10 Building Urban Resilience for Coastal Urban Communities: The Surprise of Tsunamis with Consideration of Human Factors

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Tsunamis: Unpredictable and Devastating Forces of Nature

Tsunamis are wild cards, often referred to as "tidal waves," are natural disasters of unparalleled destructive power (Fathianpour, Evans et al. 2023b). These massive waves have the potential to cause significant destruction along coastal areas, leaving behind a trail of devastation, injuries, and fatalities. Understanding the dynamics and impact of tsunamis is crucial for disaster preparedness and response. In this section, we delve into the destructive effects of tsunamis on human life and property, drawing from historical data to underscore the severity of these events (Couling 2014).

Tsunamis come in two primary forms: distant and local. Distant tsunamis are typically triggered by earthquakes occurring thousands of kilometres away from the coastline. These waves traverse vast ocean expanses, taking several hours to reach coastal areas (IBAWORLDTOUR 2023). For instance, as shown in Figure 10.1, the tsunami triggered by the 1960 Chilean earthquake took approximately 12 hours to reach New Zealand's east coast, 14 hours to reach Hawaii, 15 hours to reach Australia's south-east coast, and over 20 hours to reach Japan and Asia. While they may lose some energy during their journey, distant tsunamis are still formidable in scale. When they finally make landfall, they can inflict substantial damage and casualties, though to a lesser extent compared to their initial force (Chacon-Barrantes & Arozarena-Llopis 2021, Fathianpour, Wilkinson et al. 2023b).

Conversely, local tsunamis are born from events much closer to the coast, within a few hundred kilometres (Fraser et al. 2014). These tsunamis can strike with little warning, arriving at the shore within minutes of their inception (Zaki 2017). For instance, a tsunami generated by an earthquake from the Hikurangi subduction zone can reach the coast in just 7 minutes (Figure 10.2). The proximity of their source magnifies their destructive potential, resulting in significant harm and damage to immediate coastal areas (Chacon-Barrantes & Arozarena-Llopis 2021; Fathianpour, Wilkinson et al. 2023b).

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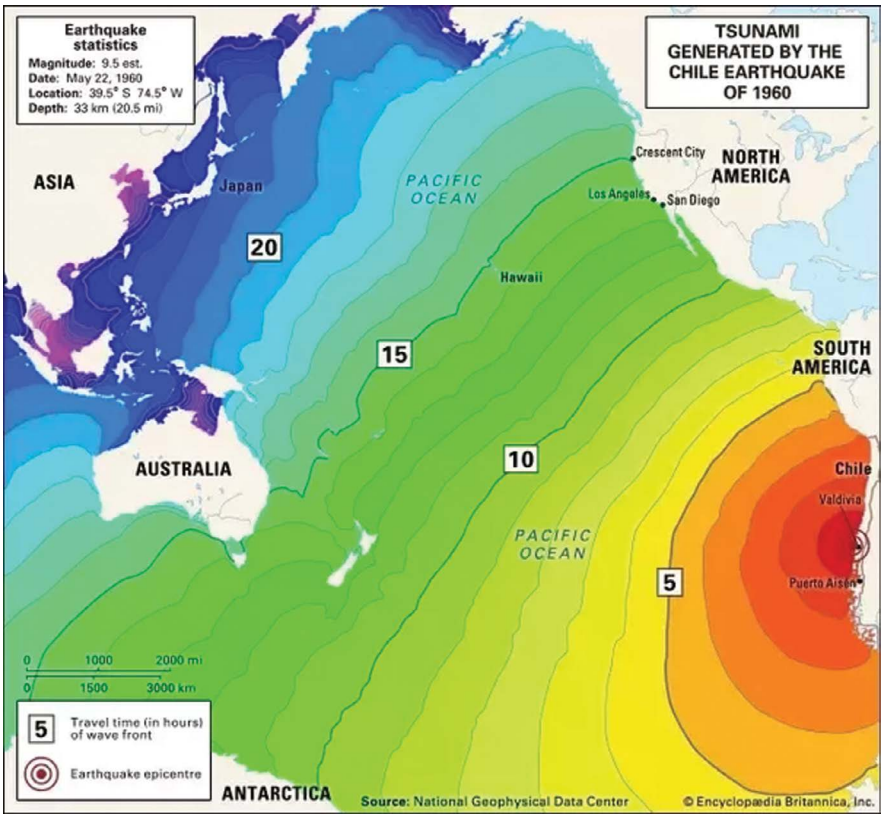

Figure 10.1 Distant tsunami arrival time, adapted from News5 2021.

Impact of Tsunamis on Human and Built Environment

Assessing the impact of local tsunamis can be particularly challenging. Unlike distant tsunamis, where damage and casualties are often distributed across vast areas, local tsunamis often strike with a devastating blow in a concentrated region (Darienzo et al. 2005). This concentration of destruction can make it challenging to separate casualties and damages based on the events that caused them, especially when the earthquake's epicentre is near the coast. In such cases, the immediate casualties associated with the earthquake and the subsequent tsunami may be reported as a single figure (Fathianpour, Wilkinson et al. 2023b).

Tsunamis are characterised by their low probability but high impact. These unpredictable giants of the sea can obliterate entire coastal communities, resulting in widespread injuries and fatalities (Takabatake et al. 2018). The energy carried by a tsunami wave is so immense that it can destabilise individuals, causing them to fall and hindering their escape to safety (Imamura et al. 2012). The consequences can be dire, with injuries and death being potential outcomes. Historically, there have been numerous tsunami events associated with severe casualties.

