



Tsunami evacuation modelling via micro-simulation model

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ABSTRACT

The associated tsunami risks posed to coastal regions in earthquake-prone areas highlight the importance of an effective emergency evacuation plan for these regions. Evacuation simulations have shown to be a valuable tool in assessing the effectiveness of existing evacuation plans and providing solutions for risk reduction, and improving community readiness. This paper describes the development of a micro-simulation evacuation model (MSEM) to assess the effectiveness of local tsunami evacuation processes and test the results with a velocity-based theoretical model. As an agent-based model, the MSEM considers both pedestrian and vehicle interactions and their interactions with each other. The models were used to assess the evacuation scenarios for a tsunami-prone city Napier, in New Zealand. The evacuation process was evaluated based on a local 8.4 Mw earthquake that would trigger a tsunami event, with an evacuation time of 50 min between feeling the initial shake in Napier City and the time of arrival of the tsunami wave. The study outlined within this paper assumes two scenarios: (1) effected population would evacuate by foot, and (2) affected population would evacuate by car, considered to take place during the afternoon at the traffic peak time. The results of the MSEM show factors such as evacuation method, lane and sidewalk capacities, and interactions between individuals affect the individuals' ability to safely evacuate. The MSEM model based on scenario 1 and 2 for Napier City, demonstrated around 85% of residents would reach designated safe area when all evacuating by foot, whilst, only 45% of evacuees will reach their designated safe zone if all individuals attempted to use vehicles as their means of evacuation.

1. Introduction

A tsunami is a series of large waves predominantly triggered by seismic activity, which can be highly destructive. In the event of such a high-risk occurrence, the population in proximity to an exposed coastline must retreat to higher ground or further inland within a short period of time to ensure their safety. Historically, tsunami events have led to many fatalities and caused significant devastation to coastal communities. For instance, the 1755 Lisbon earthquake and tsunami was reported to have caused 60,000 deaths (V. [17]). The Sumatra–Andaman earthquake and subsequent tsunami in the Indian Ocean in December 2004 resulted in 227,899 reported dead or missing [18]. The Tohoku earthquake in Japan in 2011 resulted in 18,487 recorded deaths, 6157 injured, and 2594 people reported missing [31] with it being reported that tsunami and earthquake damaged most of the northeast part of Japan [37].

The loss of life due to tsunami events can be minimised by

comprehensively understanding what would happen and predicting the evacuees' behaviour choices [26,29]. In recent years a variety of models have been developed to simulate the evacuation process of people during emergencies, such as those outlined in Mario, Dell'Orco, and Ottomanelli [30], Chu, Yu, Wen, Yi, and Chen [7], and Makinoshima, Imamura, and Abe [28], to name a few examples. These evacuation models allow for the assessment of the current transportation network's efficiency, provide insight into resource allocation for long-term transportation infrastructures upgrade plans to invest in a manner that makes the city more resilience toward tsunamis, and prepare for a disastrous situation [6]. Additionally, the use of evacuation models can also facilitate decision-makers in defining more effective evacuation plans to be implemented during emergency scenarios [29].

Evacuation process models can be used to describe the dynamic movement of pedestrians and vehicles. According to each model's methodology, they can be divided into three primary clusters named micro, *meso* and macroscopic models or combinations thereof. The

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microscale model simulates the movements and interactions of individual agents, whereas the latter two models consider the movements based on aggregate quantities [36]. The following subsection explores the tsunami evacuation process and modelling techniques to understand the requirements and enable realistic modelling of such evacuation events.

1.1. Tsunami evacuation process

The main factors influencing the effectiveness of the evacuation plan are the evacuation time (time spent to reach the nearest safe zone), the evacuee's start location, and the safe zone location [23]. With Yun and Hamada [43] showed that the risk exposure of designated safe zones, the preparedness of populations in risk-prone areas before a disaster, and the evacuation time are the most critical factors in determining the survival rate. For a localised tsunami event, where the tsunami wave arrives shortly after a local earthquake, the elapsed time between detecting/feeling the earthquake and the arrival of the first tsunami wave can be relatively short, not sufficient for everyone to evacuate, emphasising the importance of minimising evacuation times. In the Tohoku 2011 tsunami, cumulatively 67% of people who survived evacuated their respective buildings within the first 20 min after first feeling the earthquake, with data showing the survival rate decreasing for individuals evacuating from 10 min onwards [43]. The findings highlight that the evacuation process must start immediately after detecting an earthquake to improve the chances of survival from a tsunami event. For the city of Napier in New Zealand, studies have shown that the time required for individuals to evacuate their buildings and reach designated safe locations before the arrival of a tsunami wave following an 8.4 Mw earthquake is limited to 50 min [12,23].

In addition to initial delays in evacuating a building safely, external factors such as the surrounding geospatial environment can cause further delays in the evacuation process. Identifying spatial gaps, such as road capacities and potential bottleneck locations due to converging evacuation routes, could help guide decision-makers to invest money in projects that align more closely with risk reduction plans [7]. The evacuation process can be expedited by making people more aware and prepared for such events. Takabatake and Nistor [39] noticed that the total evacuation time could have an influence on the survival rate when they conducted a sensitivity analysis on the evacuation process in Vancouver Island, Canada. Another factor in the evacuation process would be the moving speed; Sun and Sun concluded that elderly people would have a lower walking speed than adults. Zhang and Wu [45] evaluated shelter accessibility in Nagoya City, Japan, analysing the routes heading to the seventeen safe zone locations across the city. The results showed that evacuation strategies should vary based on the differences in vulnerability and risk in different areas. Well-detailed simulation models that consider worst-case scenarios can provide decision-makers and individuals with locations for potential shelter positions to reduce delays in the evacuation process [41].

1.2. Evacuation modelling

As previously highlighted, most evacuation models fit into three main categories, microscopic, mesoscopic, and macroscopic. The characteristics of these different modelling types (Fig. 1) used in evacuation modelling are outlined in Chraïbi et al. [6]. Macroscopic and mesoscopic models are mostly used to simulate crowd movement density. Shi et al. [36] developed a novel mesoscopic evacuation model to simulate crowd movement within a room. The model considers crowd movement for each time step. Although the mesoscale models can provide simulation results based on the grided area, they are not appropriate for expanding the analysis based on individual movements. Therefore mesoscopic models are less seen in a large-scale mass evacuation since increasing the size and density would decrease the accuracy of the model [1].

Although evacuation modelling can be carried out at macro and meso-scales, microscopic modelling allows for the simulation of interactions between individual agents (e.g people or vehicles) with their surroundings and each other. This approach allows the modeller to simulate agents with different characteristics, such as maximum walking speed and route choice behaviour, in addition to other parameters. Previous work by Maury and Venel (20) modelled pedestrian movements based on their velocity, with their model considering spontaneous velocity for each individual and how this would change according to other individuals' interactions.

The next dimension of evacuation models is predominantly named based on the system variables, space, time and speed. A model can be discrete, continuous or a combination of the two. However, some models, such as Pathfinder [16], Exodus [11] and etc., do not fit discretely into the above mentioned categories and are cross-cutting instead. These models utilise a hybrid approach and simultaneously consider microscopic and macroscopic elements, discrete and continuous elements, and incorporate rule-velocity- and acceleration-based approaches.

There is a wide range/variety of models available for use in evacuation simulations, each considering different analysis approaches and can be defined at different spatial scales, such as simulating the effective evacuation of a building [25,30] to the evacuation of large urban areas (C.-C. [3]). However, the focus of this study is on large-scale urban evacuations.

In urban-scale evacuation simulations, models have different assumptions and methodologies but are similar in terms of input data. All models require a geospatial network, routing, and behavioural conditions that enable the simulation logic to function. First, the rules and parameters for a model under normal running conditions are defined, and then, following a trigger/disaster event, the rules and behaviours of agents and the properties of the simulation space can be updated to simulate the effects of a disaster scenario. For example, following a trigger event, the destinations of agents could be altered to reroute them to designated safe zone areas, and the underlying network that these agents traverse could be changed due to road closures.

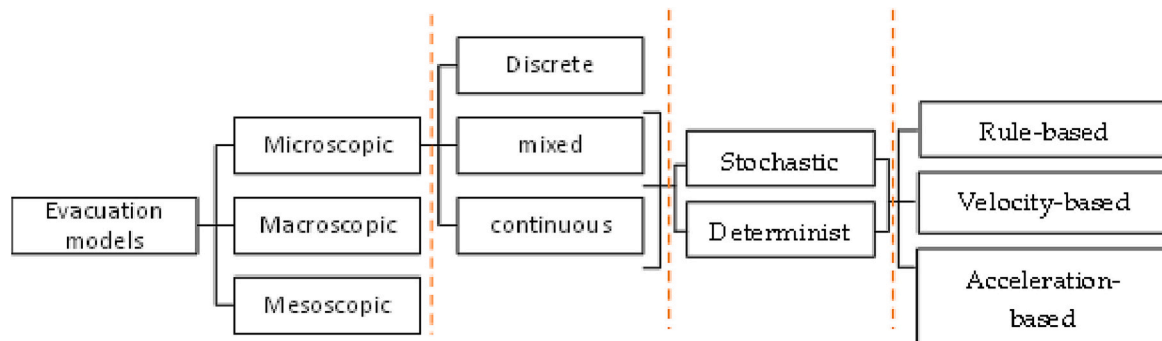


Fig. 1. Evacuation model classification (10).

