to make decisions and identify safe routes in real time. This study focuses on improving evacuation efficiency along the coast of Camaná, Arequipa, Peru. We propose the use of numerical simulations to model pedestrian movement under the guidance of a reinforcement learning-based system. Under current transportation network conditions, only 16.6% of the population is able to reach a safe area in a tsunami scenario similar to the 2001 event. To address this, several modifications to the transportation network were proposed, including the addition of new evacuation paths and the construction of vertical evacuation structures. With the incorporation of 12 new paths and 6 vertical evacuation structures, the percentage of the population reaching safety increases to 73%. These findings provide a scientific basis for planning and implementing improvements to evacuation infrastructure in tsunami-prone areas.

1 Introduction

The readiness of various stakeholders in developing cities for natural disasters remains limited [1], including communities, businesses, governments, and scientific institutions. Over recent decades, earthquakes have caused considerable loss of life and highlighted deficiencies in emergency response efforts, especially in Asia and the Americas [2]. However, countries with strong preventive cultures and advanced tools like early warning systems have managed to lessen their damages and losses. This suggests that the impact of disasters on cities is inversely related to levels of preparedness, capacity, behavior, and the efficiency of early

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responses by communities and institutions. Therefore, exploring solutions related to human behavior in risk scenarios—such as understanding how people interact within city and street networks after a disaster—is crucial.

Currently, various innovative and technological techniques, including artificial intelligence, are being studied to develop solutions. Along with Agent-Based Modeling (ABM) simulations, these approaches enable better assessments of evacuation processes. One of these methods in computer science is Machine Learning, which includes Reinforcement Learning (RL)—where an agent learns to perform actions in an environment to maximize reward. To save lives and improve community resilience to tsunamis in coastal areas, we propose adopting the work of [3, 4]. The goal is to design an evacuation plan to create an intelligent Evacuation Guidance System (EGS) for the coast of Camaná beach resort, Arequipa, Peru.

This work aims to improve tsunami evacuation modelling and advance our understanding of human–city interactions. Prior studies [4] often encode an agent's state as bare (x,y) coordinates—omitting contextual cues such as nearby evacuees—or as a full image of the environment at each time step, a representation that is computationally heavy and scales poorly to city-scale domains. In contrast, we define the state as a compact set of environment-derived features that guide agent decisions and learn policies via reinforcement learning; specifically, we train an on-policy SARSA agent. Our reward function promotes actions that increase evacuation success while accounting for heterogeneous departure times and time-varying street congestion throughout the simulation. In controlled experiments, the learned SARSA policy outperforms a Dijkstra's shortest-path baseline—delivering faster egress and reduced network congestion—indicating improved collective pedestrian behavior [4].

The EGS will play a vital role in early disaster response by supporting early warning systems and guiding evacuations during emergencies. It will also assist in identifying the most effective evacuation routes in various scenarios, thereby increasing the likelihood of evacuating more individuals within the flood zone. This study proposes creating a model within an EGS to simulate agent-based evacuations for the Camaná beach resort in Arequipa. Chosen for its high tsunami inundation risk, the goal is to boost the Expected Survival Rate (ESR). The implementation will require calibrating the EGS using local factors such as 1) the street network layout, 2) population density, and 3) designated evacuation zones.

2 Study area and Methods

2.1 Camaná, Peru

The Camaná beach resort area, located in the province of Camaná, includes beaches in the districts of Camaná, Samuel Pastor, and Quilca. These regions are connected by a street network that shares similar vulnerabilities, as shown in Fig. 1. Human settlements with the same names as the beaches are situated nearby (Figs. 1b and 1c). Figure 1b illustrates the street network within the beach area, while Figure 1c highlights the limited pedestrian access to designated refuge sites. Three factors cause this restricted access: 1) topographical variations, 2) insufficient signage, and 3) high-risk zones that cannot be effectively mitigated.