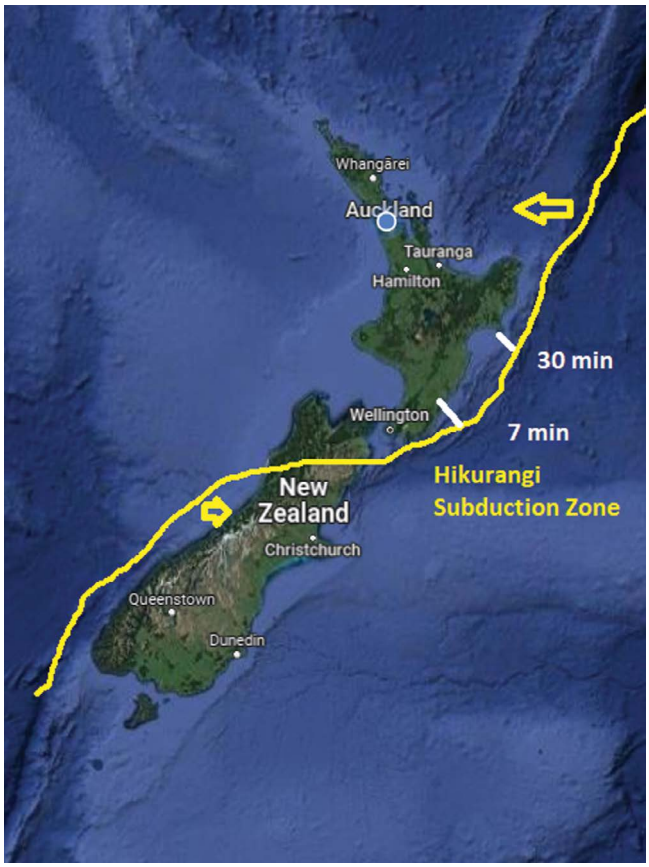

Figure 10.2 Local tsunami travel time, generated by the author

Figure 10.3 shows the tsunami distribution across the globe. The data represents the tsunami source, severity, and death toll (NCEI n.d; Gusiakov 2020).

One of the most devastating tsunamis in recent history occurred in December 2004 when the Sumatra–Andaman earthquake triggered a massive tsunami in the Indian Ocean. This catastrophic event resulted in a staggering 227,899 reported deaths or missing individuals (Gusiakov et al. 2019). Similarly, the Tohoku earthquake and tsunami that struck Japan in 2011 left a grim legacy, with 18,487 recorded deaths, 6,157 injured, and 2,594 people reported as missing (Murata et al. 2018). These tragic statistics serve as stark reminders of the destructive power of tsunamis (Fathianpour, Wilkinson et al. 2023b).

In light of the historical data and the profound impact of tsunamis on human life and the built environment, it is evident that proactive measures are essential to mitigate the devastating consequences of these natural disasters (Suppasri et al. 2013; Reid & Mooney 2023). In the following section, we will explore strategies and methodologies for reducing the risk posed by tsunamis and enhancing urban resilience.