Researchers have developed various micro-evacuation models, including Cellular automaton [22,42], Agent-based (X. [4,27,32]), and Social Force ([28]; Z. [45]), to simulate the evacuation process. However, most of these models do not consider the interaction between pedestrians and vehicles during evacuation. For instance, there are many pedestrian evacuation models [2,10,13,14], which also considers pedestrian interactions with cars during evacuation in small areas or at the egress location [26]. However, on an urban scale, the only research the author found due date is regarding fire evacuation, in which the main intention of the evacuation is to exit the burnt or propagating burning area [11]. On the other hand, always travelling far inland in tsunami evacuation is not the case and reaching a safe zone, mostly high ground is desirable. Thus, the evacuation route and safe zone location highly alter the evacuation result [21]. Therefore, the evacuation preferences under local tsunami circumstances considering the interactions of pedestrians and cars in one step, are not thoroughly investigated.

Takabatake, et al.'s model [40], for example, considers car evacuation for individuals who have a physical restriction or below-average evacuation speed on foot. In this model, the walking speed is assumed to depend on the evacuees' age and the crowd density, which is calculated based on the number of evacuees within 5 m in front of them and the width of the road. In this model, each car is considered equivalent to ten on-foot evacuees in terms of crowd density, meaning that vehicles can increase the crowd density and reduce the moving speed. The results of this model showed that this assumption could significantly reduce unnecessary pedestrian collisions.

Chu and Yu (8) developed an agent-based evacuation model that considers human behaviour in the Changhongfang Community in China, where cars are treated as parked obstacles in one of the potential scenarios. Z. Zhang and Fu [45] have also developed a simulation model based on Social Force to consider the interaction between pedestrians and vehicles in a parking lot. However, none of these models fully capture the interaction between vehicles and pedestrians during a disaster evacuation scenario in a large urban area.

The main goal of this study is to simulate the evacuation process

during a tsunami triggered by a seismic event, considering both on-foot and car evacuation as well as their interactions. The methodology used to simulate the evacuation scenario is described in the following sections, along with the methods used to create the evacuation model for Napier City. This includes the input data, such as the transportation network, routes, population distribution, and evacuation destinations. Using SUMO (Simulation Mobility Software) [46], the microscale simulation of the evacuation process considers both on-foot and car evacuation. It is also assumed that there will be traffic on the roads during the earthquake event, so baseline traffic flow is defined using traffic count data for the city.

The following sections in this paper outline an approach for building an evacuation model within SUMO. That allows for the simulation of vehicles and pedestrians to analyse the effectiveness of evacuation methods that could facilitate discussion and planning with respect to evacuation planning.

1.3. Study area

Napier City, located in the eastern part of the North Island of New Zealand at 39°28'59" S latitude and 176°55'00" E longitude, has been chosen as the case study for this research. Napier City is a coastal city bounded by the north's main outfall channel and the Tutaekuri River in the south (Fig. 2). The city has an elevation of 57 m above sea level and an annual average precipitation of 879 mm. It is vulnerable to various natural hazards such as liquefaction, earthquakes, flooding, volcanoes, and tsunamis.

2. Methodology

The aim of this study is to develop a model that can analyse the efficiency of a tsunami evacuation plan scenario. As mentioned in the introduction, microscopic models are well-suited for simulating detailed evacuation scenarios, as they consider the movements and interactions of individuals separately. Aguilar and Wijerathne (40) have also noted

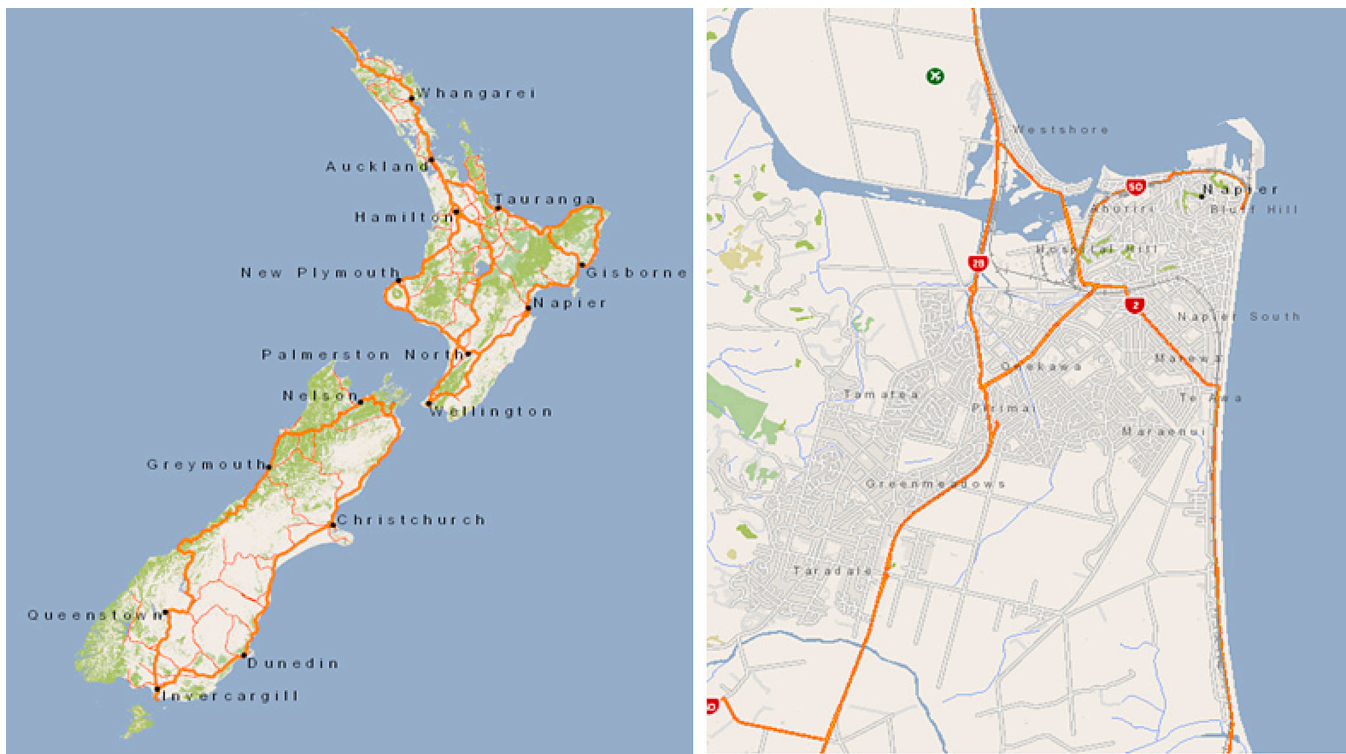


Fig. 2. Napier City, New Zealand, adapted from google.

that a continuous 2D space allows for the simulation of individual interactions. Therefore, this study has chosen to use a microscopic model within a space-continuous environment. The critical factor in evaluating the effectiveness of an evacuation plan is the evacuation time. An individual is considered to have survived if they reach a safe zone before the arrival of the first tsunami wave. The success rate of the evacuation scenario is based on the percentage of individuals from the total modelled population that reach safety within the allotted timeframe. A higher success rate indicates a more resilient evacuation plan.

In this study, different evacuation methods were evaluated to calculate the survival rate based on the time individuals take to reach a safe zone while following the shortest path. The effectiveness of these evacuation methods was assessed using the Microscopic Evacuation Simulation Model (MSEM) and compared to a simplified theoretical velocity-based model for reference. The details of each model will be explained in the following subsections.

2.1. MSEM model design

This model follows the methodology used by Evans et al. [8] and Pyatkova, Chen [35], in simulating the evacuation process using the traffic modelling software SUMO. SUMO was chosen as the platform for simulating the evacuation model in the event of a tsunami because it is capable of considering movement in a microscopic, space-continuous, time-discrete, deterministic velocity-based environment [24]. SUMO is typically used to model urban traffic flow, but it has also been used to simulate evacuation processes in recent years [5]. For example, Evans et al. [8] used SUMO to simulate the impact of flooding on traffic flow in Bristol, while Filippidis et al. [11] developed a model to simulate the fire evacuation process. In this model, vehicles and traffic are modelled using SUMO, while urbanEXODUS controls pedestrian interaction with vehicles.