The population census within the ten communities in the beach circuit of the Camaná resort study area, focusing on those in flood-prone zones, recorded a total of 655 individuals. This data was carefully gathered in the censuses of 2007 and 2017 for the study area. However, for research purposes, this number does not represent the entire population of the Camaná resort area, as it omits certain groups not usually included in standard counts. These groups include the periodic population and the transient population, which only reside there during the summer. As a result, the population is roughly estimated at four thousand using fewer comprehensive estimates, and around twenty thousand based on more detailed estimates [5, 6, 7].

Camaná, a resort town, is highly vulnerable to tsunamis. Its current evacuation plans are static, showing transportation routes with arrows on maps, but they do not consider how pedestrians interact with the existing transport network. The Peruvian government has not yet explored solutions like alternative routes, vertical evacuation, or additional horizontal evacuation options from flood-prone areas. The map, created in 2003 by the National Institute of Civil Defense (INDECI) [8], highlights the primary evacuation route as the road connecting the beach to the Pan-American Highway South. It also marks zones for gathering, shelter, and temporary stay, but lacks designated access routes between these zones—crucial for the effectiveness of vertical evacuation and supplementary exits.

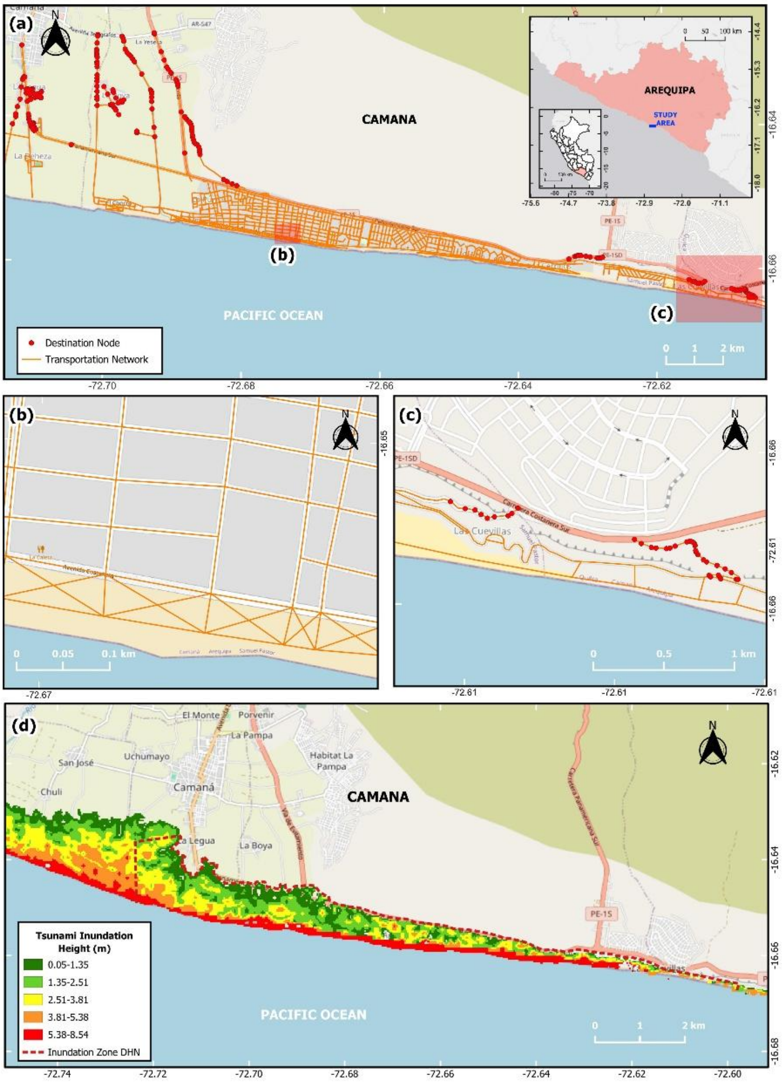

Fig. 1. (a) Location of the study area. The yellow lines constitute the graph representing the transportation network, the red marks are the location of destination nodes, and the inset shows the location of the study area in Arequipa, Peru. (b) and (c) Closer look at two zones of the study areas. (d) Tsunami inundation height based on numerical simulation. The dashed red polygon denotes the inundated area provided by the Office of DHN [9].

