



Environmental factors in tsunami evacuation simulation: topography, traffic jam, human behaviour

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Abstract

The risk a tsunami, a high-rise wave, poses to coastal cities has been highlighted in recent years. Emergency management agencies have become more prepared, and new policies and strategies are in place to strengthen the city's resiliency to such events. Evacuation is a highly effective response to tsunamis, and recent models and simulations have provided valuable insights into mass evacuation scenarios. However, the accuracy of these simulations can be improved by accounting for additional environmental factors that affect the impact of a tsunami event. To this end, this study has been conducted to enhance an evacuation simulation model by considering topography that impacts traffic mobility and speed, traffic congestion, and human behaviour. The updated model was employed to evaluate the effectiveness of Napier City's current evacuation plan, as it can realistically simulate both pedestrian and vehicular traffic movements simultaneously. The simulation demonstrated in this paper was based on a scenario involving an 8.4 Mw earthquake from the Hikurangi subduction interface, which would trigger a tsunami risk in the area. Based on this event, the final evacuation time (time between after the shake is felt and the arrival of the tsunami wave at the shoreline of Napier City) is considered to be 50 min. The results of the MSEM model are presented within two categories, (1) survival rate and (2) safe zone capacity. The evacuation simulation model used to examine the environmental factors in this study is the Micro-Simulation Evacuation Model (MSEM), an agent-based model capable of considering both pedestrian and vehicular interactions. The results showed that the steep pathway to the safe zone would markedly decrease the moving speed and reduce the survival rate, highlighting the need to have supporting vertical evacuation to reduce the number of evacuees heading to steep routes. Additionally, the modelling and assessment of mass evacuation by vehicles has highlighted regions of severe congestion due to insufficient network capacity. Through highlighting such regions, the model aid policy makers with a more targeted approach to infrastructure investment to improve flows of traffic in mass evacuation scenarios and increase survival rates.

Keywords Emergency management · Evacuation modelling · Pedestrian evacuation

1 Introduction

Mass evacuations are an inevitable response to fatal hazards such as tsunamis. A local source tsunami comes on short notice after an earthquake, forcing individuals on the coastline to retreat inland and/or to higher ground. Due to the potentially relatively short timeframe between feeling the first shake of an earthquake and the arrival of a tsunami wave, preparedness is key for maximising chances of survival. Evacuation simulations can boost readiness by providing insight into possible scenarios, and the results can be translated into new regulations and infrastructure upgrades for coastal cities (Chraïbi, Tordeux et al. 2018, Makinoshima et al. 2018). Knowing spatial gaps, such as road capacities and potential bottleneck locations, could help decision-makers invest money in projects that align more closely with the risk reduction plans (Chu et al. 2019). Additionally, information can be disseminated to the public in the form of revised and more region-specific evacuation plans, making people more aware and prepared for such events.

Recently, researchers have shown great attention to evacuation simulations focusing on the accuracy of the models (Makinoshima et al. 2018, Takabatake et al. 2020a, b, Takabatake, Nistor et al. 2020b, Wang and Jia 2020). Takabatake et al. (2020a, b)'s simulation showed that vehicles already on the road would act as an obstacle in pedestrian evacuation. To emphasise this drawback, Wang and Jia (2020) considered the vehicle and pedestrian interactions in the agent-based evacuation simulation. These interactions were also considered in Fathianpour, Evans et al. (2023) whereby the interactions of vehicles already present in the road network were considered along with evacuees either by car or foot that originated from within buildings.

Although Fathianpour, Evans et al. (2023) have shown the speed reduction influence of vehicle movement due to the traffic, the literature showed an evident lack of consideration in the pedestrian moving speed variation due to the steep roads heading to high ground. Moreover, the impact of vehicle behaviour has not been considered. Conversely, another scenario would be that vehicles tend to change their direction and reroute in case of a traffic jam.

Many important factors influence evacuation times, such as awareness of tsunami, a sense of importance in collecting belongings, finding one another before the evacuation, etc. Nevertheless, the reaction time (the time an individual spends after feeling the earthquake getting out of the building) significantly influences the evacuation process (Sun and Sun 2019). Furthermore, additional factors influence evacuee speed and evacuation time, such as evacuees' group behaviour (Shields et al. 2009) and population age distribution (Arce et al. 2017).

This research aims to boost the evacuation simulation model (Fathianpour, Evans et al. 2023) to consider the abovementioned spatial and behavioural impacts in an evacuation process. The model would be used to evaluate both the existing evacuation plan and the effectiveness of proposed enhancements aimed at optimising the evacuation procedures. The result of the current study was then reported to show the resiliency level of the evacuation infrastructure capacity, and the safe zone capacity. The results would then be compared with the baseline model results to show the importance of the used factor in this model.

1.1 Topography

One of the potential parameters that can affect the movement of pedestrians is the terrain topology. With part of the evacuation process with respect to reducing risks from tsunamis involving moving to higher ground; when modelling the evacuation of pedestrians on foot, it is essential to consider the effects that moving uphill may have on their movement speed (Chen et al. 2022).

Most researchers have considered the Lease-Cost-Distance (LCD) approach for simulating evacuation, where LCD utilises GIS data to assess the impact of topography such as steep routes in evacuation planning. These simulation results are mostly used in general education and preparedness (Wood and Schmidlein 2012). However, there has been less interest in considering the spatial details in agent-based and scenario-based evacuation simulation designs, which provide more detailed information on the requirements to prepare and boost the resilience level of a community toward such a catastrophic event.

Pingel (2010) considered the slope influence on the constancy sense of walking path choice in mountain ranges through LCD. His findings outlined that whether an individual is walking uphill or downhill, the slope would reduce their walking speed. Wood and Schmidlein (2012) quantified this theory by discussing the sensitivity of tsunami evacuation time to various factors such as elevation and travel speed, where Tobler's walking speed of hikers' equation (Tobler 1993) was included within the model to simulate the effect of a steep routes on evacuation time. The results showed an 80% increase in survival rate once individuals run fast rather than walk slowly in an evacuation scenario. Based on the simulation results, he proposed that a public-health campaign is required to educate residents on the importance of being able to walk briskly.