SUMO is a versatile platform with a range of functionalities and associated tools that can handle tasks such as route finding, visualisation, emission calculations, and import transportation networks from a variety of sources, including OpenStreetMap, VISUM, and MATsim to name a few examples. As an open-source platform, SUMO can be enhanced with custom models and offers various Application Programming Interfaces (APIs) that allow for remote control of simulations. In addition, SUMO can simultaneously model multiple modes of transport and their interactions with each other. The Microscopic Evacuation Simulation Model (MSEM) has been developed to facilitate the simulation of evacuation scenarios by leveraging the capabilities of SUMO to consider both pedestrian and vehicular evacuation as well as their interactions in a single tool.

This model considers individual interactions by using SUMO built-in feature, which reduces the moving speed of individuals in a collision. Also, when facing a lane width reduction, the model considers a reduced number of individuals continuing the route simultaneously. For instance, if the sidewalk width is 5 m, it is assumed that two people would commute side by side. But when the sidewalk width reduces to 3 m, the model considers one of the two individuals can proceed, and the other should wait to go afterwards. In this situation, the walking speed would significantly be reduced, and the potential traffic jam and collision would have a domino effect on the whole walking speed on edge.

To run an evacuation scenario within the SUMO platform, different data sets are required to model pedestrian and vehicle movements. These include a network file (which includes sidewalks and roads with all intersections and routes), a population distribution file (which specifies the starting points for each individual), and a safe zone file (which specifies the final destination that individuals should reach). For the purposes of this study, it is assumed that each vehicle can carry up to three people from the same household when simulating vehicle movements. For example, if five people lived in one household, two vehicles would be required – one to transport three people and the other to transport the remaining two people. For the derivation of evacuation

routes, the model has been set to utilise the A* algorithm to determine the shortest path to the closest designated safe zone.

Fig. 3 illustrates the Microscopic Evacuation Simulation Model (MSEM) components that simulate the evacuation of citizens from their residences at different times of the day. In this model, a proportion of the population (P) will evacuate on foot, while the remainder (1-P) will evacuate by car. The model also considers the current state of traffic on the road network and the behaviour of vehicle occupants when a tsunami alarm is triggered, such as whether they will park and exit the vehicle to proceed on foot to a safe zone or drive to a safe zone. These underlying parameters are influenced by the time of day, while the population distribution and traffic volume on the roads vary throughout 24 h.

To develop an evacuation model for both on-foot and by-car scenarios, it is necessary to create a model representation of the city and identify the origin (households/businesses) and destination (safe zones) of residents within the city, as well as their respective routes based on their mode of transport. This approach provides the basic underlying data for evacuation routes based on the shortest distance from a residence to the nearest safe zone. However, in a real-world model, additional factors must also be considered.

2.1.1. Transportation network data

In simulations using the traffic simulation software SUMO, a vectorised network file is utilised to represent the layout of the transportation network. This file consists of edges (roads) and nodes (junctions) and includes additional information such as the number of lanes, speed limits, traffic light locations and schedules, and other rules that regulate the flow of traffic within the network. The data for this network file can be either manually created or imported from various sources, with the data used in this study sourced from OpenStreetMap (OSM). To convert OSM data into a format that can be interpreted by SUMO, the “netconvert” tool can be used to transform the data into a *.net.xml file. This file includes various details about the properties of sidewalks and roads, such as traffic light locations and speed limits for controlling vehicular movements, as well as built-in functionality for estimating the locations of crosswalks at intersections and defining traffic light schedules at intersections if this information is not present in the original input file. Fig. 4 illustrates the network for Napier City as depicted in the SUMO software.

2.1.2. Defining safe zones for evacuation

Safe zones are designated locations or areas that are situated inland or at higher elevations where individuals can seek refuge during a tsunami event. These areas were chosen based on evacuation zones established by the Regional Emergency Management Agency and are listed on their website [20]. As shown in Fig. 5(b), in this study, for Napier City, two natural safe zones are identified to be named Hospital hill (in green polygon) and West zone (purple polygon). These locations were mapped using ArcGIS software, and the edges within the network file within these safe zones were identified to create a reference table for use in defining the endpoints of evacuation routes in the subsequent model setup process.

2.1.3. Defining population distribution

The population data used in this simulation was obtained from GNS and includes the geospatial coordinates of pedestrians in both day and night scenarios. The data contains the number of residents occupying each building.

Napier City has a population of 62,241 people, with around 48% males and 52% females. The median age is 42 years old. Fig. 6 depicts the age distribution in Napier City [33].

Napier City has solid natural hazards (earthquake and tsunami) training. Therefore, it is essential to know what percentage of the Napier residents have lived long enough in Napier City to have benefited from the training. Fig. 7 shows that more than 64% of Napier residents have

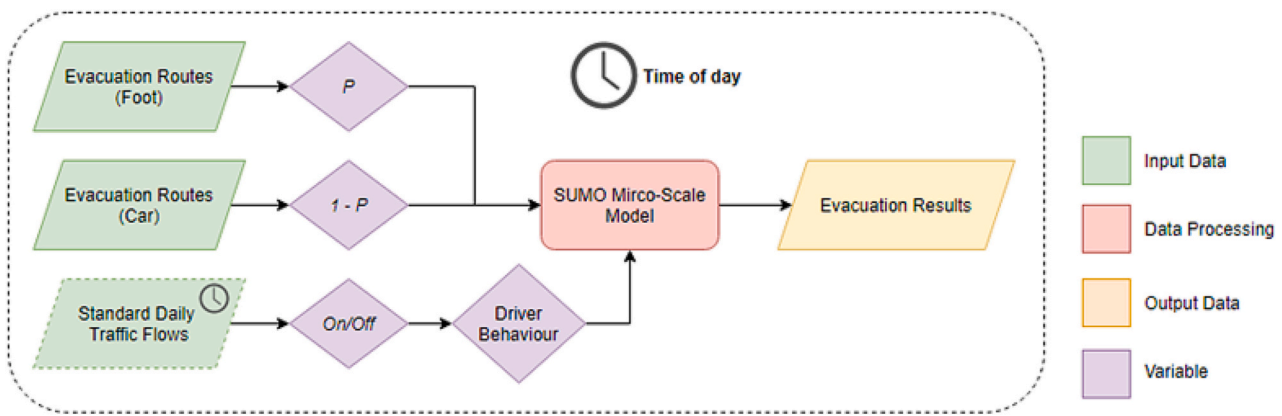


Fig. 3. Evacuation modelling flow chart.



Fig. 4. Screenshot of Imported Napier City network file in SUMO.

lived in Napier for more than ten years, with only around 6% living in the city for less than a year (NZ, 2018).

Since the population in residential buildings and office locations have lived more than one year in Napier City, a great understanding of what to do or where to go due to previous training or having other friends that are familiar with the evacuation paths insight to follow is expected. On the other hand, tourism accommodation providers are primarily located in evacuation zones. It is assumed that the tourists do not necessarily know the evacuation plan; However, they benefit from the blue line project (Group, 2022), a continuous thick blue line on the roads directing the nearest safe zone (hospital Hill). Once individuals get out of the building, they can follow the line and reach the safe zone.

This study considers the worst-case scenario to be the evening rush hour, from 4:00 to 5:00 PM [9]. Therefore, the population distribution and expected traffic flows are defined using the parameters for daytime evacuation simulations. The raw data was processed and simplified through several steps. First, the geospatial projection was modified to meet the requirements of SUMO. Second, to optimise the calculation of evacuation routes, locations that were already within safe zones or outside the intended modelling area were excluded. Third, using a spatial analysis tool, the nearest edge (road for vehicles and sidewalk for pedestrians), and position along that edge for each point were identified

to determine start positions for vehicles and pedestrians, respectively (Fig. 8).

2.1.4. Baseline traffic flows

In the evacuation modelling analysis, the inclusion of baseline traffic flows is considered. Average Daily Traffic (ADT) counts obtained from the Napier City Council for various locations (latitude and longitude) across the road network were used to estimate the traffic volumes at different times of day. Since the ADT count represents traffic flows as a single value (average number of vehicles passing a count location within a 24-h period), assumptions about the distribution of demands on the network must be made to represent traffic volumes at specific times of the day.

Since no real data on hourly traffic flow distribution was available, this study used reference data from another source to redistribute the ADT values over the day. Through analysis of different states in the United States, Hallenbeck, Rice, Smith, Cornell-Martinez, and Wilkinson [19] derived a dataset that shows the percentage of traffic expected to be observed throughout the day with respect to their ADT values, with the data indicating peak flows around 8:00 am and 4:00 pm. The traffic data obtained from the Napier City Council (Fig. 9) includes ADT traffic counts for over 20 years at selected locations. Therefore, the data was first transferred on an hourly basis. Time-series route distribution results were created to depict the traffic flow under normal conditions.

