Tsunami evacuation modelling and mitigation measures for Tauranga City, New Zealand

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Tsunami evacuation modelling and mitigation measures for Tauranga City, New Zealand

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Abstract

The 2011 Tōhoku earthquake and tsunami reinforced that very large, low probability tsunami can occur and have devastating consequences when they impact dense coastal populations. Tauranga has significant existing development on low-lying coastal plains and is susceptible to large, low probability tsunami generated along the Kermedec Trench. Tonkin & Taylor Ltd. have worked with Tauranga City Council to optimise evacuation routes for Mt Maunganui and Papamoa for a maximum credible tsunami event. This event was found to originate from a large magnitude nearshore event along the Kermadec Trench. Such an event would likely reach the Tauranga coastline within 60 minutes of generation precluding early-warnings or vehicular-based evacuation. Safe areas above the maximum flow extents were identified and a pedestrian-based evacuation network developed comprising the existing roading network, walkways, reserves and cycleways. Evacuation modelling was undertaken using a modified version of the *ArcGIS Network Analyst* evacuation routing extension *ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing)* to obtain safe zone population catchments, route densities and evacuation times. Evacuation modelling was undertaken in two stages; from high to low hazard and from hazardous to safe areas for a range of assumed evacuation speeds. Results showed that evacuation times to reach safe areas was up to 180 minutes for the existing network due to the extremely flat inland topography, long distances to designated safe areas and roading configurations. Evacuation was optimised using a combination of additional evacuation routes and connectors and new safe zones including the use of vertical evacuation structures (both natural and manmade). Evacuation times were reduced to less than 70 minutes for all areas.

Keywords: Tsunami hazard, mitigation measures, evacuation, safe zones, vertical evacuation structures.

1. Introduction

The Bay of Plenty is susceptible to tsunami from both regional and far-field sources [7] with previous work identifying the Kermadec Trench, some 400km away, as the most significant source of large tsunami [6, 13]. Initial modelling by NIWA and GNS [1] identified an M_w 9.0 fault on the Kermadec Trench as a maximum credible event.

Tauranga City has a population of more than 35,000 residing on a flat coastal plain. At Papamoa (Figure 1), almost the entire back dune landform has been levelled through earthworks to facilitate urban development. A large earthquake from a rupture of the Kermadec Trench would potentially reach and inundate parts of Mt Maunganui (Figure 1) and Papamoa within 60 minutes of generation. Formal warnings are unlikely to be possible within this time frame and self-evacuation is promoted by the Ministry of Civil Defence and Emergency Management (MCDEM). Warning signs from an earthquake of this magnitude would be difficulty standing and/or shaking would last more than 60 seconds. However, to effectively self-evacuate, a population must be familiar with the location of safe areas, with the route to reach these locations, and be confident that they can be reached before tsunami impact.

The Civil Defence Emergency Management Act [4] focuses on the sustainable management of hazards, resilient communities and on ensuring the safety of people, property and infrastructure in an emergency. Furthermore, Local Authorities are required to have particular regard to the avoidance or mitigation of natural hazards, including tsunami. An approach based on risk reduction, readiness, response and recovery is promoted in New Zealand and the guideline for tsunami evacuation zones [4] provides guideline for the development of tsunami evacuation zones and evacuation route maps.

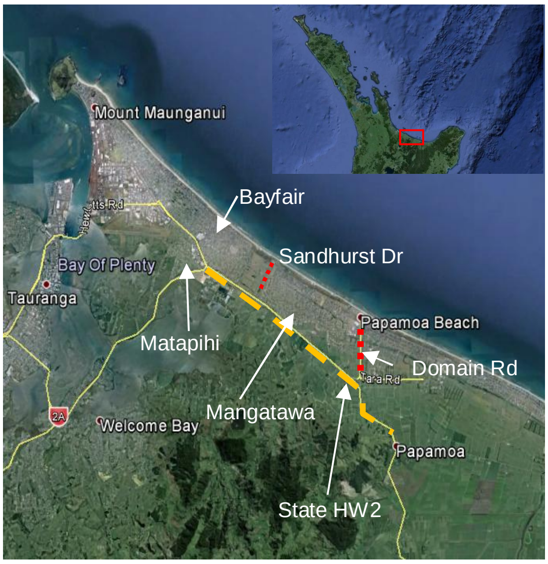

Figure 1 Site location plan (Source: GoogleEarth)

Identification of tsunami hazard extents

A maximum credible tsunami event has previously been identified for the Bay of Plenty with a shoreline wave amplitude of 13.5 m above MSL [1]. This originated from a large magnitude nearshore event along the southern Kermadec Trench and could reach the Tauranga coastline within 60 minutes of generation.