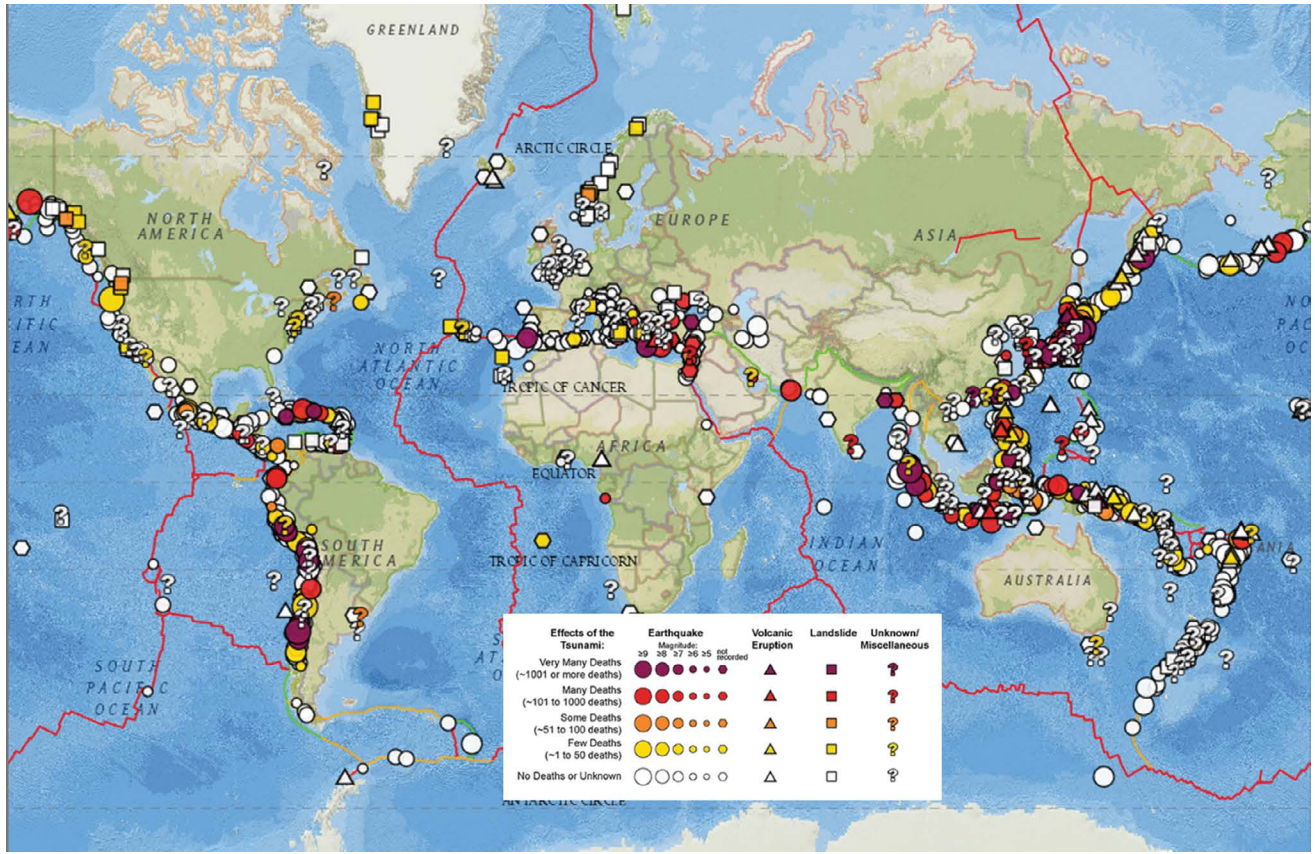

Figure 10.3 Historic tsunami, data adapted from NCEI n.d.

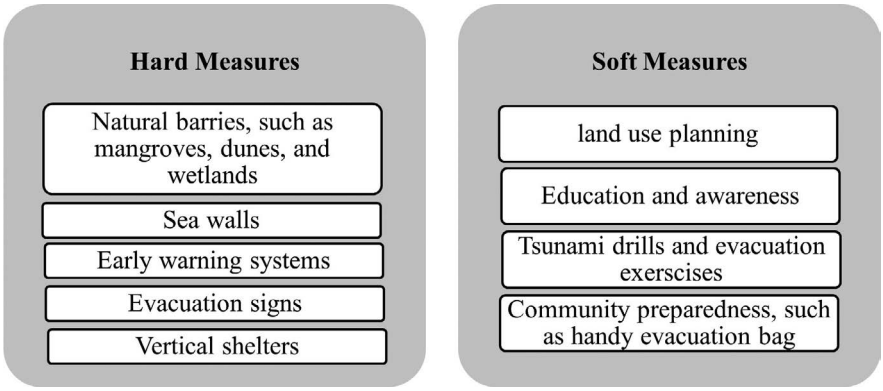

Figure 10.4 Tsunami risk reduction measures

Tsunami Risk Reduction Approaches

The heightened risk of tsunamis to both human lives and the built environment is compounded by the short notice time associated with local tsunamis. Nevertheless, a well-crafted risk reduction and preparedness strategy has the potential to significantly mitigate the threat to people and the built environment. In recent decades, practitioners and stakeholders have shown more interest in collaborating and enhancing their urban resiliency toward tsunamis (Fathianpour & Wilkinson 2023).

Diverse risk mitigation measures have been identified worldwide. As shown in Figure 10.4, two categories of risk reduction approaches have emerged to mitigate the impact of tsunamis: hard measures and soft measures (Takabatake et al. 2020). The former involves physical infrastructure and technology, such as natural barriers, sea walls (Nateghi et al. 2016), early warning systems (Teshirogi et al. 2009), evacuation signs (Lonergan et al. 2015), and vertical shelters (Mayasari et al. 2021). In contrast, the latter encompasses strategies that focus on education (Dengler 2005), awareness and community preparedness, including land use planning and tsunami drills (Dhellemmes et al. 2016).

Challenges in Tsunami Emergency Planning

Planning for tsunamis has always been a formidable task for decision-makers, particularly regarding local tsunamis with their short notice times (Fathianpour & Wilkinson 2023a). The challenge in tsunami risk reduction lies in assessing the effectiveness of each measure and determining the most optimal solution (Anggraini & Koestoer 2023).

However, it's important to note that no single measure can be considered a silver bullet solution. Tsunamis, renowned for their devastating force and sudden onset, necessitate a comprehensive and balanced approach that leverages both hard and soft measures to mitigate their impact effectively.

The risk reduction methods are discussed in this section and a summary is provided in Table 10.1. These measures are classified as hard and soft measures and cover a range from creating natural barriers to safety drills; in addition, the strength and limitations of each measure is included. In coastal risk reduction, natural barriers like mangroves and wetlands provide sustainable protection by absorbing wave energy and ecological benefits like habitat preservation and carbon sequestration

Table 10.1 Strengths and limitations of risk reduction measures

Measure	*Strengths*	*Limitations*
Hard Measures		
Natural Barriers	Sustainable and self-maintaining	Not present or effective in all coastal areas
	Offers ecological benefits	Takes time to establish and mature
		Requires protection and preservation efforts
Sea Walls	Provides immediate protection	Expensive to build and maintain
	Can prevent inundation and erosion	May disrupt natural coastal processes
	Relatively low-maintenance	Attracts more people to live on coast, subsequently increasing the number of people exposed to a higher tsunami wave height
Early Warning Systems	Provides advance notice for evacuation	Relies on efficient communication and response
	Utilises advanced technology	False alarms or system failures can erode trust
Evacuation Signs	Cost-effective and easy to implement	Alone, insufficient without education efforts
	Provides visual guidance	
Vertical Shelters	Can be located in dense populations and low access to natural safe zones	High cost to build or even certify
		Poses reliability for emergency management teams
Soft Measures		
Land Use Planning	Reduces exposure to tsunamis	Implementation and enforcement challenges
	Minimises construction in high-risk zones	Balancing development needs with risk reduction
	Saves lives and reduces property damage	Potential conflicts with stakeholders
Public Education & Awareness	Fosters a culture of preparedness	Maintaining interest and engagement can be hard
	Educates communities on tsunami risks	Overcoming language and cultural barriers
	Increases public awareness	
Tsunami Drills & Exercises	Familiarises communities with evacuation routes	Requires resources and coordination
	Identifies and addresses weaknesses in plans	May not involve all community members