Using this reference data, the ADT values were redistributed to derive estimates of traffic counts across the network for a simulated peak time of 4 pm. To achieve these 10,000 randomly generated routes were generated for the study area to form the basis of a traffic flow lookup table. Using SUMO's "routeSampler.py" script was used that sample routes from the generated lookup table and examine them with respect to the traffic counts throughout the network. The sampler script looks to find an optimum traffic flow solution to satisfy the identified traffic counts.

Once traffic flows have been selected, the SUMO traffic flow model is run within the GUI to visualise the traffic flows for that time of day. This visualisation step is used to identify and resolve any issues within the network caused by implausible traffic routes. For example, vehicles attempting to perform U-turns at the beginning or end of their journey (Fig. 10) can lead to problems during a simulation. To fix this issue, an additional Python script was developed to identify and remove these instances, which improves the flows within the network, though these can also be rectified manually.

Utilising this approach, the location of vehicles that were in transit at the time of the initial tsunami alarm are identified (Fig. 11). Upon the sounding of an evacuation alarm, vehicles in transit will identify their nearest safe zone and the occupant of the vehicle will either drive the vehicle to the safe zone or they will exit the vehicle and walk to the safe zone accordingly.

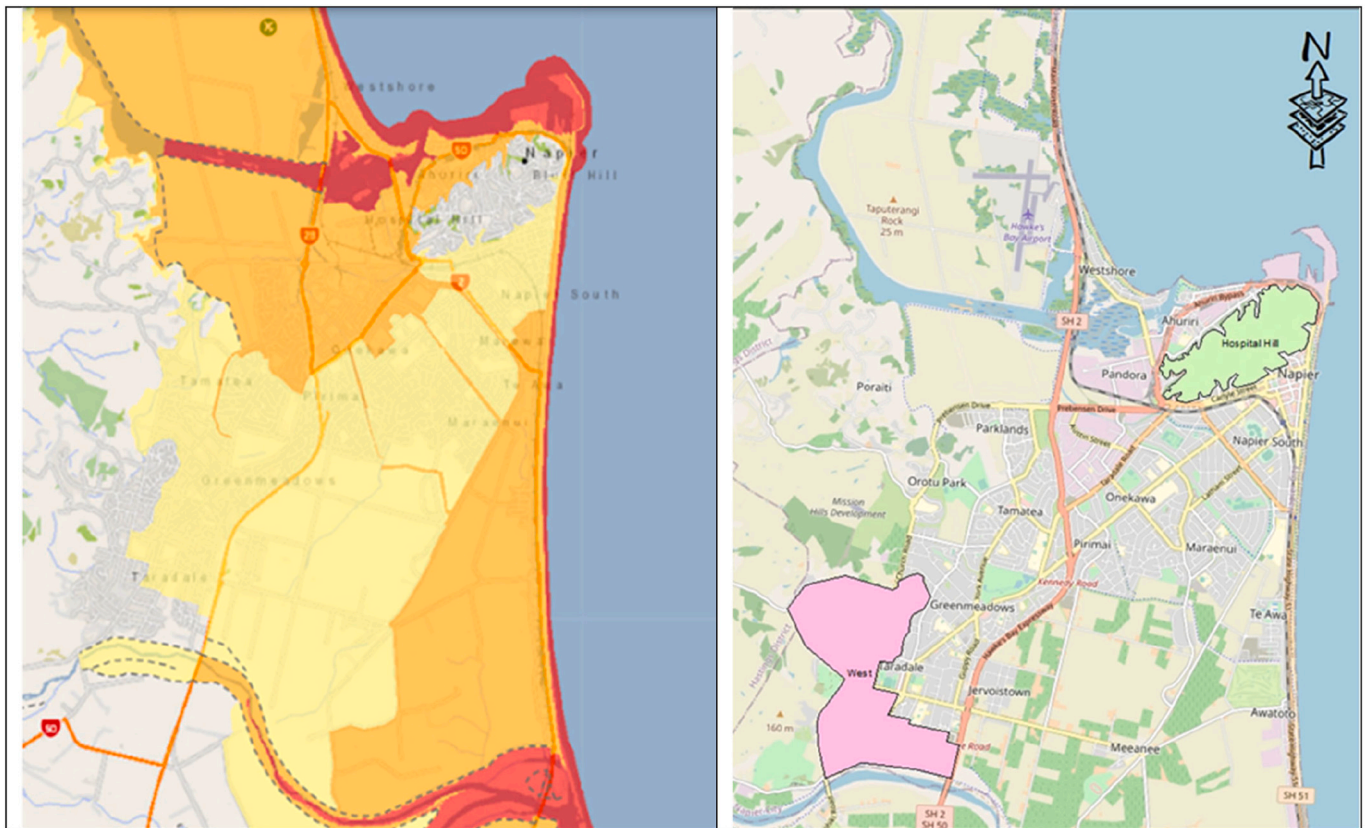


Fig. 5. Input data preparation for the model: (a) Napier City’s evacuation zone adapted from Hawke’s Bay Emergency Management Website (b) Modelled safe zones in Napier (Green: Hospital Hill Zone, Purple: West Zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

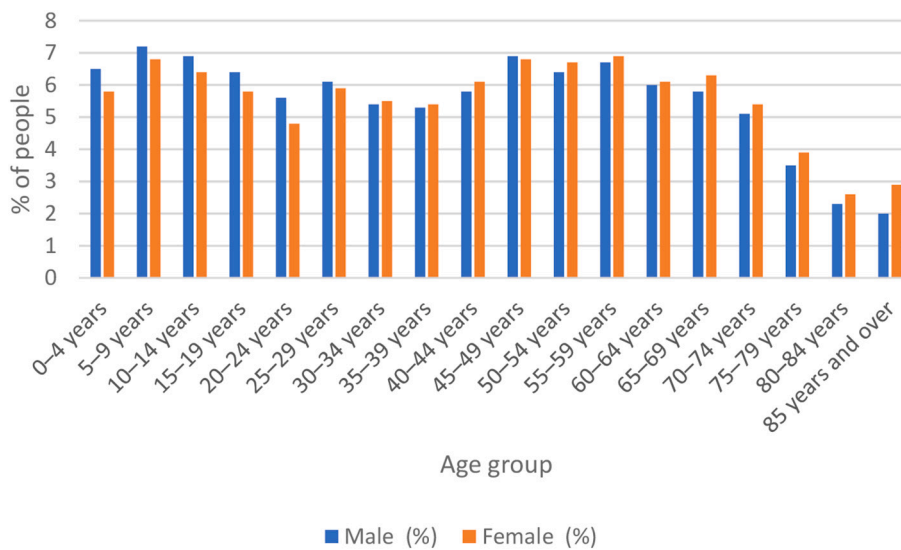


Fig. 6. Age distribution in Napier City.

2.1.5. Generating evacuation routes to safe zones for MSEM

The approach used for determining the evacuation routes from buildings to safe zones and from locations of vehicles in transit to safe zones is the same, with the exception that for vehicles in transit, it is assumed that there is only one occupant, whereas for buildings, there may be multiple occupants.

The derivation of evacuation routes for the population is divided up into two main stages. Firstly, using an iterative approach and SUMO’s

“findIntermodalRoute” tool, the shortest path from each point location to its nearest respective safe zone is identified. During this initial step, there are no constraints on the search space for each point location such that in this model, the shortest paths to both the West Zone and Hospital Hill Zones are analysed. Once the shortest path for a point has been obtained, the route is appended to the pedestrian routes file, and the associated safe zone for that point is recorded for the subsequent vehicle route analysis. For determining the shortest routes for vehicles, an

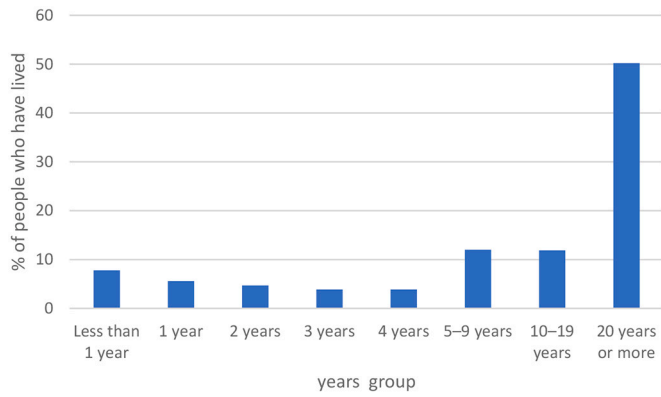


Fig. 7. Years since arrival in New Zealand for People in Napier City-2018 Censuses.