2.2 Tsunami Simulation at Camaná

The numerical simulation aligns with Bruno Adriano's proposed model. The employed equations, action mechanisms, and detailed procedures are documented in [10]. Fig. 1d illustrates the tsunami-induced flooding in Camaná. Results show the flood affects all blocks in the resort town, extending roughly 1.96 km perpendicular and 70 km parallel to the coast, with maximum heights reaching 8.54 meters. Most streets in Camaná experience floodwaters up to about 6 meters high. Such inundation can completely submerge 84.9% of single-story and 14.2% of two-story homes, totalling 99% of residences fully flooded. Meanwhile, 1% of homes (7 out of 790), which have three or more floors, may remain partially dry, providing safety for their occupants.

2.3 Intelligent Evacuation Guidance System

We utilize the approach suggested by [10] for tsunami evacuation simulation, combining reinforcement learning with an agent-based framework to enhance evacuation efficiency. The simulation depicts the movement of pedestrians, starting from within the inundation zone to safe areas. To this end, the research follows the EGS process, as shown in Fig. 2. The street network shown in the figure is obtained from an open source from OpenStreetMap, the tsunami simulation from [10], and the population from an official source. For calibration, as mentioned above, we use RL as the basis for MBAs. Furthermore, for the performance evaluation process, we use training-level data, where we have the number of evacuees at each point in time. The results presented correspond to the computational model in its 7,000th learning simulation. The selected simulation number corresponds to 100% learning by exploration, which provides us with the optimal pedestrian evacuation route. In addition, the results in terms of the total number of agents evacuated remain constant. Each simulation was carried out for 40 minutes, and a 5-minute Rayleigh mean was considered. Further details on the calibration process can be found in [4]. We assess the evacuation in two scenarios based on population size: one with about 4,500 agents, representing a time when only residents are present, and another with 20,300 agents, reflecting the summer period when beach occupancy is significantly higher. With a quantity of 4 and 18 agents per node within the street network for each experiment, respectively.

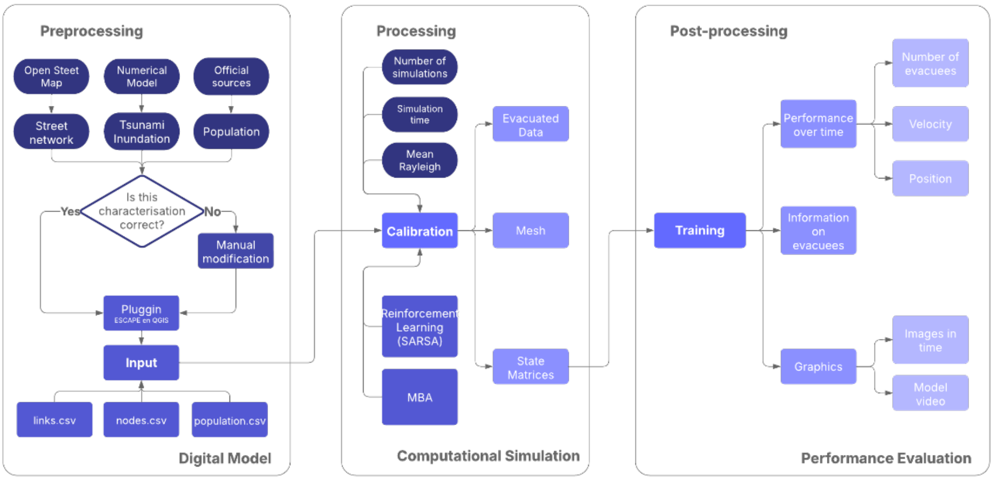

Fig. 2. Tsunami evacuation model. Preprocessing: Represents the process of digitizing the study zone. Processing: The application of the Computational Simulation with the RL Technique based on MBA. Post-processing: Includes analysis of system Performance Evaluation.