T&T [11] constructed an updated, high-resolution model domain of the Tauranga City region using LiDAR data collected in 2011/2012 and simulated tsunami propagation approaching the shore and its landfall. A timeseries of surface elevations was obtained from previous regional tsunami modelling by GNS Modelled and applied at the 50 m depth contour were. Model performance was compared to GNS model and surface elevations found within 5% at multiple inshore locations, refer [11] for details of hydrodynamic modelling. The physical characteristics of the tsunami over land were identified in terms of flood depth, velocity and flow hazard.

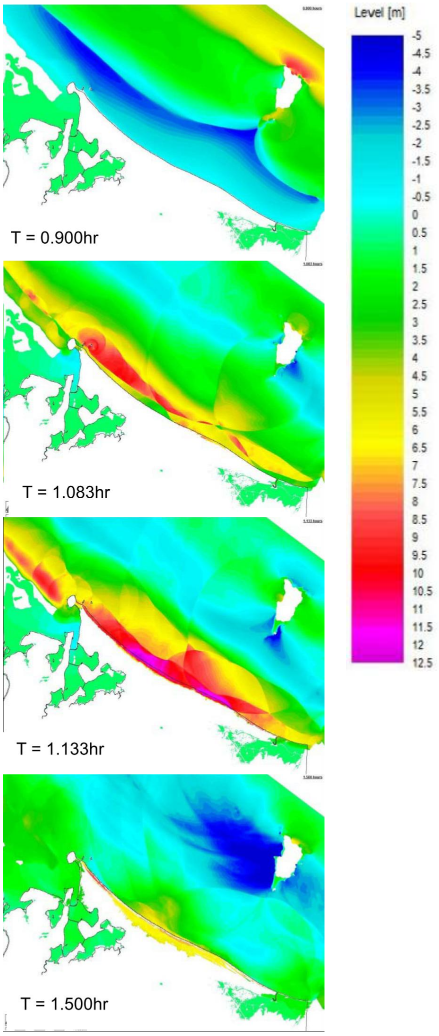

Figure 2 Nearshore Tsunami propagation of the maximum credible tsunami using a Southern Kermadec (M_w 9.0, slip = 30 m) boundary forcing.

Figure 2 shows an example of the nearshore tsunami propagation modelling undertaken [11]. The tsunami generated by the Variation of Southern Kermadec Scenario (M_w 9.0, slip = 30 m) model [1] leads with a trough approaching the coastline roughly parallel to seabed contours. The wave crest impacts the coastline at a clock time of approximately 1.1 hours from tsunami generation, overtops the beach berm and inundates the land. The bottom image in Figure 2 shows the inundation extent after 1.5 hours of generation of the tsunami.

2. Development of evacuation zones

Evacuation zones compliant with MCDEM guidance [4] have been established. A shore exclusion zone (red zone) is intended to designate areas that should be evacuated during all regional and distant tsunami scenarios regardless of size. This zone has been defined as a 10 m buffer from the coastal edge in harbour environments and to the fore dune crest along the open coast.

The orange zone is intended to be the area requiring evacuation in most if not all distant and regional-source events where an official warnings is provided. An event with maximum shoreline amplitude of 10 m (1000 to 2500 year return period) was selected for the primary (orange) evacuation area.

The yellow evacuation area is defined by the likely landward extent of inundation of the maximum credible tsunami scenario. The safe zone (grey zone) is defined landward of the yellow evacuation zone.

Figure 3 (a) and Figure 3 (b) show the maximum flood depth and tsunami hazard, Figure 3 (c) shows the extension of the evacuation zones respectively.

3. Evacuation modelling

3.1 Evacuation strategy

Evacuation strategy was focussed on self-evacuation of all zones during the maximum credible event as this corresponds to the maximum demand on route networks and evacuation safe zones. Procedures for formal evacuation (official warnings) of the red and orange zones is expected to follow similar procedures outlined here but total evacuation populations will be lower due to smaller areas being evacuated resulting in less network congestion and lower populations reaching evacuation safe zones.