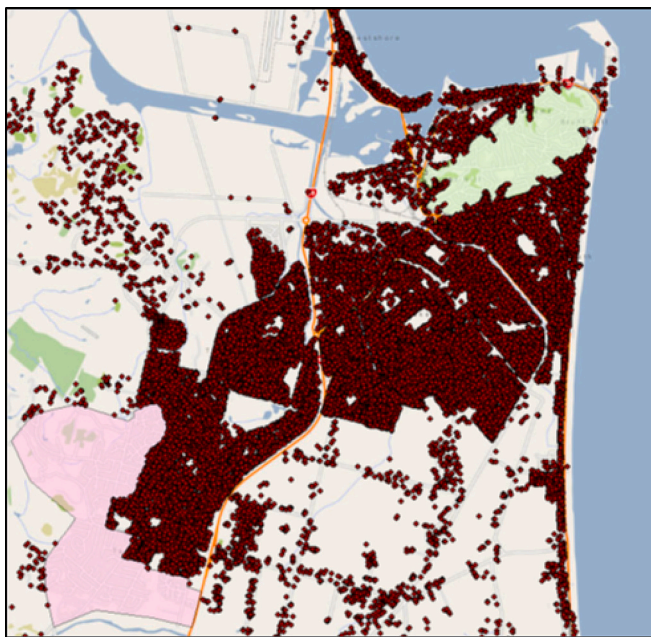


Fig. 8. Modelled population distribution within the evacuation simulation.

assumption has been made that the person/s at each point would choose to travel to the same safe zone that they would have chosen if they were to evacuate on foot. This assumption restricts the search space for the shortest route analysis for vehicles to edges within the previously identified safe zone for the pedestrian scenarios. By applying this assumption, it is possible to make a fair comparison of the effectiveness of different evacuation methods in reaching their destinations. Each evacuation route identified in this step is appended to the vehicle evacuation routes file accordingly.

The processes result in the creation of four evacuation route files:

1. Evacuate from buildings on foot
2. Evacuate from buildings by car
3. Evacuate from transit location by exiting vehicle and travelling by foot
4. Evacuate from transit location by driving to nearest safe zone

Using these four evacuation route files for reference, different scenarios can be analysed to examine the effectiveness of the evacuation method at a city scale. Table 1 outlines the destination distribution of evacuees within the model based on shortest walking route analyses.

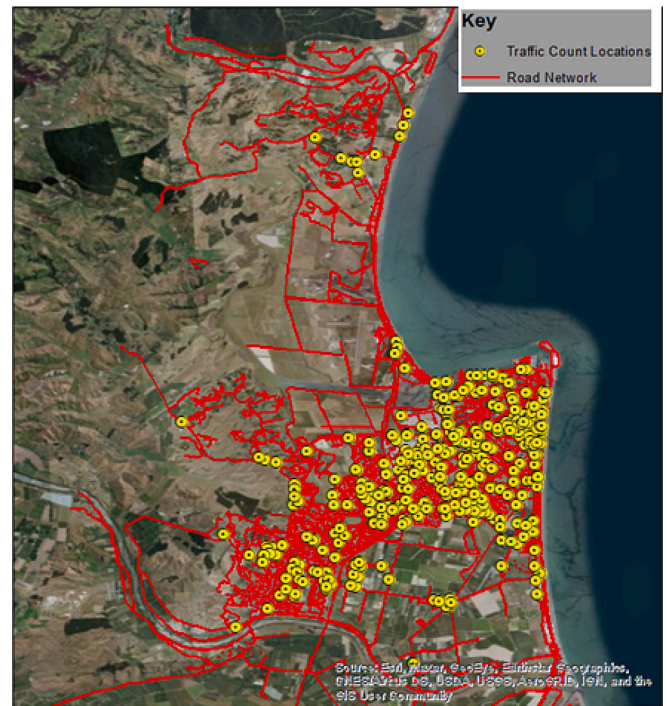


Fig. 9. Traffic Count locations used for estimating traffic flows within Napier.

The final stage of the evacuation route process is to determine the egress time for individuals evacuating from buildings and vehicles upon hearing a tsunami evacuation alarm or experiencing a post-earthquake event. In this study, a simplistic approach was adopted in which it was assumed that people would take between 2 and 5 min to exit a building. Using a random number generator within these constraints, each individual (or group of individuals if using a vehicle) was assigned a time-delay before beginning their evacuation.

2.2. Theoretical velocity-based model

The velocity-based model is a simplistic approach that analyses the route files generated for the MSEM model and estimates travel times based on either average walking speed values for pedestrians or maximum permitted travel speeds along evacuation routes for vehicles. Unlike that of the MSEM approach, the velocity-based model does not consider the interactions between agents within the network.

The theoretical velocity-based model analyses the shortest distance along roads or sidewalks (depending on the means of evacuation) and calculates journey times based on either the average walking speed for pedestrians or the maximum permitted driving speed along various route sections for vehicles. This model determines the route taken by an individual to the safe zone based on the shortest distance along the network, considering the maximum permitted travel speed along the designated route for vehicles. The success rate of the evacuation process is calculated based on the time each individual takes to reach a safe zone, with the arrival of the tsunami wave serving as a time constraint. If an individual's journey time is less than this constraint, they are considered to have reached safety. The survival rate is then calculated as the percentage of individuals that successfully reached a safe zone within the timeframe.

2.3. Scenario development

Using the four evacuation routes files defined in section 2.2.5, two scenarios were developed for analysis (Table 2). These scenarios were selected to compare the effectiveness of evacuation method in reaching

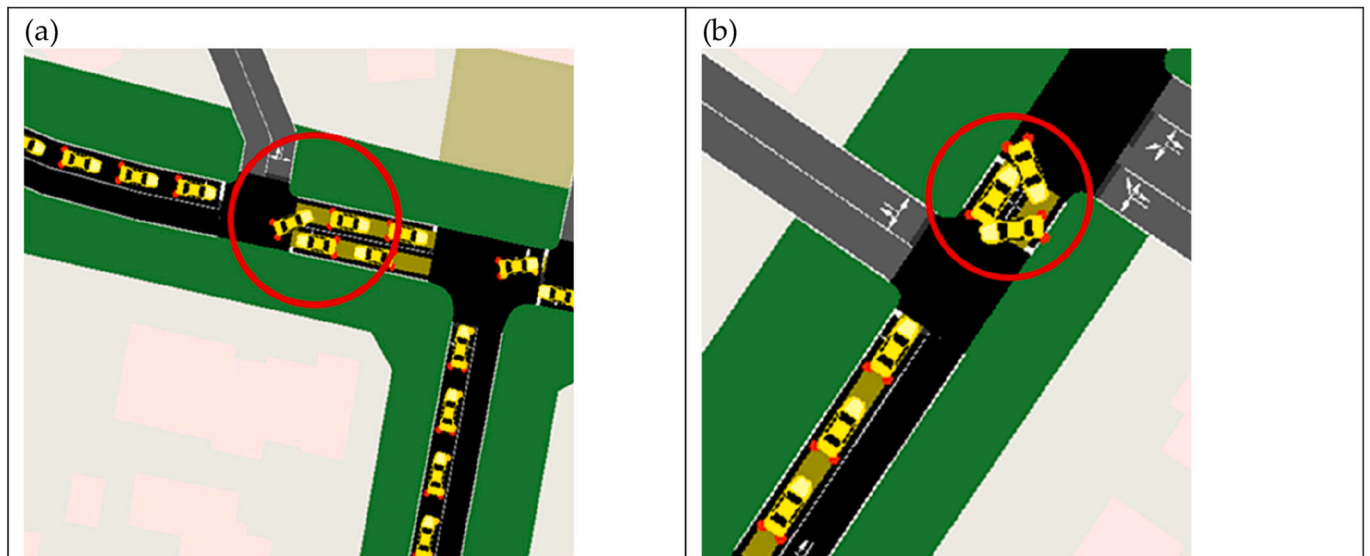


Fig. 10. Example of problematic U-Turns in routes. Left: U-turn at the beginning of the route. Right: U-turn at the end of the route.