3 Results

This chapter assesses the performance of the computational model created for the street network and agents of Camaná resort. Four experiments with sixteen scenarios are presented to guide the development of three pedestrian evacuation plans for a tsunami.

3.1 Actual state of the transportation network

Figures 3 and 4 depict the number of pedestrian agents reaching destination nodes over time. In the 4,500-agent scenario, only 747 agents (17%) evacuated successfully within 14 minutes, matching the estimated tsunami arrival time from numerical simulations. By 23 minutes—the observed arrival during the 2001 tsunami—1,967 agents (44%) had reached safety. With 20,300 agents, 2,368 (12%) managed evacuation within 14 minutes, and 4,551 (22%) did so within 23 minutes. The lower survival rates in larger populations are mainly due to slower evacuation caused by higher pedestrian density. Increased congestion significantly hampers movement. An important factor is the placement of destination nodes at the resort's edges, forcing pedestrians to cover large distances to reach safety. These results indicate that the current transportation network requires major improvements to boost evacuation efficiency.

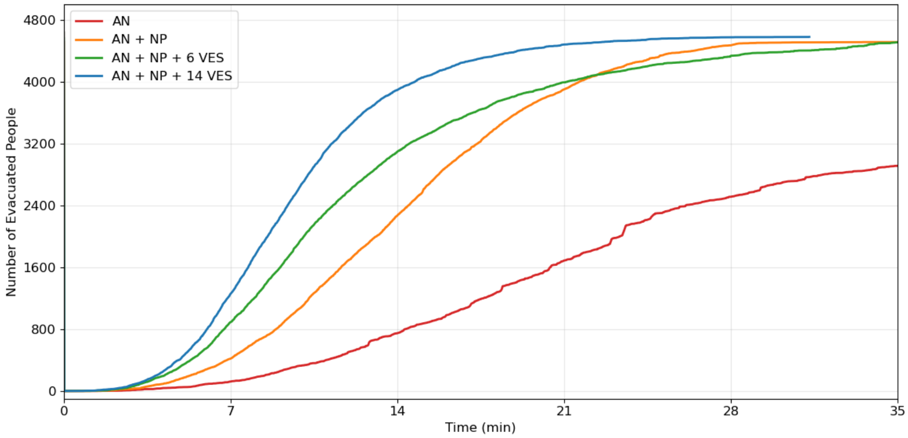

Fig. 3. Number of evacuated people vs time of a scenario with 4,500 pedestrian-agents. The red line denotes the result from the actual transportation network, the orange line represents the results of adopting additional pathways to the transportation network, and the green and blue lines are the results of using, in addition to the additional pathways, 6 and 14 vertical evacuation structures, respectively. AN: Actual network, NP: New pathways, VES: Vertical evacuation structures.

3.2 Transportation network with additional destination points

As previously discussed, several measures can be adopted to improve the tsunami evacuation process. This study emphasizes adding more destination nodes to boost accessibility and evacuation efficiency. Specifically, we suggest connecting the evacuation zone recommended by INDECI with additional pathways. Visual inspection identified 12 potential locations for constructing paths to this zone (Figs. 5 and 6). These modifications significantly enhanced evacuation results. For 4,500 pedestrian agents, 2,270 (50%) reached safety in 14 minutes, and 4,156 (92%) evacuated within 23 minutes. With 20,300 pedestrians, 6,902 (34%) reached destination nodes in the first 14 minutes, and 13,558 (67%) evacuated within 23 minutes. These improvements considerably increased evacuation rates compared to the current transportation network. The most notable improvement was in the 4,500-agent scenario, where safety within 23 minutes rose from 44% to 92%. The 20,300-agent scenario showed the least progress, with evacuees within 14 minutes increasing from 13% to 34%. While these enhancements are significant, further measures are necessary to ensure satisfactory evacuation outcomes, especially at higher population densities.