Conversely, traversing slopes within natural terrain topologies to safe, higher ground may not always be an option for coastal cities, for instance in cases where a coastal city is located within low-lying topography. For example, evacuation simulations of San Pedro de la Paz, Chile, have shown that due to absence of high natural topographical features for people to evacuate to, man-made vertical evacuation infrastructures could be an alternative solution (Qüense, Martínez et al. 2022).

1.2 Traffic congestion

Takabatake et al. (2017) examined the influence of the moving speed on the evacuation time and survival rate in an agent-based model, whereby congestion density is based on the number of agents in a particular location at a specific time with respect to the road width at the relative location. Different constant walking speeds were thus assigned to each agent, based on the derived pedestrian congestion densities on the roads. In dealing with the implications of congestion, Barnes, Dunn et al. (2021) proposed the use of vertical evacuation centres located between long-distance routes and in congested areas. Although the results provided an evacuation route plan where everyone would be safe when tsunami waves arrived, the car-pedestrian interactions were ignored. Additional research looking into the implications of congestion outlined in Wood et al. (2016) proposed solutions to deal with congestion/overcrowding located near assembly points, where their research showed that evacuees unable to reach their designated assembly point could be re-routed to an alternative assembly point or shelter. Also, LCD evacuation model was used to assess evacuation route paths and shelter accessibility (Faucher, Dávila et al. 2020). By identifying the positions where the crowd is created since they cannot enter the shelter, the model

was notified to reroute the pedestrian to another safe zone. However, there is a lack of literature showing the rerouting of vehicles and individuals as a result of traffic jams.

1.3 Human behaviour

Research by Barnes, Dunn et al. (2021) examined human behaviour in an evacuation scenario based on individuals' gender and age, where the work evaluated the effect of group interactions on evacuation time. The results showed that grouping evacuees by age and gender had minimal impact on overall evacuation times. Mayasari, Astuti et al. (2021) also considered group walking speed in their evacuation simulation. The Floyd Warshall algorithm was used to determine the minimum routes each individual should take to understand the minimum evacuation time for an individual at risk of a tsunami. In conclusion, the findings revealed that when accounting for the evacuation of elderly individuals, their walking speed could be as slow as 0.751 m/s, leading to an extension in their overall evacuation duration. Addressing this scenario effectively involved proposing the implementation of vertical evacuation strategies. Nevertheless, (Wood et al. 2014) recognised that no vertical shelter can ensure the safety of every individual.

Furthermore, Wood et al. (2016) used the LCD model to investigate the minimum travel speed that keeps pedestrians safe. Therefore, considered a 20 min evacuation time for all residents and calculated the minimum travel speed individuals require to reach a safe. The results showed that more than 80% of individuals would reach the safe zone in time if they at least walked at the same speed as an impaired adult (0.89 m/s).

In a study by Kim et al. (2021), the impact that fear may have on an individuals' walking speed during a catastrophic event was considered. Here, four behavioural modes in the model were investigated: (1) the lookup for the best destination, (2) the need to avoid collision with the walls, (3) the tendency to look for less congested areas, and (4) the tendency to follow the stream. He used numerical equations to model the detail of fear propagation in different evacuation scenarios. Moreover, Ito, Kosaka et al. (2021) used agent-based evacuation modelling to estimate human behaviour in a local tsunami, where evacuees were divided into two classes based on the level of familiarity with the area of (1) basic evacuees and (2) following evacuees. The research considered that after the earthquake shake, no one would be able to evacuate in the first 90 s, and there would be a 5 min action time for basic evacuees to get out of the building. Here the basic evacuees would begin to evacuate after the 5 min action time, whereas the "following evacuees" would not start moving until seeing other evacuees' movement directions.

2 Methodology

Based on the literature review, (1) topography, (2) traffic congestion, and (3) human behaviour are identified as critical factors in the accuracy of an evacuation simulation. Therefore, the MSEM model outlined in (Fathianpour, Evans et al. 2023) was modified to reflect these factors. The effects of each improvement factor in the evacuation modelling are assessed based on the success rate. The evacuation success rate is evaluated through two aspects, (1) survival rate and (2) safe zone locations. The subsections describe the method used to consider each improvement factor, following how the success rate is evaluated. Napier City was chosen as the case study.

This study provides improvements to a micro-scale evacuation simulation model (MSEM) based on previous work (Fathianpour, Evans et al. 2023). The MESM model simulates different tsunami evacuation scenarios based on the traffic dynamics and the time required for individuals to reach a safe zone. The model was constructed through Python coding and the SUMO platform (Fathianpour, Evans et al. 2023). The SUMO platform provides an environment where vehicle and pedestrian movements can be modelled simultaneously within an agent-based model and has features for enabling dynamic route finding, visualisation, and agent to agent interactions.

By assigning a start points to agents and potential safe zone destinations, the model (using the selected a-star algorithm) calculates the which safe zone an agent should travel to and the optimum route the agent should take to reach that destination.

2.1 Topography

Moving uphill, requires more work by an individual and, therefore, would impede their maximum walking speed. Via the analysis of slope data in relation to the road network, we can define which edges within the network have steep gradients and adjust the speed of pedestrians, accordingly, referencing Tobler’s hiking function (Fig. 1) outlined in (Pingel 2010). Analysing topographical data of the region with respect to the transport network and utilising Tobler’s hiking function, a lookup table was generated (Table 1 that contains information that the revised MSEM can reference for modifying the speed of individuals traversing sloped sections of the network Fig. 1).

2.2 Traffic congestion

In this study, the simulation model was improved to suggest new routes for individuals, both vehicles and pedestrians, in the case facing traffic congestion. The Astar algorithm was used for route estimation, and the routing by effort function was defined in the model