Evacuation modelling has been undertaken in two stages; first to evacuate people in high hazard zones (fatality likely) to areas of low hazard (fatality unlikely) and then to evacuation people from all hazard zones to points of safety (safe zones). This strategy was adopted as preliminary modelling [11] showed that evacuation of all people within inundation areas directly to safe zones was unlikely achievable due to the long travel distances and the primary focus is on preservation of life.

Evacuation is assumed to occur by self-determination based on natural warnings signs (i.e. sustained or violent ground shaking) for the maximum credible tsunami event as per advice by MCDEM [4] as waiting for official warning could result in delayed evacuation or non-evacuation.

Evacuation is assumed to occur by walking only as preliminary work by NZTA (pers. comm. 17 Jan 2014) found that road congestion resulted in evacuation times of 4-6 hours for vehicle-based evacuation. This is supported by findings from the 2011 Tohoku tsunami in Japan where roadways quickly exceeded capacity where cars are used [3]. This pedestrian evacuation approach is advocated by Fraser et al. [3] with roadways kept clear for emergency vehicles and evacuation of severely mobility impaired.

Finally, evacuation is assumed to occur along a defined pedestrian network comprised of the existing roads, walkways, cycleways and reserves. While faster evacuation may be possible with ‘direct line’ evacuation, access across private property, fences, swampy areas and waterways cannot be guaranteed, particularly during night time.

3.2 Evacuation model

Evacuation modelling has been undertaken using the ArcGIS Network Analyst evacuation routing extension ArcCASPER [9]. This model routes evacuees along a network via the shortest path and provides evacuation times, densities along the network and populations reaching safe zones. Assumptions for modelling are set out below.

3.2.1 Evacuation timing

Research following the 2011 Tohoku tsunami in Japan found that there are often significant delays in evacuating caused by a variety of reasons including lack of awareness of tsunami potential and desire to find family members [8] and that delays significantly increase the likelihood of not reaching safety [3]. For modelling purposes it is assumed that people take 10 minutes to feel the earthquake and decide to self-evacuate then an additional 10 minutes to depart based on maximum pre-evacuation times found in [9]. Based on a tsunami arrival time at the coast of 60 minutes for a maximum credible event from the Southern Kermedec region, 40 minutes has been set as a target evacuation time for the extreme and high hazard areas (red and orange) and 60 minutes for the lower hazard (yellow) zone given that the tsunami takes some 10 to 20 minutes to propagate across the foreland.

3.2.2 Walk speed

A mean evacuation speed of 2.5 km/hr has been assumed. While significantly higher speeds are likely to be possible by most of the able bodied population (i.e. [10], report free movement evacuation walk speeds of 4.3 to 6. km/hour), some of the population will be older or younger, may be carrying baggage, walk distances may be long (> 2 km) and may occur in the dark and some congestion is likely. Sensitivities of 2.0 and 3.0 km/hour were also tested.

3.2.3 Population

Population density was based on Resident Population Projections for 2016 from the SmartGrowth 2011 Population and Dwelling Forecast at meshblock level. Meshblocks are approximately one residential block.

A ‘night time’ scenario was tested with all residential population being home at the time of evacuation. A ‘day time’ scenario was also tested. This conservatively assumed that; all residential population are home, that industrial and commercial centres are occupied by employees and beach populations range from 50 persons/100 m to 10 persons/100 m. Additional patrons in commercial areas (i.e. shoppers or diners) are assumed to predominantly come from the residential population with influx from outside the evacuation area balanced by outflux. This is likely a reasonable assumption except for the few busiest days of the year.

3.3 Evacuation network

Initial evacuation modelling was undertaken using a pedestrian network comprised of:

- Existing local roads;
- Walkways;
- Cycle ways;
- Reserves and esplanades.

Bridges were not included in evacuation modelling. While most bridges are likely to be sufficient to withstand tsunami impact, large ships docked near bridges could potentially be swept into the bridge with unknown consequences. Furthermore, land adjacent to bridges are likely to be subject to severe inundation and people should evacuate inland toward higher low hazard areas rather than through this high hazard area.