(Osti et al. 2009). However, their effectiveness depends on their presence and maturity, limiting their applicability (Tanaka et al. 2011). Engineered sea walls offer immediate defence against tsunamis but come with substantial construction and maintenance costs and potential disruptions to natural coastal processes. Also, *sea walls* can inadvertently foster overconfidence and encourage more people to settle along the coast, which, in turn, amplifies the risk when faced with a tsunami of greater magnitude (Parady et al. 2019).

Early warning systems are crucial for timely evacuation, yet their success requires efficient communication and maintenance to avoid eroding public trust due to false alarms. Evacuation signs, while cost-effective, depend on integrated education efforts to convey their significance effectively to all individuals. Vertical shelters are strongly advisable for vulnerable populations, such as the elderly and children, who may have difficulty evacuating to natural safe zones or for cities which do not have easy access to natural high ground (Wood et al. 2014). They also offer a cost-effective solution when strategically placed in densely populated areas. Nevertheless, although they have been embraced by residents and implemented in various cities as their preferred choice (McCaughey et al. 2017), a noteworthy drawback arises from the reluctance of local officials to formally designate specific structures as safe zones, frequently citing concerns regarding their dependability (Fathianpour, Wilkinson et al. 2023a).

On the other hand, *land use planning* is a critical soft measure that effectively reduces community exposure to tsunami risks by limiting development in high-risk coastal areas, thereby saving lives and reducing property damage. Nevertheless, its implementation and enforcement can be challenging due to political, economic, and social factors, highlighting the need to balance development needs and risk reduction goals (Puppim de Oliveira & Fra.Paleo 2016). Public education and awareness campaigns play a pivotal role in fostering a culture of preparedness, educating communities about tsunami risks, and increasing awareness, empowering individuals to make informed decisions during a tsunami event (Bandecchi et al. 2019). Also, tsunami risk awareness practice needs to be carried out by emergency management practitioners. Wehrle et al. (2022) introduced a tool called "serious games" designed to create a controlled and structured platform for meaningful discussions among decision-makers. Serious gaming is recognised as a valuable research instrument that enhances stakeholders' *situational awareness*, thereby contributing to enhancing infrastructure resilience and its evaluation (Table 10.1).

However, maintaining public interest and engagement can be challenging, particularly among tourists from regions with rare tsunami occurrences and those from foreign-language-speaking countries. This underscores the need for concerted endeavours to surmount language and cultural barriers to achieve effective outreach (Nguyen et al. 2018). *Tsunami drills and evacuation exercises* offer practical training, familiarising communities with evacuation routes and procedures, ultimately reducing panic and confusion during actual events while enabling the identification and rectification of response plan weaknesses (Chen et al. 2022) (Table 10.1).

It is clear that each of these tsunami risk reduction measures has its own merits and limitations, emphasising the importance of a multifaceted approach (Takabatake et al. 2020). Natural barriers, sea walls, early warning systems, and evacuation

signs all offer valuable contributions to mitigating tsunami risks, but none can single-handedly provide comprehensive protection. With their destructive power and unpredictable nature, tsunamis necessitate a strategic amalgamation of hard and soft measures to minimise their impact effectively. Only a well-managed, integrated plan can harness the strengths of these measures while mitigating their respective limitations (Alexander 2002). Furthermore, a resilient city necessitates a risk reduction strategy and demands a pragmatic response plan (Table 10.1).

The response plans for tsunamis vary depending on the distance between the earthquake's epicentre and the coastline. In cases of local tsunami risk, immediate evacuation is typically recommended as the primary response. New Zealand recommends local tsunamis as soon as you feel a long and strong earthquake, wait for the shake to be over, and then evacuate to the high ground or far inland (HBEM 2021).

The evacuation plan should be evaluated to assess its practicality and identify potential risks. A valuable approach for evaluating evacuation plans, including identifying potential enhancements and making optimal recommendations, is through the use of simulations (Takabatake et al. 2020; Fathianpour, Babaeian Jelodar et al. 2023). The simulation of the evacuation process depends on various factors (Aguilar et al. 2019). To ensure evidence-based results, it is essential to quantify and prepare the relevant factors as input data (Fathianpour & Wilkinson 2023).

Effective Factors in Evacuation Processes

Various factors, such as individual reactions, risk perception, and response stages, significantly influence how people respond when faced with the threat of a disaster like a tsunami. The success of evacuation plans hinges on accurately representing these behavioural attributes in simulation models. Data on how people recognise risks, their actions, and their movement patterns during evacuations is essential for developing effective emergency response strategies (Arce et al. 2017).

Numerous studies have explored the multifaceted nature of human reactions during the onset of an impending tsunami. When people face a disaster like a tsunami, their reactions can vary significantly. How each person typically behaves and responds in such situations influences these variations. People do not all react the same way when confronted with a disaster; their responses can differ. Their characteristics and behaviours influence these responses and the specific circumstances at the time disaster strikes (Yasufuku et al. 2017; Yamato et al. 2019).