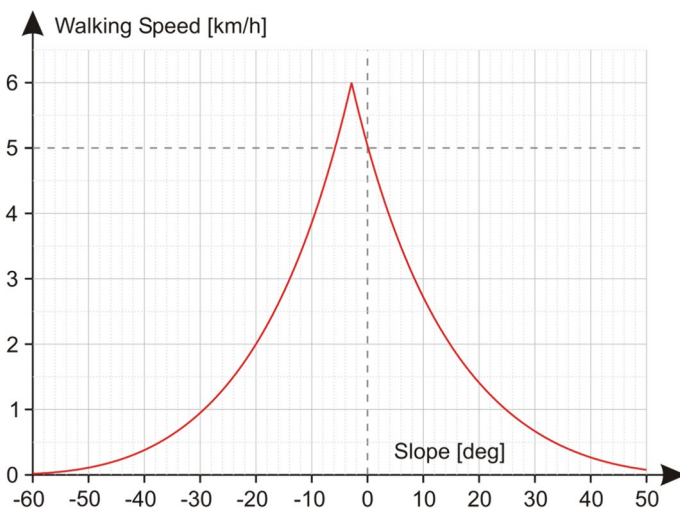


Fig. 1 Tobler hiking function chart

Table 1 Input slope data

| Slope ID | Lane ID | Edge ID | Slope (degree) | Tobler speed (m/s) | Speed Reduction (%) | Start position (m) | End position (m) |
|----------|------------------|----------------|----------------|--------------------|---------------------|--------------------|------------------|
| 0 | -109,372,871#0_0 | -109,372,871#0 | 1.163 | 4.691 | 0.069 | 0 | 48 |
| 1 | -109,372,871#0_0 | -109,372,871#0 | 1.163 | 4.691 | 0.069 | 48 | 76 |
| ... | ... | ... | ... | ... | ... | ... | ... |
| 11 | -117,598,111#3_0 | -117,598,111#3 | 0.699 | 4.826 | 0.042 | 0 | 160 |

to reroute vehicles if they are stuck in a traffic jam. The route by effort function simultaneously considers the travel time and distance to the destination. The distances to the destinations are calculated every 5 min, and new routes are estimated based on the traffic jam to have the least travel time to the destination (Krajzewicz, Erdmann et al. 2012).

2.3 Human behaviour

Previously the group behaviour impact of pedestrians in evacuation has been investigated by (Mayasari, Astuti et al. 2021). This study investigates the effect of group evacuation for vehicles by considering two evacuation choices when choosing to evacuate by car (Scenario 3 and 4).

2.4 Data analysis

The improved MSEM data results are compared to the baseline MSEM model developed by (Fathianpour, Evans et al. 2023). The considered critical factor is the survival rate. The city of Napier in New Zealand was chosen as a case study to assess the extent of enhancement contributed by each factor to the MSEM model.

2.5 Case study

A case study was chosen to evaluate the influence of environmental and human behaviour on an evacuation scenario. The case study selection criteria are listed in Table 2. Napier City was chosen as the case study based on the mentioned criteria.

Napier City has been chosen as the case study since it is vulnerable to various natural hazards such as liquefaction, earthquake, flooding, volcanoes, and tsunami (Taylor 2016). Napier City is a coastal city located in the eastern part of the North Island, New Zealand, situated geographically on 39 °28' 59" S latitude and 176 °55' 00" E longitude. Napier City is bounded by the north's main outfall channel and the Tutaekuri River in the south. The city's elevation is 57 m above sea level, and currently, the annual average precipitation is 879 mm. As Fig. 2d shows, a large area of Napier City is vulnerable to tsunamis.

2.5.1 Considered tsunami scenario

Based on the analysis provided by Fathianpour, Babaeian et al. (2022), the worst-case scenario for tsunami evacuation in New Zealand is the evacuation process after a Hikurangi

Table 2 Case study selection criteria

| | Case study selection criteria |
|---|--|
| 1 | Must be at a high risk of tsunami |
| 2 | Must have a central business district |
| 3 | Should have at least three suburbs involved in the tsunami evacuation zone |
| 4 | Preferably be located in New Zealand for data collection easement |

8.4M_w earthquake in Napier City, and Wellington City, New Zealand. The required time to evacuate from the buildings has been estimated based on the population density data and Sun and Sun (2019) experimental study. Based on the preprocessing data, the maximum action time has been identified to be 5 min. It is assumed that the usual traffic flow is already on the road while the earthquake starts, to make the simulation model realistic, pedestrians would evacuate after the shake has stopped and, due to the road obstacles (cars traffic), do not have the chance to travel through the street. Four scenarios have been developed based on the evacuation mean choice. (1) People evacuating from properties by foot, vehicles already on the road at 4 pm, rerouting to safe zones and travelling by car; (2) People evacuating from properties by foot, Vehicles already on the road at 4 pm: People exit vehicle and travel to the nearest safe zone by foot; (3) People evacuating from properties by car, Vehicles already on the road at 4 pm: Rerouting to safe zones and travelling by car. (4) People evacuating from properties by car, Vehicles already on the road at 4 pm: People exit vehicles and travel to the nearest safe zone by foot. Table 3 shows a summary of how the scenarios are defined.

The inclusion of topography primarily affects pedestrian movement, specifically in scenarios 1, 2, and 4. However, traffic congestion is a common factor across all scenarios as they all consider road traffic. The human behaviour function focuses on group evacuation. It should be noted that function is only investigating the effects of group evacuation when people prefer evacuating by car. Therefore, this function is only applicable to scenarios 3 and 4. To examine the effect of shared rides on overall survival rate, we compared scenarios with 1, 2, and 4 evacuees per car against the baseline scenario with 3 evacuees per car in previous models.

3 Results and findings

3.1 Topography

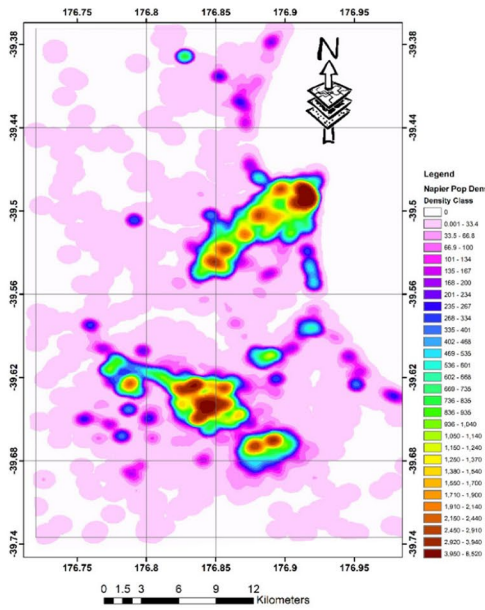
The influence of steep roads on walking speed is identified as the key impact of topography in this study. Therefore, the topography data on the evacuation process does not have an impact on scenario three, where evacuation on foot is not considered an option. However, Analysing the sloped simulations for scenarios 1, 2 and 4 highlights that considering the impact of steep routes can reduce the survival rate (Fig. 3). In scenario 1, the results shows that not considering slope impact can lead to a distortion in the perceived risk level, leading