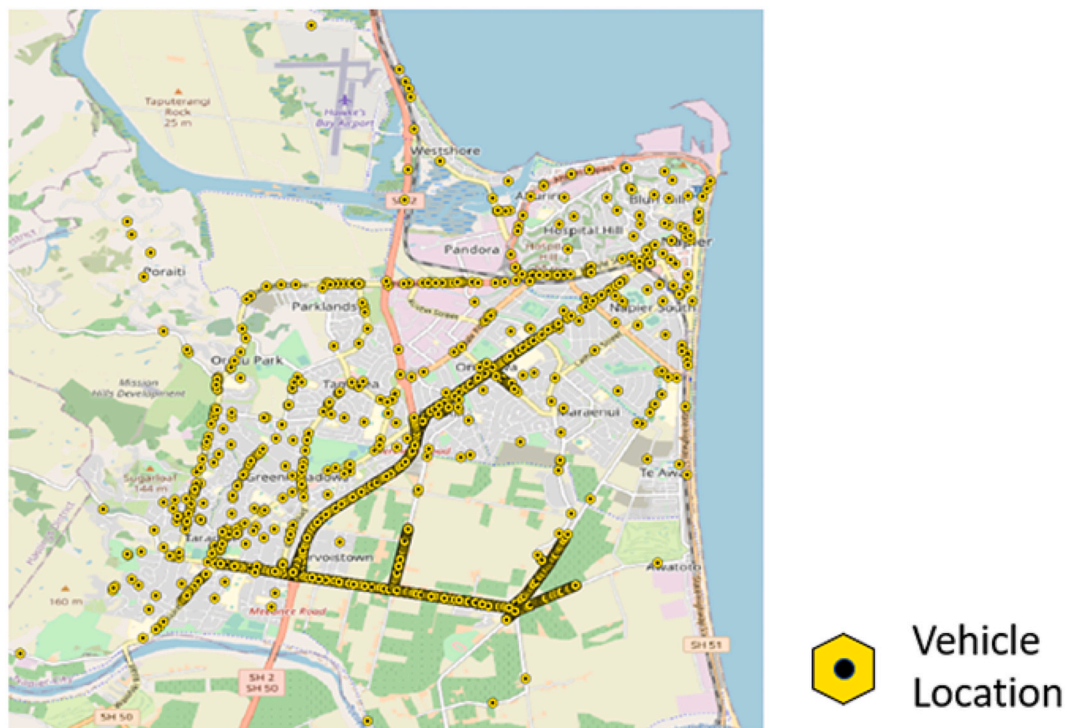


Fig. 11. Location of vehicles in transit at 4 pm during time of tsunami alarm.

Table 1
Evacuation Zone Distribution.

	Number of Evacuees	% of population
Hospital Hill	52,103	69
West Zone	23,662	31

the nearest identified safe zone regions.

In this paper, we first developed an MSEM scenario to validate the model against an evacuation drill. Then based on the worst-case scenario for local tsunami evacuation in Napier City [9], two scenarios have been developed based on the mean of transport. In each model, the traffic on

Table 2
Defined scenarios for evacuation assessment.

Scenario ID	Building resident evacuation method	Traffic on the road evacuation method
SC1	Walk	Walk
SC2	Car	Car

the road at the evacuation warning time is to (1) exit the car and head to a safe zone on foot in scenario 1 and (2) reroute toward a safe zone by car in scenario 2. On the other hand, all other affected populations which are inside the building at the tsunami warning time would

commute (1) on foot in scenario 1, and (2) by car in scenario 2. It is assumed that all the population is either in a building or on the traffic in a car. It should be noted that in scenario 2 where people are evacuating from buildings by car it is assumed that each car will take three individuals. Therefore, if a building occupies five residents, it is assumed that two cars would head toward the safe zone.

3. Results and findings

The primary goal of this study is to simulate the evacuation process following a Hikurangi 8.4Mw earthquake in Napier City, New Zealand. It is assumed that the normal traffic flow at 4 pm (Fig. 11) is already on the road when the earthquake starts and that citizens within the city will evacuate after the shaking has stopped and proceed to travel to their nearest safe zone. This study evaluates the evacuation process in Napier City using the two simulation models described in section 2. The results of these models are then compared to highlight the advantages of a micro-scale model.

3.1. Theoretical velocity-based model

Using the shortest route files derived via the MSEM approach, the travel times for agents (pedestrians and vehicles) were calculated.

3.1.1. Scenario 1 (SC1)

Based on the described methodology, the initial step is calculating the shortest distance between an individual start location and the nearest safe zone. Table 3 provides a sample of the evacuation route attributes for pedestrian data containing the edge ID, length, and coordinates. The edge is the path that individuals can commute on, which can have several lanes (road lane in black and sidewalks in grey), while the Lane is one of the parts of the edge with the traffic going in a specific direction. (Fig. 12).

Having these data and assuming a walking speed, each individual's time to pass a route can be estimated. Consequently, a python script was used to calculate an individual's total time according to the edge length and walking speed. In this study, it is assumed that individuals' walking speed would be 1.2 m/s. Then in 50 min, this would cover a 3600 m (3.6 km) distance. Therefore, anyone who has to walk a distance greater than 3.6 km to a safe zone would not make it.

The result shows that around 4.4% of people need to commute more than 3600 m by foot to reach a safe zone, with the maximum journey length an individual would take being approximately 9893 m. The evacuation success rate would be 95.6% since a number of 35,372 individuals are located within the 3600 m of safe zones. Based on the abovementioned calculation, the number of individuals reaching safety is represented in Fig. 13.

3.1.2. Scenario 2 (SC1)

In this study, the network file for car evacuation simulation was the

Table 3
Road details sample required for estimating evacuation time via velocity-based model.

FID	edge_id	lane_id	allow	length
24,438	784,652,915	784,652,915_0	pedestrian bicycle	92
27,486	87,231,742	87,231,742_0	pedestrian	94
8223	-441,371,101	-441,371,101_0	pedestrian delivery bicycle	99
16,862	391,860,253#0	391,860,253#0_0	pedestrian	99
24,707	84,722,158#0	84,722,158#0_0	pedestrian	99
4241	-342,862,842	-342,862,842_1	unknown	99
4240	-342,862,842	-342,862,842_0	pedestrian	99
28,196	89,908,664#4	89,908,664#4_0	pedestrian delivery bicycle	99
28,342	94,319,637#0	94,319,637#0_0	pedestrian bicycle	100

same as illustrated in section 2.1.5. In this scenario, it is assumed that all residents would travel by car to their respective safe zone. As described earlier, each vehicle has been defined as having a maximum occupant limit of three people, meaning the number of vehicles (individuals) in the SC2 scenario is reduced to 16,267. As the average speed limit on Napier City roads is 50 km/h (13.89 m/s), a car travelling 41,670 m or less would reach the safe zone in 50 min. The assumptions of this model result in an even higher survival rate for scenario 2, with all individuals reaching the safe zones in less than 8 min (Fig. 14).

3.2. Model verification

As the last tsunami occurred over 70 years ago and there is no official documentation around what happened, this study has compared the MSEM model outputs with the tsunami evacuation drill project back carried out in 2016. The tsunami evacuation drill was exercised on the 8th of September 2020 at 10:00 am by the emergency management team of Napier Port. The drill started with a warning for an earthquake with a follow-up evacuation notice. As the port has adopted the "blue line project" [15] to navigate evacuees to safe zones, employees working on the main site evacuated on foot and followed the blue lines to reach the safe zone on top of the buffer hill (Hospital hill). On the other hand, the port employees working on the Themes street depots, located on the city's northwest side, preferred to evacuate by car as they considered they might not make it in time if they commuted on foot. This shows the requirement for an evacuation model to consider both on foot and by car to be realistic. The overall results show that everyone reached the safe within 10 min.

As the model is supposed to represent the same situation as the drill, the input data was altered to align the MSEM model with the evacuation drill scenario. First, the traffic data used in this scenario represented the traffic running at 10:00 am. Next, since Napier Port was the only drill participant in this scenario, the author has cleaned the population distribution data to only consider the daytime residents of the port as the evacuees.

As everyone is reaching the safe zone before the tsunami arrival and the data provided by the drill shows the time spent until the last person reaches the safe zone, the same calculation has been provided for validation. The results of the MSEM model also showed that the last evacuee would reach the evacuation zone after 10 min and 47 s. The represented number is the average of ten consequence run, and the results have all been similar up to 2 decimals.

It should be noted that although the MSEM model reduces moving speed when there is a traffic jam or collision, there is no sign of collision and walking speed reduction in the current scenario. The rapid and without-collision evacuation depicted in this scenario may result from the consideration that only the port employees are the evacuees. However, in other scenarios, the model's capability to simulate the effects of the crowd is observable, where other evacuees would occupy the routes toward the safe zones. Therefore, this evacuation scenario is just used for verification purposes. The results have been summarized in Table 4.

3.3. MSEM model

In this study, a total of two scenarios were conducted. As the assumption of the individuals' behaviour contains stochastic elements, each scenario was repeated 10 times to consider the effects of uncertainty in the simulation [34]. Fig. 15 shows the relationship between the number of simulation repetitions and the average time to evacuate all of the agents in scenario 1. The authors ran a total of 13 simulations to ascertain the point at which further simulations do not significantly affect the results. As a result, the noted average value is calculated after ten simulation runs. As shown in Fig. 15, the mean value after ten simulation repetitions lies within ±0.5% of the mean value after 13 simulations are carried out. Since this study uses average values as its results and the assumptions in the model are minimal, the authors

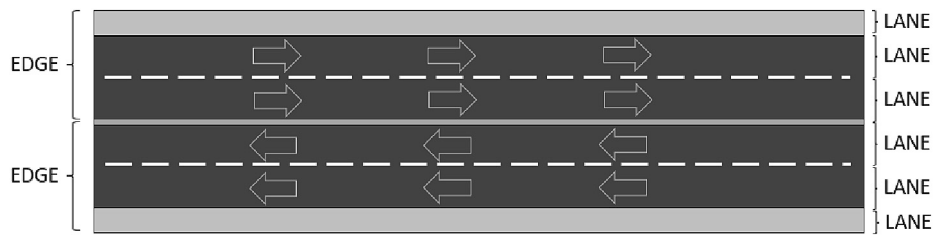


Fig. 12. Edge and Lane in a network (road lanes in black and sidewalks in grey).