Following initial modelling results, evacuation network improvements were incorporated to more effectively evacuate the population to safety. This included foot bridges over drains and additional path and cycle ways over private land where future roads are planned or negotiations are to be entered into with land owners.

3.4 Evacuation safe areas

‘Safe’ zones were initially defined to include areas at least 1.5 m above the maximum flow extents to account for inaccuracies in the tsunami characterisation or in the flow modelling and for potential future sea level rise (i.e. are future-proofed). They were also required to have either safe connection to inland areas or adequate size and facilities to cater for an evacuated population. FEMA guidance [2] recommends that at least 1 m^2/person is allowed for stays of 12-24 hours. Additional safe areas were added iteratively as either additional land, buildings or roadways have been identified as being suitable now, or in the future, for vertical evacuation points as necessary.

3.5 Results

3.5.1 Existing network

Initial results show that people are able to evacuate from medium-high hazard zones to low hazard within 40 minutes in all locations except for at the eastern end of Papamoa. Evacuation times here exceed 40 minutes as people must travel along a roadway before moving inland, see Figure 3 (d). Improvements to the inland network are proposed to address this.

Most areas are found to be evacuatable to safe areas within 40-50 minutes. The Bayfair area is evacuatable within 60 minutes, with most of the population moving to the high area at Matapihi. Additional safe points in these areas would assist in evacuating these areas. Evacuation time between Sandhurst Drive and Domain Road evacuation times increase up to 90 minutes as populations need to move up to 1.5 km along the coast to reach an inland connector.

Findings indicate that the existing evacuation network is not sufficient to successfully evacuate the resident population in several areas to safe points before arrival of a wave associated with a maximum credible event. Major issues include:

- Long distances to safe locations;
- Cul-de-sac design in roading and subdivision layout preventing interconnectedness within the network;
- Waterways, swampy areas and swales impeding natural evacuation paths;
- Infrastructure impeding natural evacuation paths.

3.5.2 Developed network

Progressive additions to the evacuation network have been implemented within the model to improve evacuation times. These include:

- Access across drains (e.g. foot bridges);
- Addition of future planned roading;
- Additional evacuation safe zones, where either additional land, buildings or roadways have been identified as being suitable now or in the future for evacuation.

Due to the long travel distances to suitable evacuation safe points, vertical evacuation points are proposed to allow timely evacuation of the resident population. These proposed vertical evacuation points include augmentation of some existing relic dune crests.

Using this developed evacuation network and safe zones, evacuation of all extreme and high hazard areas occurred in less than 40 minutes. Evacuation to safe zones was achieved in less than 40 minutes for the majority of the population. Some small pockets near the coastline had evacuation times of up to 60 minutes due to long travel distances to safe points. These people may encounter tsunami water during evacuation, however, flows are likely to be significantly less hazardous away from the coast and not likely to result in fatalities. Figure 3 (e) shows the evacuation times to safe zones for the developed network.

Flow densities along major evacuation routes have been analysed to check for points of potential congestion. Mean flow rates are found to generally be less than 1 person per second and, given the population moving in one direction, should be manageable for the existing network.

4. Implementation of mitigation measures

4.1 Safe zone constraints and opportunities analysis

The constraints and opportunities analysis commenced with key assumptions which included:

- For vertical evacuation structures the freeboard requirements above the modelled inundation level;
- Safe zones being assessed by pedestrian movements;
- The safe zones may be occupied for an approximate period of 24 hours;
- No safe zones include for the provision of shelter, toilets, potable water, power supplies or emergency food supplies;
- Signage mounting locations and attachment methods will be designed to be as resilient as possible to impact damage;
- A Traffic Management Plan will need to be developed and implemented to create a closed network along State Highway 2.

From there we assessed many factors at each safe zone, including: landownership; legal and physical access; landform and topographic characteristics; planning and consenting implications; physical work requirements; financial costs; and general considerations, such as the sequencing of future urban development and infrastructure which could provide vertical evacuation functionality.

4.2 Safe zone prioritisation

A scoring system was developed for application to each safe zone to identify a prioritisation regime for the development and/or implementation of the safe zones and any related network improvements [12]. This was necessary due to three main factors that varied substantially for many of the safe zones and that fact that Tauranga City Council's ("TCC") ability to realise the safe zones is limited by the funding available to them through the Annual Plan and Long Term Plan. The three factors were cost, difficultly and criticality.