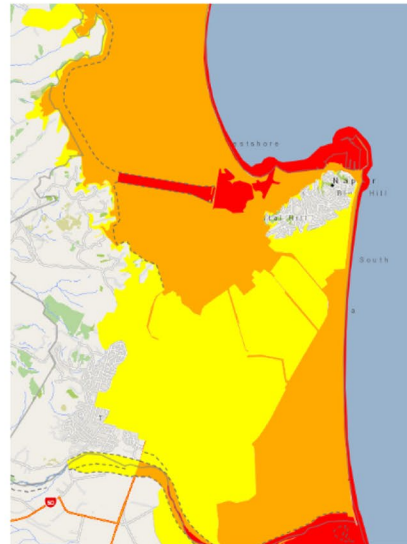
a



b



c



d

Fig. 2 Cas study location **a** country overview, **b** Napier City, **c** Population density map, **d** Tsunami evacuation map adapted from (Hawke's Bay Emergency Management 2021)

Table 3 Evacuation scenario description

| Scenario ID | Building resident evacuation method | Traffic on the road evacuation method |
|-------------|-------------------------------------|---------------------------------------|
| SC1 | Foot | Reroute/car |
| SC2 | Foot | Exit/walk |
| SC3 | Car | Reroute/car |
| SC4 | Car | Exit/walk |

to an inflation of survival rates by approximately 10%. Whereas in scenario 2 this value is more significant and reaches around 15%. However, scenario 4 which vehicular evacuation is the predominant mode, this discrepancy diminishes significantly to a mere 2%.

The results indicate that taking the slope factor into account results in difference in moving speed, highlighting the significance of considering the walking speed when planning for pedestrian evacuation.

3.2 Traffic congestion

Figure 5 shows an observable increase in the survival rate when allowing individuals to reroute to the next shortest path leading to the safe zone, thereby enhancing the realism of the simulation. However, the inclusion of the rerouting option introduces a degree of uncertainty in the results. The model randomly chose individuals to enter the simulation within a 2–5 min time frame. After the initial 5 min, everyone had exited the building and was heading to the safe zones. This random selection of evacuees entering the simulation is believed to introduce uncertainty into the final evacuation time. In order to address this issue, the researchers conducted a total of 80 runs of the model and observed that by the 65th run, the survival rate had reached a state of stabilisation within a range of 0.05 standard deviations from the mean (Fig. 4). The following results are therefore based on the averaged data obtained from these runs.

The results of the reroute function due to traffic congestion in the MSEM model are compared with the baseline model results. This function is only effective in scenarios 1, 3 and 4, (all except 2), since scenario 2 does not include car evacuation.

Figure 5 illustrates the improvement in the MSEM model's survival rate results achieved by this function. Evacuating by foot seems to give the highest percentage in terms of survival rates. The effects of rerouting to avoid congestion and improve survival rates seem to be more beneficial for vehicles than pedestrians. This is highlighted in particular with scenarios 3 and 4, where there are substantially more vehicles on the road due to people evacuating from properties by car.

In the first scenario, where most residents are expected to evacuate on foot, and the road traffic is relatively low, the results exhibit only minor variations. Whereas, in scenarios 3 (7%) and 4 (7%), the difference in the survival rate is tangible when considering this function. In scenario three, the continuous rerouting leads to an increase in traffic congestion and unsuccessful U-turns in the model. This emphasises the importance of avoiding the use of cars during evacuations and suggests that individuals should abandon their vehicles in the event of traffic to increase the chance of survival. The results of the reroute function in scenario four support this idea, as the survival rate is higher compared to scenario three. This can be attributed to a reduced number of evacuees travelling by car due to individuals