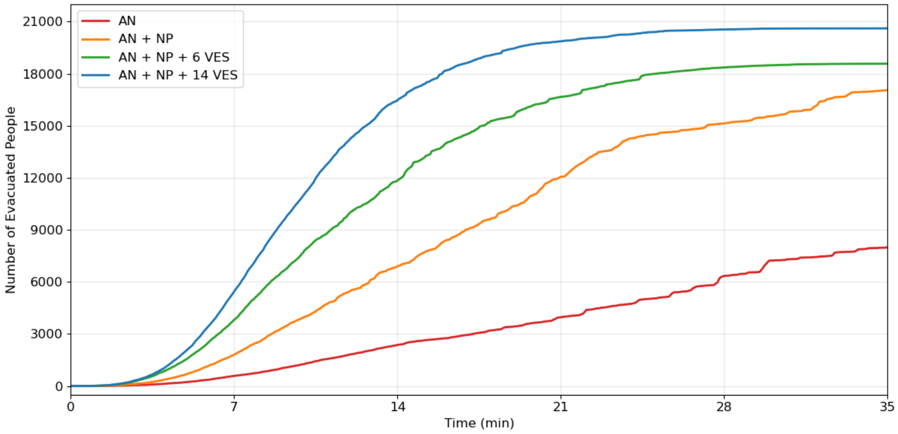

Fig. 4. Number of evacuated people vs time of a scenario with 20,300 pedestrian-agents. The red line denotes the result from the actual transportation network, the orange line represents the results of adopting additional pathways to the transportation network, and the green and blue lines are the results using, in addition to the additional pathways, 6 and 14 vertical evacuation structures, respectively. AN: Actual network, NP: New pathways, VES: Vertical evacuation structures.

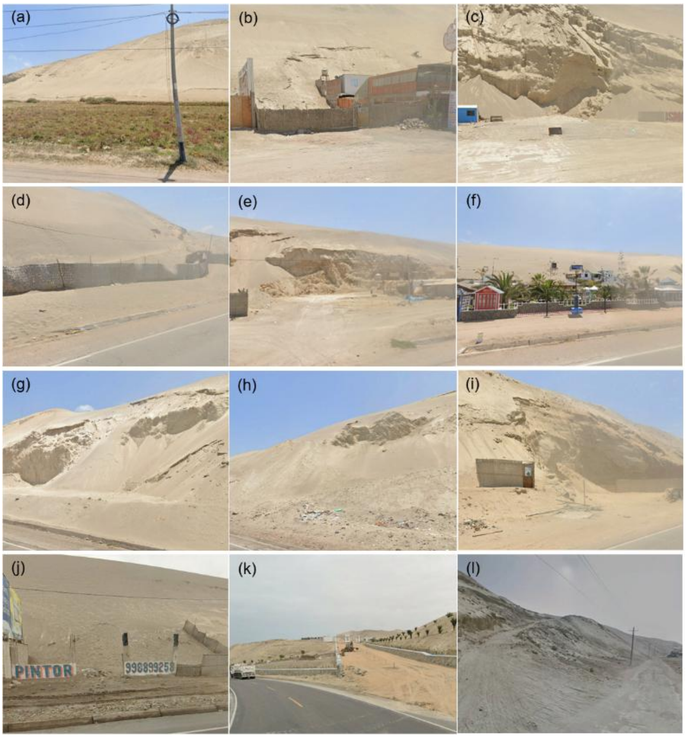

Fig. 5. Photos of the potential location to connect additional pathways with the current transportation network. Their location is shown in Fig 6.