Makinoshima et al. (2020) have systematically categorised these behaviours into four stages: risk recognition, response activity, evacuation movement, and additional activity and evacuation stages. An essential element in understanding these responses is how individuals process information during the early notification stages of evacuation. Diverse backgrounds and psychological predispositions contribute to different perceptions of tsunami risk. Even when residents share a similar level of awareness, they make distinct choices concerning evacuation. The level of risk awareness, often shaped by the reception of risk education and information, significantly impacts individuals' evacuation behaviour. Recent tsunami evacuation management practice emphasises the crucial role of community leadership in assisting residents during evacuations (Payne et al. 2020). Unfortunately,

tourists, who may lack local knowledge and understanding of warning signs, are often overlooked in evacuation planning. Tourists can be more vulnerable to disaster events than permanent residents due to their unfamiliarity with the area and limited access to information (Fathianpour, Wilkinson et al. 2023b).

Additionally, the influence of group behaviour, as noted by Harnantyari et al. (2020), is substantial; high awareness among residents, coupled with witnessing others evacuate, has proven instrumental in saving lives during past tsunami events. Overall, Fathianpour and Wilkinson (2023) state that the behavioural factors in the evacuation process can be summarised as:

> (1) resident reaction time, (2) resident moving time, (3) tsunami awareness, (4) provided evacuation training, (5) time of day the tsunami occurs, (6) the preferred mode of evacuation, (7) the possibility of rerouting to pick up children or elderly relatives, (8) motivation to evacuate, (9) seek help from their family and friends, (10) confusion in choices, (11) risk of disorientation.

Their research can be used to categorise the behavioural attributes in tsunami evacuation (Figure 10.5).

The time it takes to react and move swiftly becomes crucial in local tsunami evacuations due to the short notice provided before the tsunami wave arrives. Individuals must recognise that a delay in taking action may result in an inability to reach safety on time. Therefore, the ability to recognise the signs indicating the necessity for evacuation becomes important (Fathianpour & Wilkinson 2023), with witnessing others evacuate being a highly effective trigger that reduces disorientation and enhances overall survival rates (Payne et al. 2020), corroborated by Harnantyari et al. 2020.

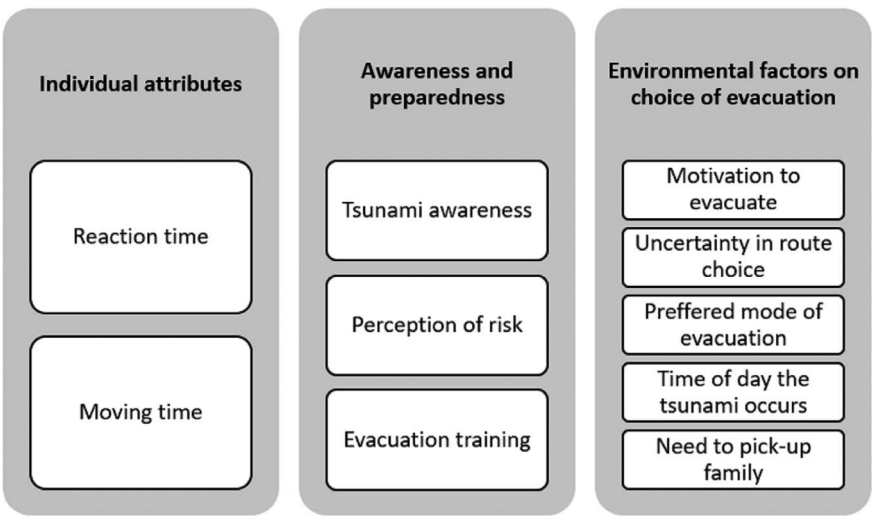

Figure 10.5 Effective factors in evacuation processes

Although tsunami awareness and evacuation training are known to reduce the risk of disorientation (Wachtel et al. 2021), real-life situations following an earthquake often lead to less predictable responses due to overwhelming emotions, consistent with findings by Wei et al. (2017). Nevertheless, it is essential to maintain and sustain training and awareness programmes, as they serve as vital instruments in consistently fostering a heightened perception of tsunami risk and encouraging individuals to evacuate. Additionally, these training programmes can catalyse individuals to select the most appropriate evacuation mode (Fathianpour & Wilkinson 2023).

The timing of a tsunami event is another significant factor, as it varies based on individuals' locations, affecting their decision-making and the visibility of evacuation route signs. Ensuring the visibility and comprehensibility of route signs is crucial. Evacuation route signage should utilise non-linguistic symbols and graphics, considering that tourists and foreigners may not be fluent in the country's native language. During daytime, when people are at work or school, there may be a tendency to detour to pick up family members, potentially delaying evacuation. Conversely, at nighttime, when people are sleeping, the level of consciousness to make an evacuation choice diminishes, further compounded by reduced visibility of evacuation route signs, potentially leading to individuals getting lost even if they attempt to evacuate (Lonergan et al. 2015).

Evacuation Simulation: A Decision-Making Tool

In recent years, there has been notable progress in developing various evacuation models designed to simulate evacuation processes during emergencies. *Evacuation simulation models* are primarily categorised into three main types: microscopic, mesoscopic, and macroscopic. Microscopic models excel in simulating individual interactions among agents, making them suitable for capturing detailed behaviours, such as pedestrians' route choices and varying walking speeds. Mesoscopic models, which yield simulation results based on gridded areas, are less frequently used for large-scale evacuations due to diminished accuracy as the size and density increase. In these models, areas are divided into cubic sections connected by nodes. These models primarily focus on tracking changes within the grid cells rather than the movement of individual agents. The accuracy of the model decreases depending on the grid size and scale. Macroscopic models, on the other hand, focus on crowd movement density but lack the granularity of microscopic models.