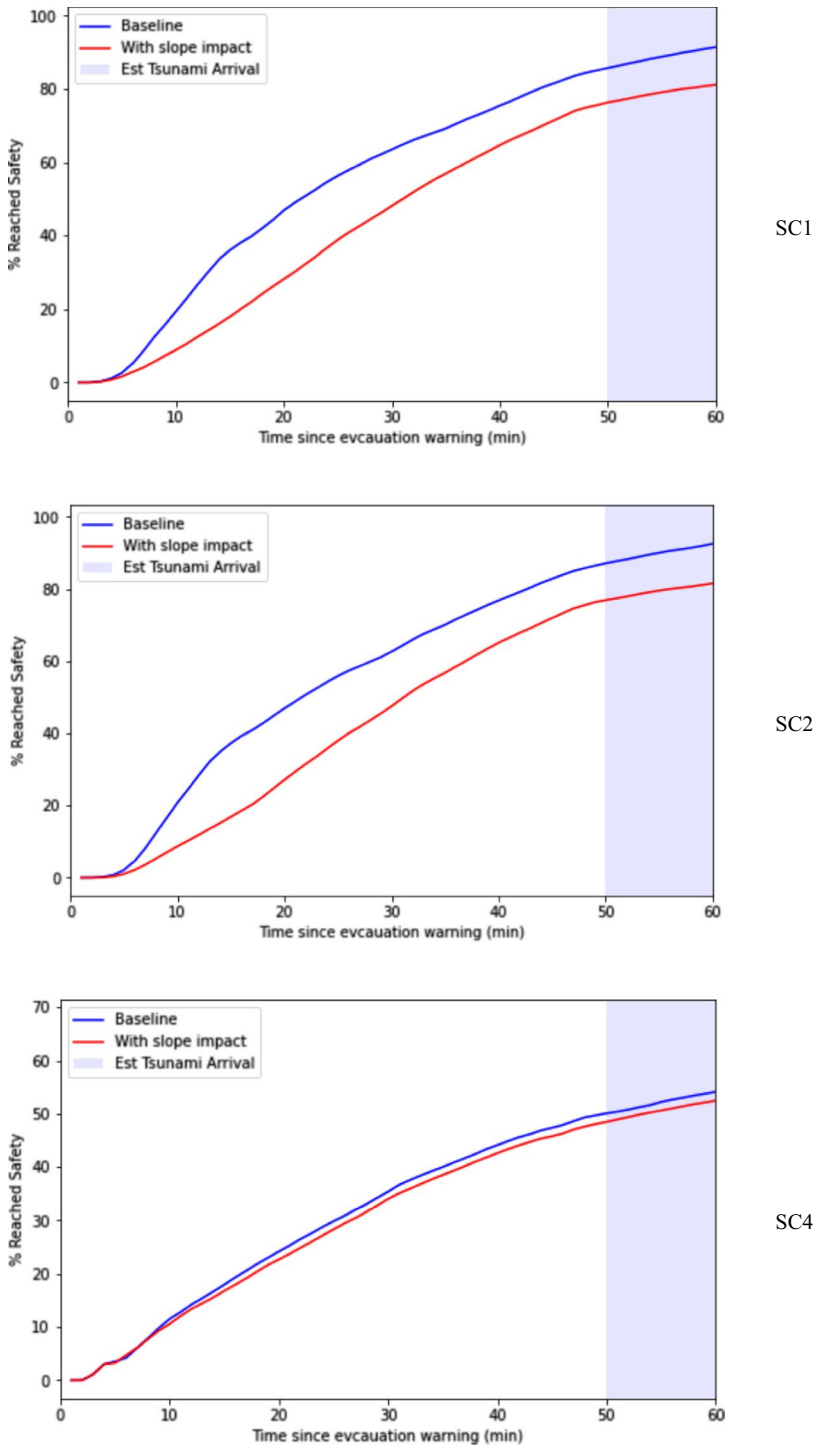


Fig. 3 Percentage of individuals at risk, the effects of steep roads

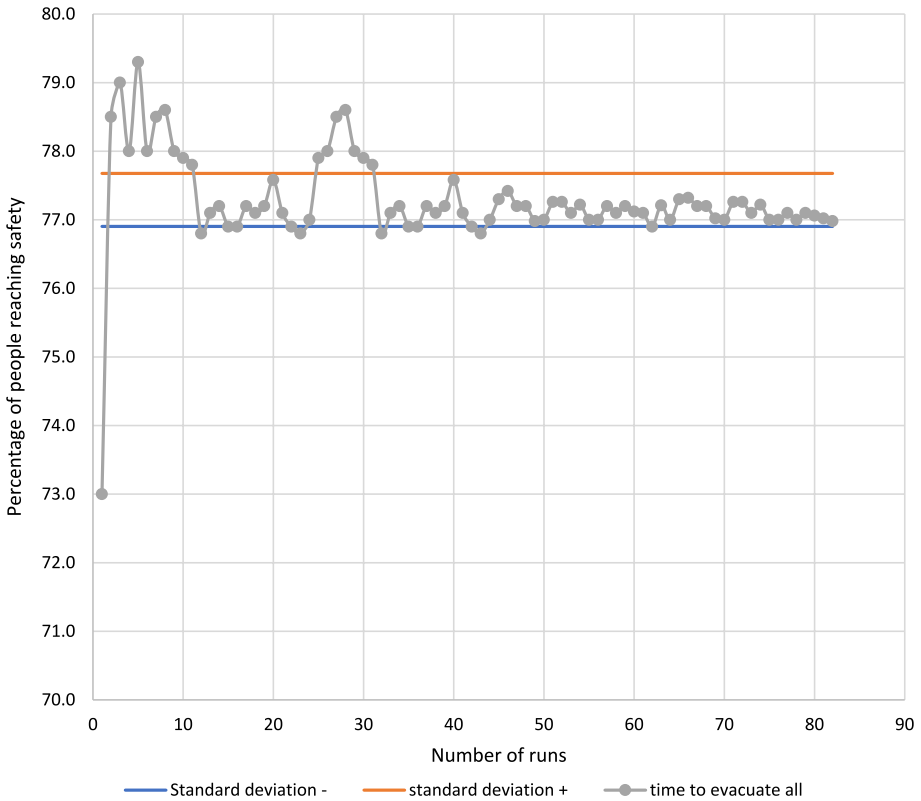


Fig. 4 Relationship between the number of simulation repetitions and time to evacuate 100% of the population in SC1

abandoning their vehicles on the road, which ultimately reduced traffic congestion during evacuation.

3.3 Human behaviour

Previously, for evacuation by vehicle MSEM model defined to allow a maximum of three people per vehicle. To analyse one aspect of human behaviour the MSEM was modified allow for either less or more (up to four) people per vehicle to see how the changes vehicle occupancy and number of vehicles on the road during the evacuation influences survival rates. The results of the model show that although the overall survival rate would increase when people evacuate in larger groups, this is not advisable for everyone.

While Fig. 6 demonstrates that increasing the number of passengers in each car would enhance the overall survival rate across all scenarios, Fig. 7 reveals that this enhancement is marginal for individuals destined for Hospital Hill. For instance, in scenario 3, having just 1 passenger in a car result in a mere 2.2% of evacuees bound for Hospital Hill reaching safety. Conversely, with cars at maximum passenger capacity, only 5.1% of individuals successfully reach Hospital Hill. As a result, this suggestion bears minimal influence on the