Cost: Some safe zones only required signage to be effective whereas others required up to $1M to be developed or implemented.

Difficulty: Some safe zones were located on public land and required no physical works due either to natural topographic features or vertical evacuation functionality, so provided a high degree of certainty in terms of being able to identified and used immediately. Conversely some safe zones were likely to be very complex in terms of development/implementation due to factors such as being located on private land, requiring substantial physical works, and there being cultural sensitivity around landform modification.

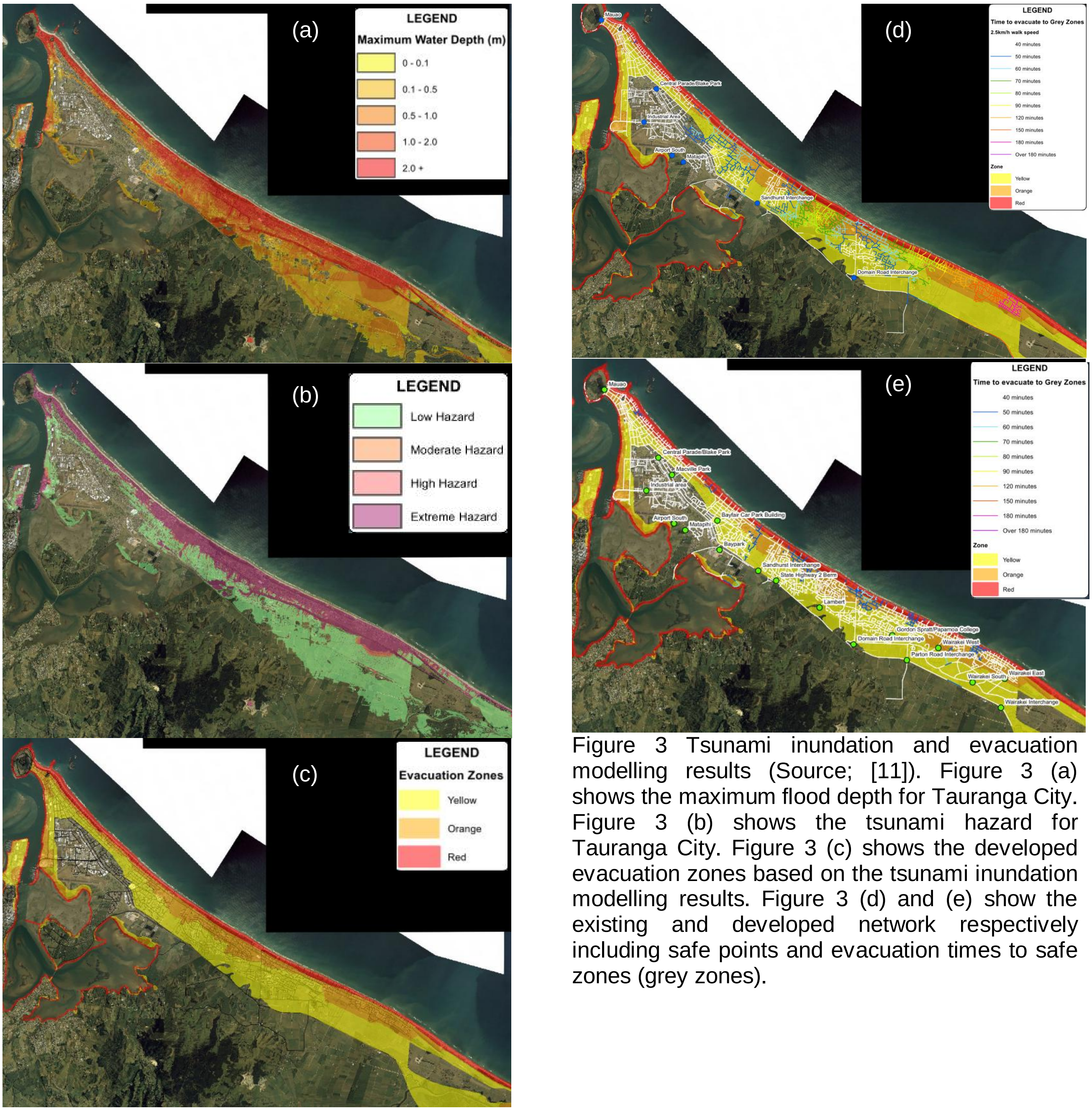

Figure 3 Tsunami inundation and evacuation modelling results (Source; [11]). Figure 3 (a) shows the maximum flood depth for Tauranga City. Figure 3 (b) shows the tsunami hazard for Tauranga City. Figure 3 (c) shows the developed evacuation zones based on the tsunami inundation modelling results. Figure 3 (d) and (e) show the existing and developed network respectively including safe points and evacuation times to safe zones (grey zones).