Hybrid models, like Pathfinder and Exodus, do not neatly fit into these categories; they combine elements of both microscopic and macroscopic approaches, offering a broader perspective. In urban-scale evacuation simulations, diverse models are available, each with unique assumptions and methodologies. These models necessitate geospatial network data, routing information, and behavioural conditions to simulate evacuation scenarios effectively. Moreover, the evacuation models need to be specialised for tsunamis, as most existing models are geared toward fire evacuation, with tsunamis requiring different considerations, such as reaching high ground. Table 10.2 summarises the reviewed evacuation simulation models used in tsunami evacuation planning.

Table 10.2 Reviewed evacuation simulation models used for tsunami evacuation planning

Evacuation Simulation Model	*Characteristics*	*Modelled Entities*	*Reference*
Cellular automaton	Microscopic model with discrete elements.	Pedestrian	(Kirchner & Schadschneider 2002; Vranken et al. 2021)
Agent-based	Microscopic model simulating individual agents with various characteristics	Pedestrian, Vehicles	(Chen & Zhan 2008; Lumbroso & Tagg 2011; Nakanishi et al. 2020)
Social force	Microscopic model considering social forces and interactions	Pedestrian, vehicles	(Makinoshima et al. 2018; Zhang & Fu 2022)
MSEM	Micro-simulation, continuous in time and space	Pedestrian and cars simultaneously	(Fathianpour, Evans et al. 2023b)
Pathfinder	Hybrid model combining microscopic and macroscopic elements – not on urban-scale	Pedestrian, vehicles	(Guo et al. 2022)
Exodus	Hybrid model incorporating rule-velocity- and acceleration-based approaches	Pedestrian, vehicles	(Filippidis et al. 2020)
SUMO	Microscale simulation of evacuation processes considering pedestrians and cars	Pedestrian, vehicles	(Lopez et al. 2018)
Particle swarm optimisation	Microscopic model, focuses on pedestrian movement	Pedestrian	(Izquierdo et al. 2009)
Fluid dynamic	Macroscopic models, where large-crowd group movements are modelled with non-linear partial differential equations – no interactions between agents considered	Any type of agent	(Hughes 2003)
Queuing models	Macroscopic model, based on representing the movement of pedestrians as a flow on a geometry graph	Pedestrian	(MacGregor Smith 1991)

These evacuation models can function as an evacuation time predictor, providing information on the time it takes for individuals to reach safety, the path they would take, and their ultimate destination. However, few models are designed to provide input on multiple purposes, such as evaluating the effectiveness of existing transportation networks, informing strategic resource allocation for long-term infrastructure upgrades to bolster a city's resilience against tsunamis, and preparing for catastrophic scenarios. Furthermore, these models prove invaluable in assisting decision-makers by providing insights into formulating more efficient evacuation plans drafted for emergencies. Therefore, the next step is to translate the simulation data into evidence-driven recommendations.

MSEM: A Simulation Platform for Mass Evacuation

Among all evacuation models mentioned above, the Micro-Simulation Evacuation Model (MSEM) is a sophisticated tool designed to simulate and analyse the evacuation process during emergencies, with a particular focus on tsunamis where immediate mass evacuation is required. Developed using Python and integrated into the SUMO platform, MSEM operates on an agent-based model, treating individuals as autonomous agents with distinct characteristics and behaviours. This unique approach provides a comprehensive understanding of how people react and make decisions during evacuations, making MSEM an invaluable asset in disaster preparedness and response efforts.

MSEM utilises various input data to initiate simulations and make informed assessments. The primary input data include geospatial information, encompassing details of the physical environment, such as road networks, buildings, hazard zones, and safe zone locations. This spatial data is fundamental for creating a realistic simulation environment. Additionally, MSEM incorporates individual attributes of evacuees, including mobility, familiarity with the environment, and specific behavioural parameters. This data enables MSEM to simulate how different individuals respond to evacuation scenarios. This event-specific data, such as the time the evacuation triggering event (e.g., an earthquake) occurs, serves as the basis for initiating the simulation and assessing the time-sensitive nature of the evacuation. Another specific aspect of MSEM is that it simultaneously considers pedestrian and vehicular evacuation by considering the interactions between pedestrians and cars.

Therefore, the normal traffic on the road at the time of the evacuation is critical input data into the model. Furthermore, MSEM acknowledges the influence of the topography. This is particularly relevant because safe zones are predominantly situated in elevated areas, and the varying road slopes can impact the speed at which individuals move during evacuations. MSEM can also incorporate behavioural aspects of individuals, including group evacuations, passenger load per vehicle, and rerouting options during high traffic congestion. Figure 10.6 is an example of required input data used to assess the resiliency of the Napier City evacuation plan using MSEM (Fathianpour, Evans et al. 2023a; 2023b; 2023c).