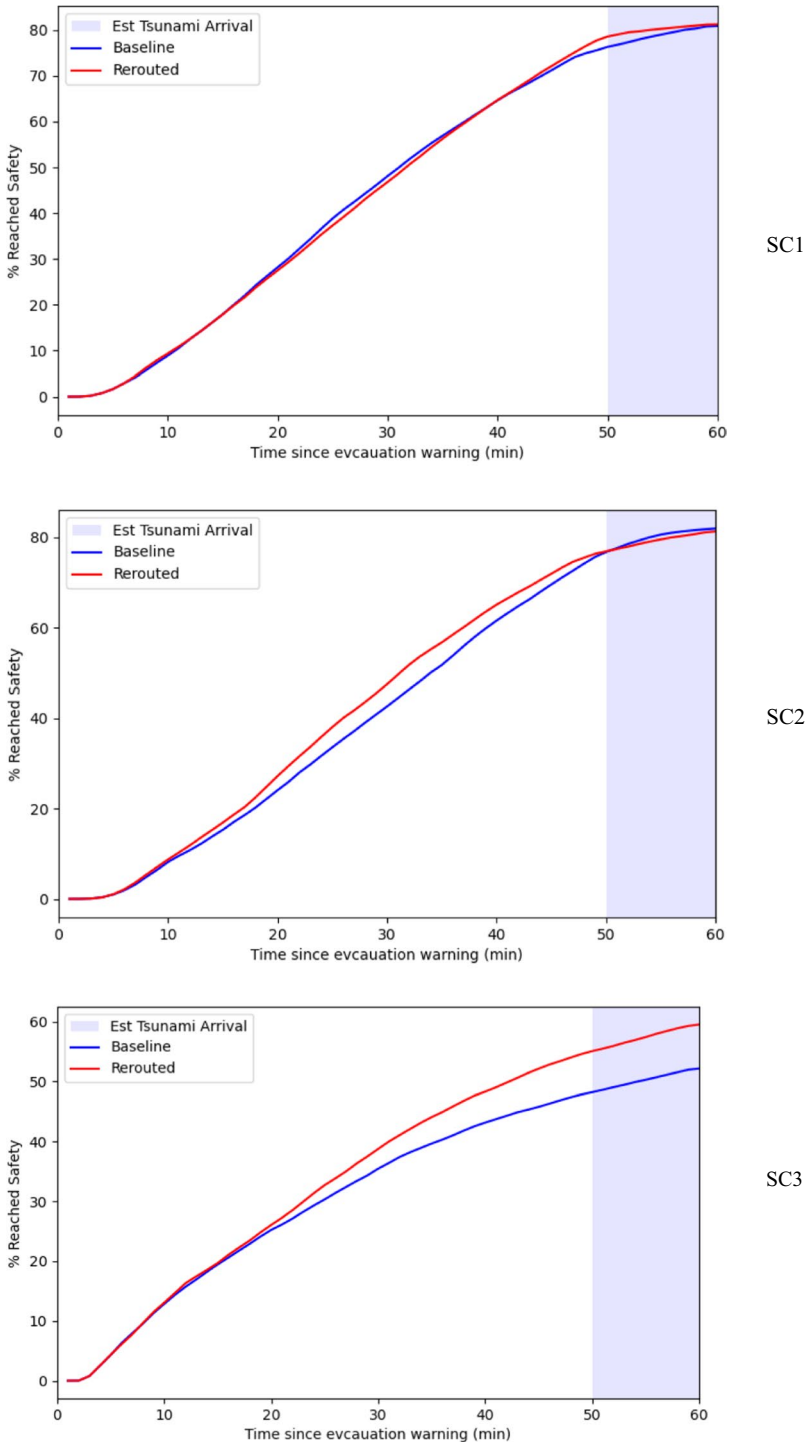


Fig. 5 Percentage of people reaching safety (comparing the results of evacuation model considering the traffic congestion and rerouting option)

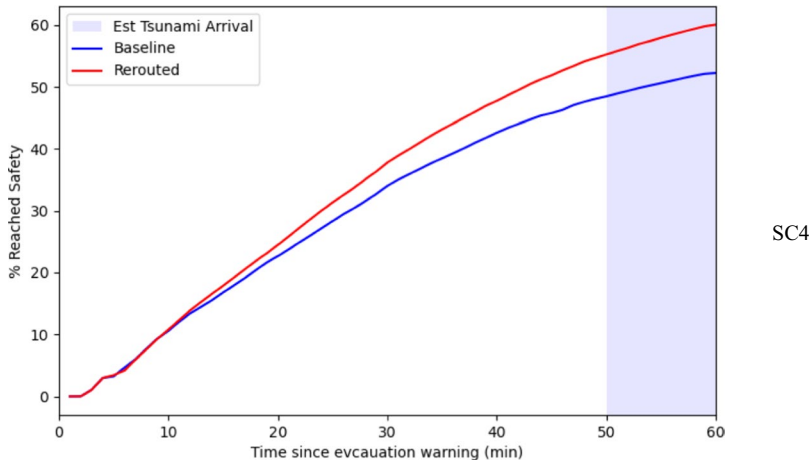


Fig. 5 (continued)

northern sector of Napier. Nevertheless, it remains a viable proposition for residents of the southern vicinity.

Although the number of evacuees heading to each zone is relatively equal, the limited effectiveness of evacuating individuals to Hospital Hill via car is primarily attributed to the significant traffic congestion in the area. This congestion is exacerbated by the fact that Hospital Hill has fewer access points (13) compared to the West Zone (18)(Fig. 8). Additionally, a substantial portion of evacuees tends to converge on the five access points located in the southeast area of the safe zone.

4 Discussion

This study has advanced the MSEM simulation model in order to be able to assess effectiveness of different behavioural strategies in evacuation planning with the MSEM simulation model and advise the requirement of interventions for future planning development.

Tsunami safe zones are evacuation destination since they are high enough to keep people safe from the tsunami wave and inundated surface. In order to get people from low-lying area to this high ground, they should pass a high-steep path. In tsunami evacuation where time is limited, the topography of the path plays a significant role (Pingel 2010). The evacuation modelling during the steep slope showed a significant reduction in the survival rate in travelling toward high grounds. The steadiness in the reduced amount in the results of considering different evacuation scenarios supports the fact that the MSEM model is correctly reporting the effects of the steep roads on the moving speed. Taking into account the impact of topography on survival rates, it becomes clear that locating a vertical safe zone near uphill edges would be highly beneficial. This approach would decrease the number of individuals required to ascend, resulting in an increase in survival rates (Zhang et al. 2019). Hsiao, Sun et al. (2021) examined the same initiative for evacuating people at risk of flash floods and identified that vertical evacuation/shelters are the best practice when considering it to accommodate elderly people. The location and capacity of the vertical