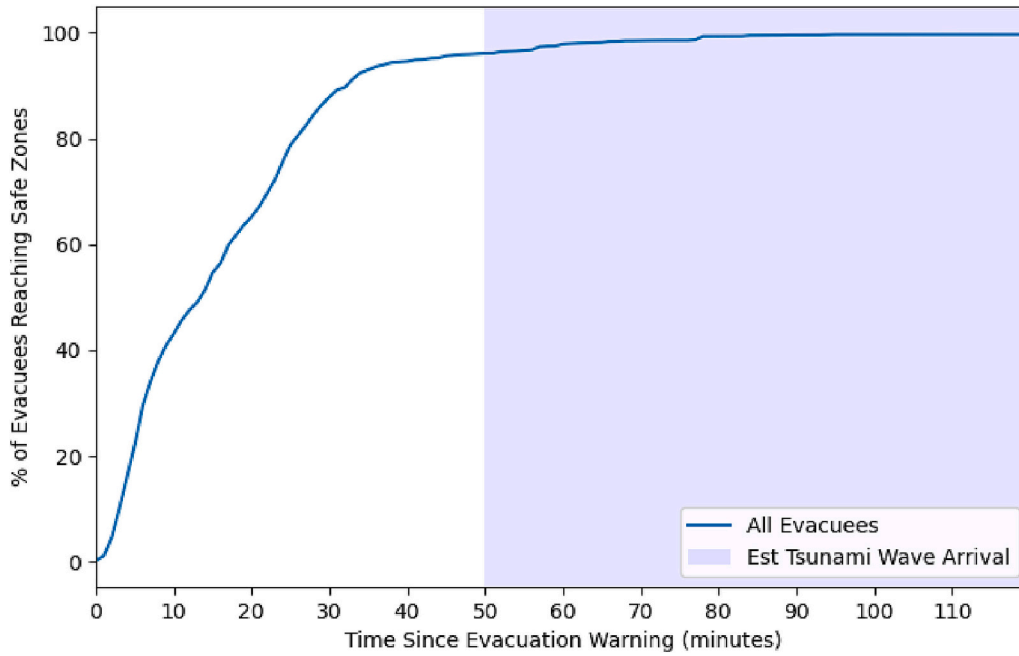


Fig. 13. Percentage of population successfully reaching nearest safe zone: Scenario 1 (Velocity-Based Model).

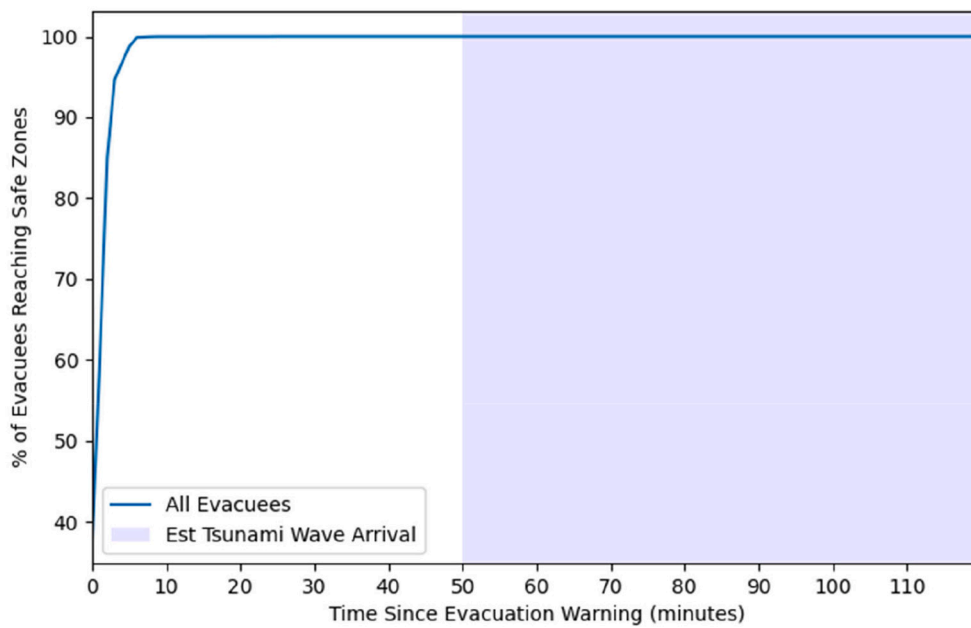


Fig. 14. Percentage of the population successfully reaching the nearest safe zone: Scenario 2 (Velocity-Based Model).

Table 4
Summary of validating MSEM model with Evacuation Drill data.

Scenario			Time takes evacuees to be safe	
Suburb	Time	Number of people evacuated (EST)	Evacuation Drill	MSEM model
Napier Port	The 8th of September 2020. 10:00 am	350	10'	10' 47"

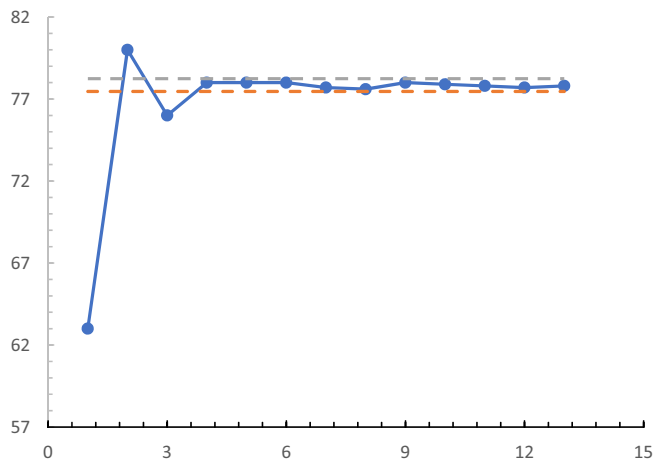


Fig. 15. Relationship between number of simulation repetitions and time to evacuate 100% of population.

Table 5
Summary of scenario development.

Scenario	Time to evacuate 54%		Time to evacuate 87%		Time to evacuate 100%	
	Mean	Standard Deviation	Mean	Standard deviation	Mean	Standard Deviation
SC1	24.5	0.21	50.0	0.38	77.8	0.33
SC2	50	0.32	NA	NA	NA	NA

determined that ten times represented the optimum number of simulations for each scenario. Table 5 shows a summary of the results. Three indicators of the effectiveness of the evacuation procedure were computed. Namely the average time across the ten simulations that it takes for 87% of individuals to reach a safe zone (which is the percentage of the people who reached the safe zone by the tsunami wave arrival in SC1), 54% of individuals to reach the safe zone (percentage of the people reached the safe zone by the tsunami wave arrival in SC2) and the time taken by all (100%) of individuals to evacuate.

3.3.1. Scenario 1 (SC1)

Fig. 16 illustrates the time it would take for Napier City residents to reach a safe zone on foot during a tsunami based on the results of the MSEM. The simulation output shows that during a rush hour traffic scenario, approximately 87% of Napier City's residents would be able to evacuate safely on foot with 95% of those travelling to West Zone reaching there safely and 83% of those travelling to the Hospital reaching there before the first arrival of the tsunami waves at 50 min.

3.3.2. Scenario 2 (SC2)

In contrast to those evacuating by foot Fig. 17 shows a reduction in the population reaching safety within 50 min if they all decide to drive to the nearest safe zone by car. In this scenario, only about 54% of the population reach their nearest safe zone within the 50-min timeframe.

Also, the result shows that at the beginning, the proportion of the evacuees heading to the west zone reached safety is higher than Hospital Hill. However, after 35 min, the results favour the individuals heading to Hospital hill. The reduction in numbers reaching the west zone can be due to heavy traffic jam on the routes heading toward the west zone.

4. Discussion

There has been significant interest in simulating evacuation scenarios for disaster risk reduction and preparedness purposes. It is important to evaluate the strengths and weaknesses of existing models in order to develop novel models. Nakanishi et al. [32] used an agent-based model to simulate the typhoon evacuation process in Kasuga City and found that most people reached safe zones 50 min after the evacuation warning was issued. T. Takabatake, Nistor, and St-Germain (2020) used the Artist 4.0 platform to simulate the evacuation scenario in Vancouver, Canada and found that the tsunami would catch many people, but the highly populated Tofino Central Business District (CBD) would be safe. This highlights the importance of knowing where people are located at the time of a tsunami warning. Trindade et al. [41] simulated the evacuation process in Cascais City, Portugal using the ArcCasper tool of ArcGIS and found that more than 80% of evacuees would reach a safe zone before the first tsunami wave arrived. Given that most residents of Cascais City live in a tsunami evacuation zone, it is suggested that a vertical safe zone would be preferable for areas where people would not have sufficient time to reach a safe zone, or alternatively, residents and businesses could be relocated to low-risk areas.