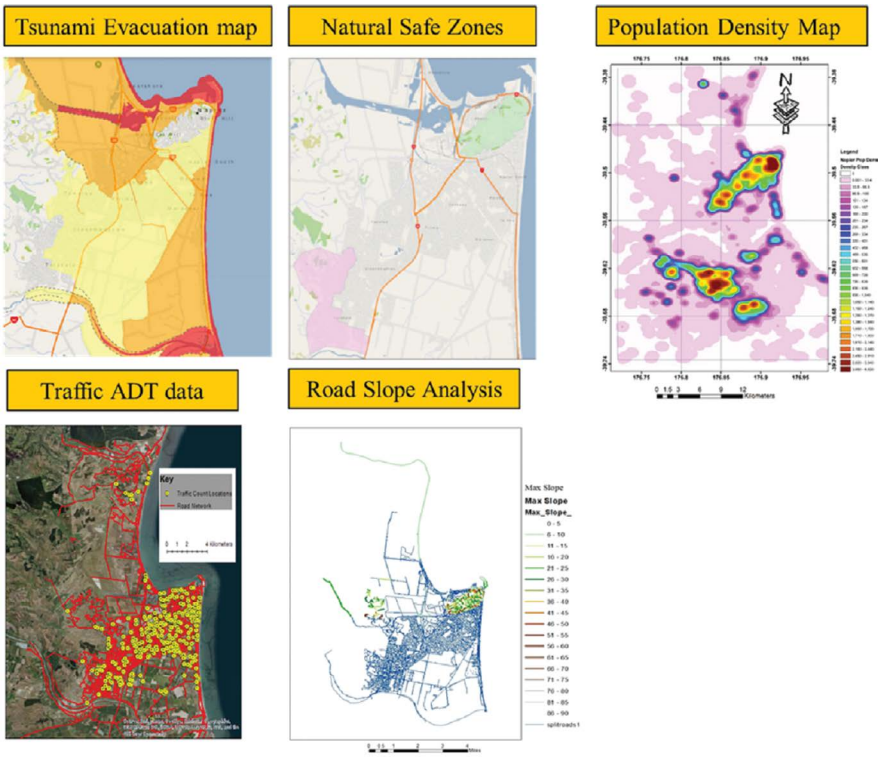

Figure 10.6 Example of required input date for MSEM: case study of Napier City, New Zealand, adapted from Fathianpour, Evans et al. 2023b

MSEM's simulation process involves several key components and calculations. It simulates the behaviour of individual agents (evacuees) based on their attributes and the evolving situation. Each agent autonomously decides on actions such as selecting evacuation routes and reacting to changing conditions. The model also considers predefined safe zone locations where evacuees should reach during an evacuation. It calculates the time required for each individual to reach the nearest safe zone, utilising shortest-distance algorithms. There are a few algorithms developed in this area, such as Dijkstra and A-star. The A-star algorithm is famous for its fast simulation process (Krajzewicz et al. 2012). This algorithm considers various factors, including the time it takes to reach a specific node from the starting point (denoted as g(n)) and a heuristic function (h(n)), estimating the cheapest path from that node to the destination. It operates on weighted graphs and starts from a specific node, searching for the path with the lowest cost (f(n)). The analysis iteratively examines all possible shortest paths from a starting location to safe zone boundaries, ultimately selecting the shortest route that adheres to permitted road and vehicle travel directions (Fathianpour, Evans et al. 2023a; 2023c). This calculation provides insights into evacuation timeframes and potential bottlenecks. Additionally, MSEM accounts for people following others as a trigger of evacuation.

The utilisation of MSEM generates valuable outcomes and insights. It offers a detailed perspective on individual behaviour during evacuations, facilitating a deeper comprehension of various agents' responses to disaster scenarios. While the evacuation simulation model outputs data on individuals' paths, including the edges travelled, start times, and arrival times, this information alone does not provide practical input for emergency management strategies. Therefore, these findings must be translated into actionable policies.

Translating Simulation Output to Decision-Making Factors

This section intends to bridge the gap between simulation data and practical policy recommendations for enhancing tsunami evacuation processes. Therefore, a structured framework is employed to evaluate the effectiveness of these evacuation processes (Figure 10.7) (Fathianpour, Evans 2023).

Survival Rate

At the heart of this evaluation lies the crucial survival rate metric, which serves as a barometer of a successful evacuation. Factors influencing survival rates include the safety of evacuation locations, pre-disaster preparedness, and the time it takes for individuals to initiate and complete evacuation.

A survivor is defined as an individual who successfully reaches a safe zone ahead of the approaching tsunami wave. To determine survival, the time it takes for individuals to reach safety is compared to the expected arrival time of the tsunami wave. The individual is considered a survivor if the travel time is shorter than the anticipated wave arrival. The survival rate is then calculated as the percentage of people who successfully evacuate and reach safety out of the total population at risk (Fathianpour, Evans et al. 2023c).

Transportation Network Capacity

The capacity of the transportation network emerges as a pivotal determinant of the success of an evacuation plan. It dictates the maximum number of individuals

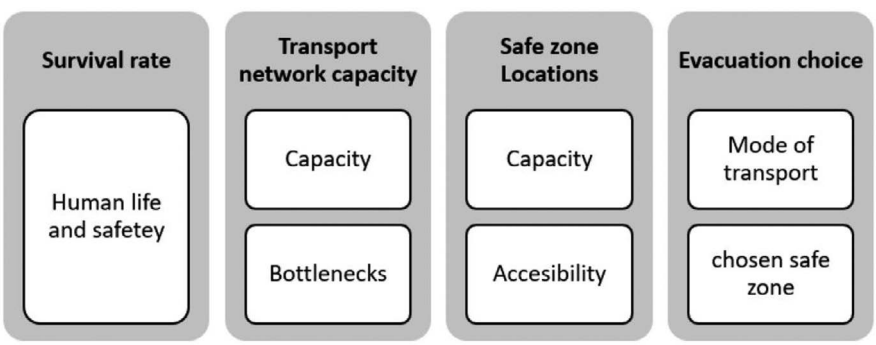

Figure 10.7 Evacuation simulation translation framework

or vehicles that can be accommodated within a specific timeframe. Notably, the capacity of individual lanes within the transportation network significantly impacts movement speed, which, in turn, affects the overall outcome of the evacuation. Finding an equilibrium between an effective transportation system and cost-efficiency is of utmost importance. Identifying road capacities and potential bottlenecks helps guide informed decision-making regarding transportation network investments, ensuring optimal allocation of resources (Liu et al. 2021).