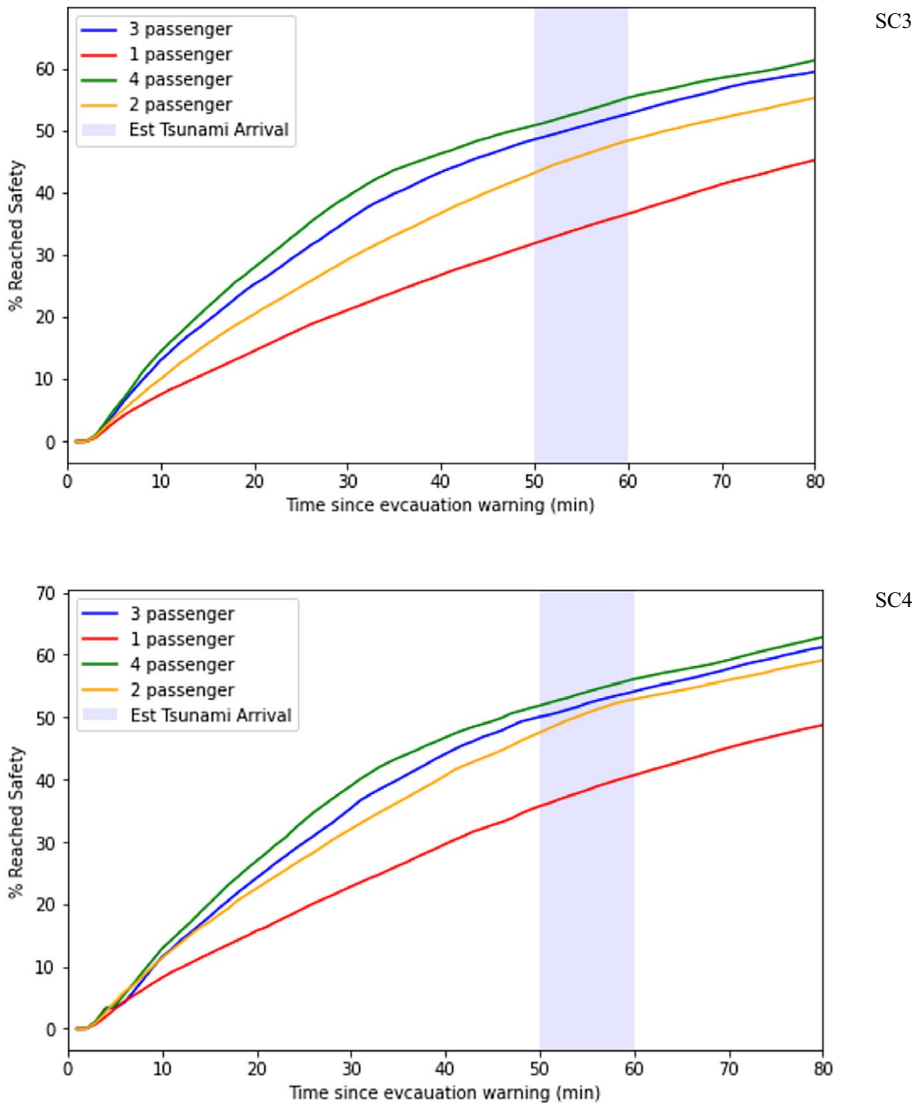


Fig. 6 Percentage of people reaching safety if they decide to drive as groups

evacuation should be evaluated based on the evacuation zone area's population density and distance to natural safe zones (Selkregg and Aufrecht 2014).

Heightened traffic conditions would exacerbate the challenges faced by individuals seeking safety during a mass evacuation. To delve deeper into this issue, we focus on peak-hour traffic, characterised by a high volume of vehicles on the streets, particularly during after-school pickups (Fathianpour, Babaeian et al. 2022). The results of the MSEM model indicated that if considering individuals tend to not stay in traffic and constantly try to change their route, would lead to more U-turn and road blockage and would worsen the situation. As mentioned in the result section, the advise on not to evacuate by car stays

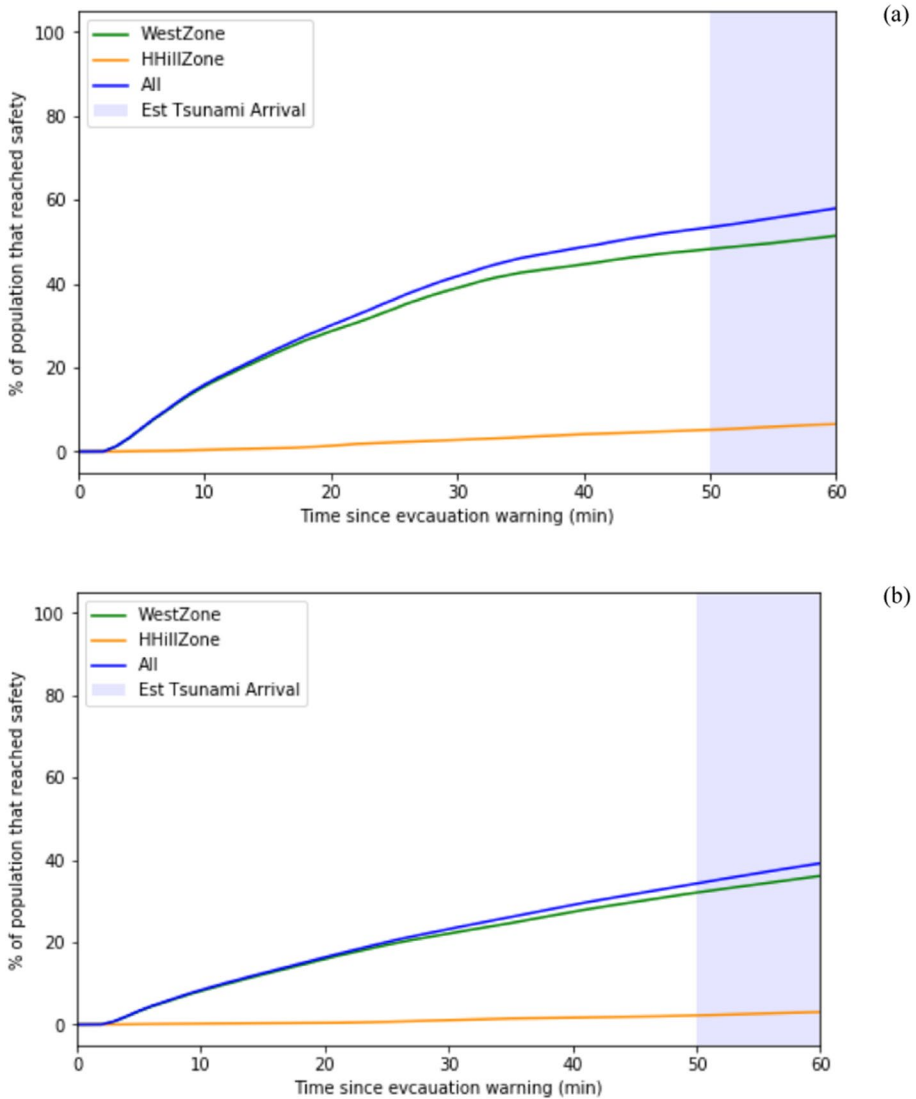


Fig. 7 Percentage of people reaching safety in scenario 3 while: **a** 4 passenger per car, **b** 1 passenger per car

relatively acceptable, especially when (Pingel 2010) considering other behaviour activity such as accidents, people leaving their car to continue the way to safety on foot (Takabatake et al. 2020a, b), and complexity in tsunami evacuation such as damaged roads (Takabatake, Chenxi et al. 2022). The general recommendation would be to evacuate by foot instead of utilising a vehicle where it is possible.