Criticality: This looked at whether each safe zone and any related network improvement was required immediately, required in the short term, or required in the long term.

Following the completion of the priority scoring exercise a recommendation was provided to TCC to optimise the safety benefits and prioritise the most critical safe zones from an allocation provided in the 2014-2015 Annual Plan.

4.3 Safe zone and network improvement works underway

TCC determined that they would use the current funding available through the Annual Plan to construct evacuation bridges in the Bayfair area and a vertical evacuation structure ("VES") near Papamoa Beach (Figure 1).

The pedestrian evacuation bridges where required to evacuate an extensive population of approximately 5000 people seaward of State Highway 2 to the safe point adjacent to State Highway 2 (TEL) at Mangatawa. These network improvements are critical as without them people would be stranded on the seaward side of a drainage swale system.

The bridges have been designed as importance level 4 (IL4) structures to NZS 1170 due to their important function post disaster. IL4 structures are required to be designed for an earthquake with a return period of 1 in 2500 years.

The purpose built VES is located within the modelled inundation extents due to the lack of interconnectedness within the roading and local purpose reserves within the relevant evacuation catchment. This lack of interconnectedness provides an impediment to evacuating the population landward of the extents of the tsunami inundation within the requisite time period.

The VES will be comprised of an earth mound shaped for pedestrian access along the batter slopes up to the crest. The VES will be approximately 3 m high and include an allowance for freeboard above the modelled inundation level. The VES has been designed as an IL4 structure, and has been sited and designed to be resilient against the design seismic loading and liquefaction.

5. Summary

This assessment has considered the impact of a very large, low probability tsunami impacting the Tauranga coastline and the implications for evacuation of the population. This maximum credible event would likely reach the Tauranga coastline within 60 minutes of generation.

Nationally compliant maps for evacuation zones have been produced by TCC with red, orange and yellow zones. These correspond to a shore exclusion zone to be designated off limits in the event of any expected tsunami, an orange zone to be evacuated in most, if not all distant and regional source official warnings, and a yellow zone covering the maximum credible tsunami event to be evacuated by self-evacuation or formal evacuation procedures. These zones correspond to areas of extreme, high and low hazard under a maximum credible event.

Evacuation modelling was undertaken in two stages; first to evacuate people in high hazard zones (fatality likely) to areas of low hazard (fatality unlikely) and then to evacuation people from all hazard zones to safe zones. Targets for evacuation of these zones are 40 and 60 minutes respectively. Evacuation is assumed to occur by self-evacuation based on natural warning signs and is assumed to occur by walking (or cycling) only with roadways kept clear for emergency vehicles and evacuation of severely mobility impaired.

Evacuation modelling has been undertaken using the ArcGIS Network Analyst evacuation routing extension ArcCASPER. This model routes evacuees along a network via the shortest path and provides evacuation times, densities along the network and populations reaching safe zones.

Findings indicate that the existing evacuation network is not sufficient to successfully evacuate the resident population in several beach fronts to safe points before arrival of a wave associated with a maximum credible event.

Evacuation network improvements were added to mitigate the major issues identified above and optimise evacuation paths. Additional evacuation safe zones were added and include natural features on public and private land, as well as structures such as buildings, and road infrastructure. Additional vertical evacuation points were required due to the long distances inland to natural safe zones clear of the extents of the modelled inundation.

Following the evacuation network improvements, the safe zones were prioritised based on costs, difficulty and criticality. TCC determined to construct evacuation bridges and vertical evacuation structures ("VES") as these network improvements are critical as without them people would be stranded. Both the bridges and VES have been designed as importance level 4 (IL4) structures and to be resilient against the design loading and liquefaction.

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