A usage-based scoring model calculates the capacity of the transportation network. This method ranks the roads based on how often they are used. In this system, the most-used road receives a score of 1. Subsequent items are then assigned higher scores in ascending order of usage frequency (Fathianpour, Evans 2023c).

Safe Zone Capacity

Safe zone locations within urban areas constitute another critical aspect of evacuation. These safe zones can be shelters, elevated terrain, or far inland areas. The availability of multiple safe locations with increased capacities plays a pivotal role in reducing the average evacuation time (Birkland et al. 2006, Sun & Sun 2019). Historical data underscores the importance of offering diverse evacuation options, such as vertical evacuation centres in low-lying areas, as this correlates with higher survival rates (Suppasri et al. 2013). However, the design and evaluation of shelters must consider their locations and anticipated demand to prevent overcrowding, which can potentially create secondary disasters during evacuation (Muhammad et al. 2017).

The safe zone's accessibility and location are investigated based on the percentage of individuals who reach each safe zone. A balanced distribution indicates a sustainable and well-placed safe zone arrangement where a similar percentage of individuals reach each safe zone. Conversely, if one safe zone consistently has a low percentage of arrivals, it may signal inaccessibility due to traffic congestion. In such cases, establishing a vertical evacuation centre at a midway point to ensure timely access is recommended (Fathianpour, Evans 2023a).

For instance, in the safe zone capacity in vertical evacuation, the number of evacuees reaching the zone is the main driver to identify if the safe zone is out of capacity. If the number of people reaching each safe zone is more than the identified capacity of the building, the safe zone would be known to be out of capacity.

Individual choices made during the evacuation process also considerably affect its effectiveness. Decisions regarding actions to take, destinations to reach (Wang et al. 2016), and the mode of transportation to employ (Wood & Schmidtlein 2012) all influence the overall evacuation strategy.

Precise simulation models are invaluable tools for decision-makers and emergency management officials, offering insights into network upgrades and shelter locations that can minimise delays and improve survival rates. While various simulation projects have been undertaken to capture survival rates in evacuation scenarios, the challenge lies in translating these findings into practical policies and procedures. MSEM tends to overcome that challenge by leveraging simulation results to evaluate the efficiency of current evacuation processes and

infrastructure and propose improvements based on the evacuation simulation results. The goal is to identify potential weaknesses in the existing infrastructure and highlight areas where improvements can be made. This research seeks to continually empower policymakers, emergency planners, and communities to enhance their tsunami evacuation plans by translating simulation outputs into actionable decision-making factors.

Conclusion

In summary, despite the various risk reduction approaches available for tsunamis, it is essential to scrutinise the suitability of each and formulate a comprehensive risk reduction strategy. Simulation emerges as one of the most effective means to assess the emergency management plan. As evacuation is an inevitable response to local tsunamis, evacuation simulation is the preferred method to evaluate what is needed to enhance the resiliency of a tsunami-prone community.

The Micro-Simulation Evacuation Model (MSEM) is a powerful tool that employs agent-based modelling to simulate and assess evacuation processes during emergencies, particularly in tsunami scenarios. It utilises input data encompassing geospatial information, individual attributes, and event-specific data to provide insights into behaviour, safe zone allocation, and communication dynamics. The outcomes include the time and path each individual would take to reach safety. This model comes with additional features to enhance the translation of the simulation output to policy and strategies.

Translating simulation outputs into decision-making factors is instrumental in strengthening tsunami evacuation processes. Survivability rates, transport network capacities, safe zone locations, and individual evacuation choices are criteria for assessing evacuation processes. By integrating simulation data into policy recommendations and infrastructure improvements, communities can better prepare themselves to mitigate the devastating impacts of tsunamis and safeguard the lives of their residents.

This insight aids in crafting more effective evacuation plans and response strategies. By simulating different scenarios, MSEM helps decision-makers allocate resources strategically. It also offers insights into the most efficient evacuation routes and timing, allowing decision-makers to optimise evacuation plans, reduce congestion, and improve overall safety. Lastly, MSEM can be utilised for realistic training and drills for emergency responders and the public, helping participants become familiar with evacuation procedures, communication protocols, and resource utilisation.

Practical Orientations

Overall, the findings of this study have emphasised that to build resilience for human and built environment, it is important to consider the following practical considerations:

- Language barrier – tsunami evacuation signs must be nonlinguistic
- Tsunami awareness and evacuation training are top priorities in any tsunami-prone city, and simulation models are a great tool for evacuation training

- Evacuation management is a subjective matter to the area; different strategies for different suburbs
- The choice of evacuation mode significantly impacts the resiliency of the evacuation plan
- Vertical evacuation is recommended for highly dense areas located far from natural, safe zones

Overall this study has proposed a valuable tool (MSEM) to assist emergency management officials to draft an evidence-based plan for the reduction and readiness' phase of the 4 Rs of resilience (Reduction, Reediness, Response and Recovery).

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