It is always advised to consider accommodating as many individuals as possible within a vehicle to reduce the traffic congestion (Agatz et al. 2012). Based on this advice, most individuals seek to evacuate with their loved ones. This approach in normal situations would help alleviate traffic congestion and facilitate the maximum number of people reaching

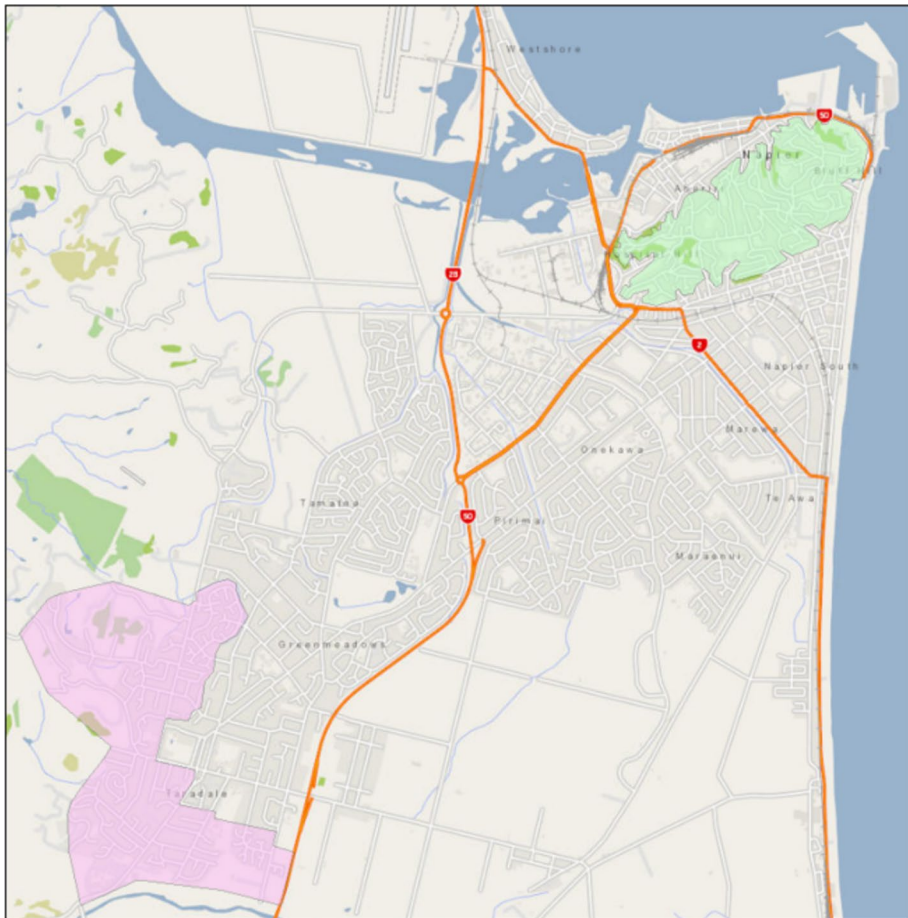


Fig. 8 Safe zone access point analysis: Hospital hill in green, and West zone in pink

safety within a specified time period. However, it is essential to note that this consideration would lead to an additional delay time as a result of an increased number of stops or boarding time in an mass evacuation scenario. In many cases, evacuating with numerous vehicles can result in individuals abandoning their cars in traffic jams, effectively turning them into obstacles on the road (Takabatake et al. 2020a, b). The result of the MSEM model highlights the fact that there should be different strategic planning suggestions in different suburbs. The findings indicated that despite cars being fully occupied, the enhancement in survival rates is modest for individuals heading to Hospital Hill, whereas it registers an increase for those destined for the West Zone. These findings imply that under certain circumstances, car evacuation may not be effective due to high traffic congestion. Likewise, Zhang et al. (2019) has confirmed that a successful evacuation plan must be planned based on the detailed circumstances. therefore, based on the MSEM result, different interventions are required for different suburbs in evacuation planning.

5 Conclusion

The results of this study has stretched the knowledge as an improved model and also has provided practical advised.

5.1 Theoretical implications

Local tsunamis are more destructive and cause a higher number of fatalities since they come on short notice, making evacuation planning more complex. Evacuation simulation has shown to be a useful tool to provide insight into the decision-making process. This study has advanced an evacuation simulation model (MSEM model), previously developed by the authors of this study and used it to evaluate the efficiency of some evacuation behaviour and characteristics. The MSEM was improved to produce a more accurate model. The MSEM model showed the effects of (1) the spatial feature of the area, (2) drivers rushing to find a faster route, and (3) additional passengers in each car on the evacuation survival rate.

5.2 Practical implications

Based on the results represented in this paper, there is a strong message to people to ignore using cars for tsunami evacuations unless they are not able to evacuate on foot. In addition, the message to decision-makers is to consider vertical evacuation for certain areas as people would not be able to reach high ground in the short notice time. Deliberating on evacuation routes and understanding the topography crucial for safe passage further underscores the need for decision-makers to provide support for individuals navigating high and steep routes to safety.

5.3 Limitation and future study

Given that local tsunamis typically follow earthquakes, it's probable that roads could be obstructed by debris or damaged by seismic activity, rendering the anticipated evacuation routes impassable. Another promising area for research entails integrating these potential route blockages into evacuation planning. This could involve developing a dynamic model capable of rerouting evacuees in real-time as they encounter road obstructions.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Azin Fathianpour and reviewed by Barry Evans. Azin Fathianpour wrote the first draft of the manuscript, and all authors commented on previous versions of the manuscript.

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Declarations

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