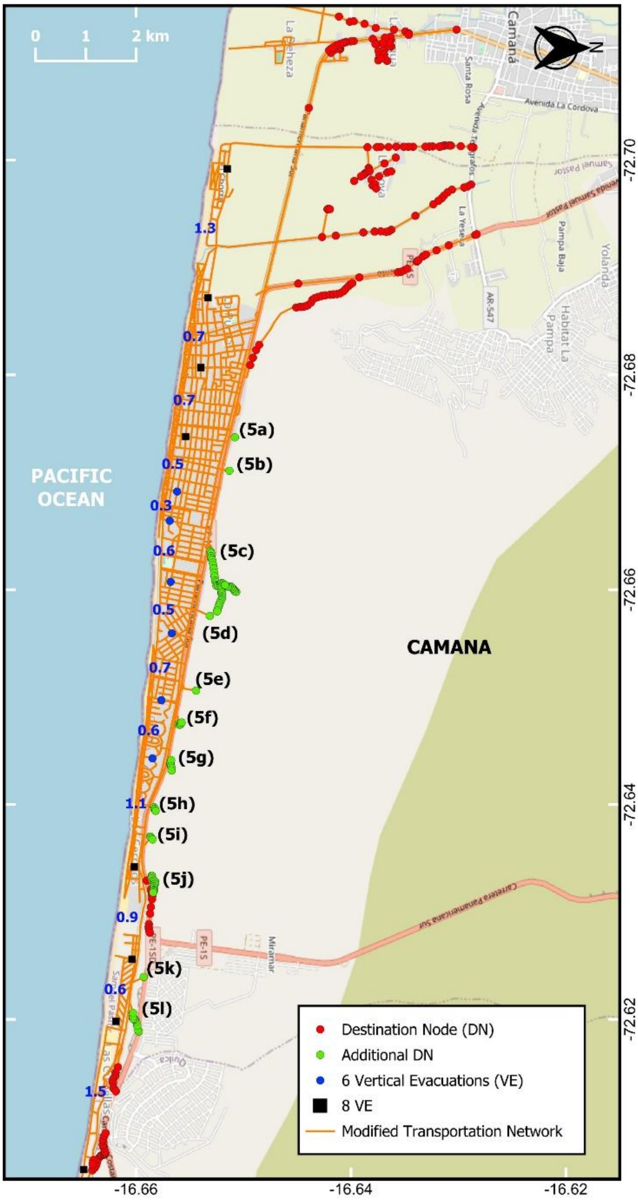

Fig. 6. Modification of the transportation network (See original network in Fig. 1a). The green circle marks denote new destination nodes representing new pathways that evacuate the inundation zone (See Fig. 5 for photos of their potential locations). The blue circle and black square marks are new destination nodes representing vertical evacuation structures. The blue number is the spacing distance between vertical evacuation structures.

Alongside expanding pathways within the evacuation zone, we evaluated how placing destination nodes—identified as vertical evacuation structures—along the coast affects evacuation. These points were examined in various setups, with the number of destination nodes varying and evenly spaced along the shoreline. Our goal was to determine the minimum number of vertical evacuation structures needed to boost evacuation efficiency significantly. As shown in Fig. 7, results reveal notable trends in the percentage of pedestrians evacuated with different counts of vertical evacuation nodes. Initially, the survivor rate increases linearly with up to four nodes. However, adding more nodes—such as six—produces a more substantial improvement, surpassing what the linear trend would suggest. A similar pattern appears with 14 vertical evacuation nodes.

Among 4,500 exposed pedestrians, 68% evacuate successfully within 14 minutes when six vertical evacuation nodes are installed. This figure rises to 84% with 14 nodes. However, during a 23-minute evacuation period, adding vertical evacuation structures does not produce significant improvements, indicating that most evacuees would likely have already reached safety within this time.