The proposed MSEM model can be used in future emergency management policy planning since it inclusion of dynamic walking speed assumptions in the case of pedestrian and vehicle interactions and collisions, as well as the consideration of sidewalk width in network capacity. Also, the MSEM model demonstrates that movement speed is a significant factor in evacuation. Similarly, Sun and Sun [38]) found that elderly individuals would take more time to reach a safe zone. Lumbroso and Tagg [27] also demonstrated that the shortest distance is not always the fastest route.

The result of these presented scenarios outlines the importance of the assumptions in evacuation modelling and shows how different criteria can change the effectiveness of an evacuation plan.

4.1. Recommendations

Based on the proposed evacuation model, multiple recommendations can be extracted.

- The MSEM model provides a holistic and in-depth insight for emergency management officials to understand and examine potential vertical evacuation centres in areas that are highly dense and would have a lower survival rate.
- Another insight that the evacuation simulation model provides is that different suburbs require different strategies. In the case of Napier City, it is assumed that if the residents of the southern part of the city evacuate by car directly to the west zone on the shortest path, the evacuation rate would be higher. On the other hand, the residents of the northern part of the cities must avoid cars and evacuate on foot to be safe. W. Zhang, Wu, and Yun [44] also noted that the evacuation and resilience strategies in different city suburbs should vary according to their spatial position and vulnerability.
- Also, the choice of evacuation means is another critical characteristic of an evacuation plan. Table 6 shows the percentage of evacuees considering evacuating on foot or by car in the Napier City evacuation simulation by MSEM model. The results indicate that evacuation via foot appears to be more efficient than a car. The lower survival rate among individuals who tend to evacuate by car can be because the most straightforward path could not always be the best route. This can be due to many factors, such as it might get inundated

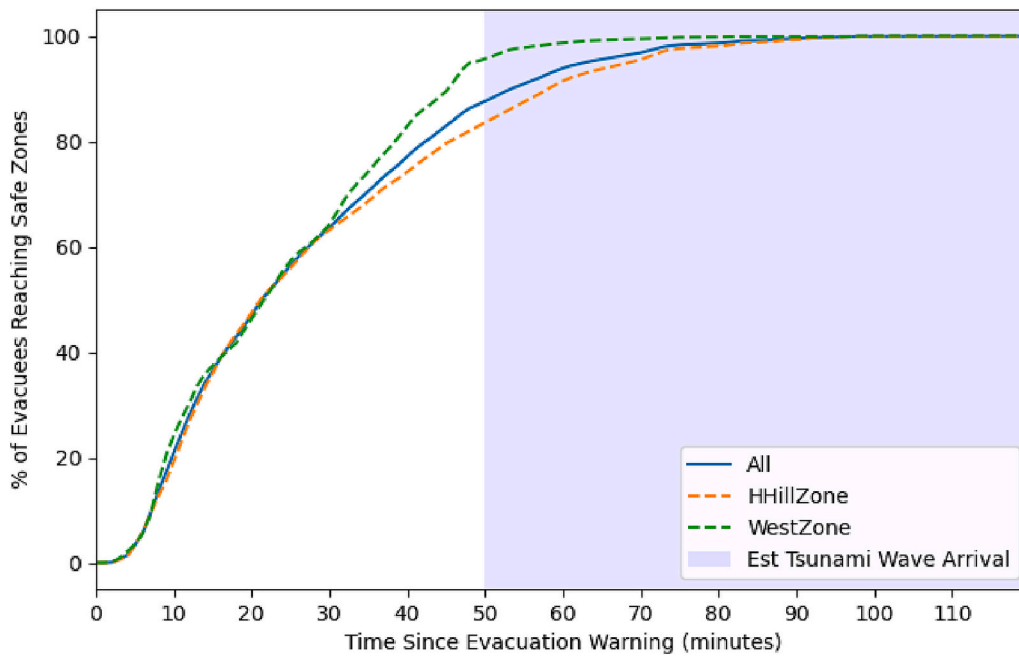


Fig. 16. Percentage of population successfully reaching nearest safe zone: Scenario 1.

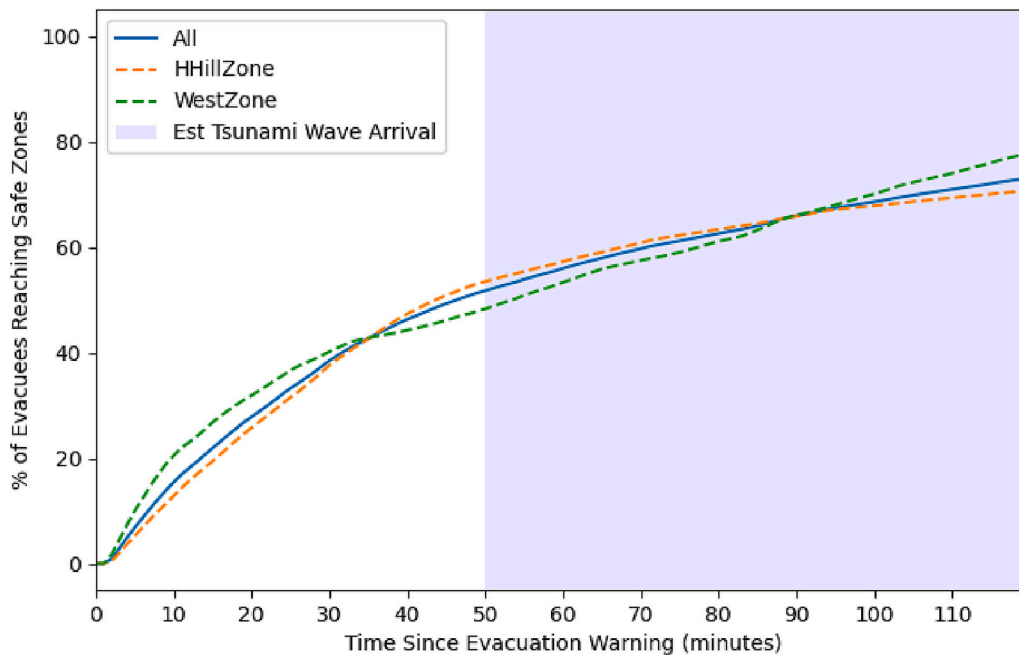


Fig. 17. Percentage of population successfully reaching nearest safe zone: Scenario 2.

Table 6
Percentage of safe evacuees in Napier City after a tsunami.

	Napier City Population Data	Population after the screening process	The evacuated population before 50 min	Evacuated percentage
SC1	48,800	37,497	30,000	80
SC2	48,800	37,497	22,000	48.6

earlier, there would be a bottleneck, or the edge might have less capacity, which causes more traffic. Kitamura et al. [23] confirmed that there is no guarantee that the shortest distance is the best route for evacuation.

4.2. Further work

Every evacuation simulation model has assumptions and has not captured all human behaviour aspects. For instance, Tomoyuki Takabatake, Fujisawa, Esteban, and Shibayama (2020) ignored car crashes and assumed all cars would reduce their speeds near an intersection. Likewise, this study does not consider vehicular behaviour, such as car

accidents and disobeying the rules, which would worsen the situation.

The MESM model has the capacity to transfer some assumptions to real data. For instance, some further work directions to improve the model are assuming (1) vehicles to use both right and opposite sides of the road, (2) the influence of the topography on the moving speed, (3) road closures due to the earthquake, (4) considering individuals wrong choices of routes.

5. Conclusion

The MSEM model has the privilege of considering the short path route and the interaction of individuals and different evacuation means concurrently. The MSEM model showed that a realistic evacuation simulation could give decision-makers a better vision of the evacuation scenario. The model can be used as an evidence-based decision-making tool, which can give insights on new policies and infrastructure improvement to reduce the risk of a tsunami. The Napier City case study and scenario development also clarified that the spatial area distribution, choice of evacuation mean and evacuees moving speed plays a significant role in a successful evacuation plan.

Credit author statement

Dear editor,

This manuscript has been drafted by the main author and been revised and reviewed by all coauthors.

The methodology used in this paper has been developed by the first two authors and been supervised by the other two. The below table has summarized the workload.

Author	participation
A1, Azin Fathianpour	Writing manuscripts, developing methodology, data analysis
A2, Dr. Barry Evans	Reviewing the manuscript, methodology and data analysis
A3, Dr. Mostafa Bабaeian Jelodar	Reviewing manuscript and supervision
A4, Prof. Suzanne Wilkinson	Reviewing manuscript and supervision

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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