As the total exposed population increases to 20,300 pedestrians, six vertical evacuation nodes enable 58% of individuals to reach safety within 14 minutes and 85% within 23 minutes. Increasing the number of nodes to 14 raises these percentages to 79% and 97%, respectively, within the same durations. These results highlight the significant potential of vertical evacuation nodes to enhance safety, particularly in densely populated areas.

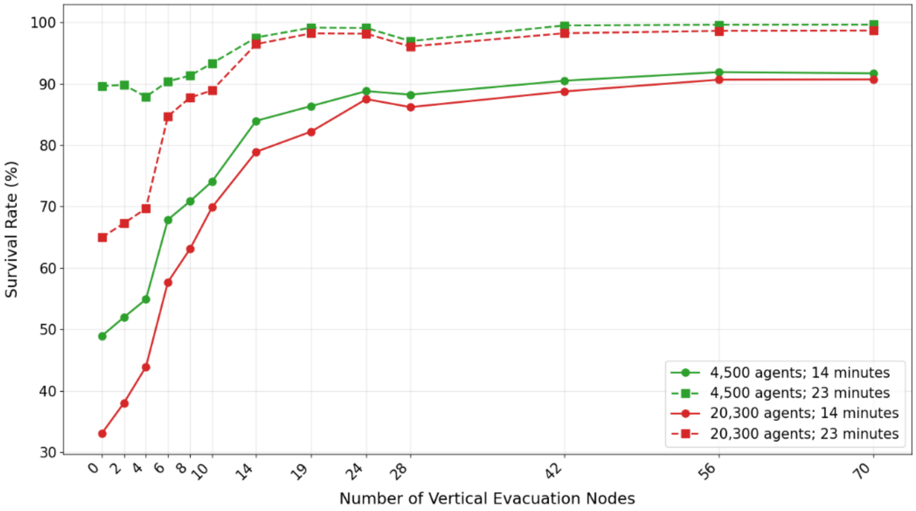

Fig. 7. Percentage of evacuated pedestrians under different numbers of vertical evacuation structures.

4 Discussion

The present study aims to evaluate the design of various pedestrian evacuation plans in response to tsunami inundation hazards by implementing a Reinforcement Learning algorithm within an agent-based model framework. The computational model, established as an intelligent guidance system for pedestrian evacuation processes, comprises between 1,124 and 1,159 street intersection nodes, with either 4 or 18 agents per node, to simulate the estimated population. Subsequently, four experiments or scenarios are proposed to reflect the designs outlined in this research, assessing the impact of adding destination nodes and increasing the number of vertical evacuation structures. These include a current street network and an improved network with specific modifications. In defining the locations of the evacuation nodes, several key considerations were identified and analysed, such as access timeliness, topography, availability, congestion in the current scenario, and the primary junctions between roads. A total of sixteen scenarios has been conducted, with the primary objective of enhancing the performance of the expected survival rate.

5 Conclusions

The results obtained from the current or baseline condition indicate a significant risk in the study area, characterized by latent danger and high vulnerability. Only 22% of the population is able to evacuate, at best, 23 minutes after the arrival of the wave in the scenario with the highest population density. This demonstrates that the existing network necessitates substantial modifications to enhance its survival rate in the face of tsunamis. Conversely, the first and second evacuation plans, in both low and high population density scenarios, demonstrate an improvement in performance. There has been an increase of up to 2,189 (46.1%) and 9,007 (42.6%) additional evacuated agents over the actual network within 14 and 23 minutes, respectively. Moreover, the most notable performance enhancements are observed with the increase in the number of vertical structures within the street network, accompanied by additional exits, as exemplified in the third proposed plan. The number of evacuated individuals increases by 826 (18.9%) and 1,623 (35.1%) within the low population density scenario, relative to the transportation network with supplementary destinations. In the high population density scenario, there is an additional evacuation of 4,946 (24.7%) and 9,565 (45.9%) individuals. These two optimal results correspond to the first 14 minutes following the tsunami wave's arrival, with 6 and 14 vertical evacuations, respectively.

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