Team 1075

REPORT 1075

If a severe tsunami warning were issued, how long would it take to evacuate the 13, 000 people who live on Te Atatu Peninsula?

01/10/11

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Summary

If a severe tsunami warning were issued, it would take **177 minutes** to evacuate the 13, 000 people who live on Te Atatu Peninsula.

The problem is open-ended as to from where the tsunami would strike, thus we analysed the serious, worst-case scenarios where a tsunami would cause the greatest damage to the Te Atatu Peninsula and give civil defence the least possible time to react. We concluded that an earthquake in the Kermadec Islands would be the most threatening and would hit the Auckland region in **139 minutes**, followed by an earthquake in Tonga, which would only take **231 minutes**.

The time taken for evacuation from the moment any one of these earthquakes struck was split up into three main steps: the notification time (100 minutes), the preparation of response time (10 minutes) and the time for physical evacuation to take place (67 minutes). We have made the assumption that, based on the question, we would be predicting that all of Te Atatu Peninsula would be inundated in the case of a severe tsunami. Therefore it would be necessary to evacuate all of the 13000 residents from Te Atatu Peninsula.

A complete evacuation is all 13,000 people being moved out of Te Atatu Peninsula. In answering the question we will take it that once they are either on the motorway heading north, or past it heading south west on Te Atatu Rd, that they have been evacuated. Therefore if a tsunami were to strike from Kermadec Island, the residents of Te Atatu Peninsula would not be able to fully evacuate.

Introduction

Tsunamis represent a nearly unfathomable, relentless force of nature known for the complete destruction of all that stands in their way. On October 2004, the great Indian Ocean Tsunami collided with the coast of Asia with the force of approximately 23,000 Hiroshima-level atomic bombs. The resultant destruction of property and assets was profound, but more notable was the tragic loss of 150,000 people. [2] New Zealand's location on the Pacific Rim puts us in a similarly dangerous position, and lives could rest on our ability to organise evacuation measures from coastal areas. In the problem proposed today, we must attempt to find the time taken to move all 13 000 residents of Te Atatu; we also estimated the window of time before a Tsunami would arrive.

We define the Te Atatu Peninsula as the area bounded by the Henderson Creek, Waitemata harbour and North-western motorway.[1]

There are 3 major components of this problem:

- How long it would take to warn people of the danger and mobilise them
    - Time for authorities to reach citizens
    - Time for people to get ready to leave

[1] Google Maps, retrieved 1 October 11 http://maps.google.com

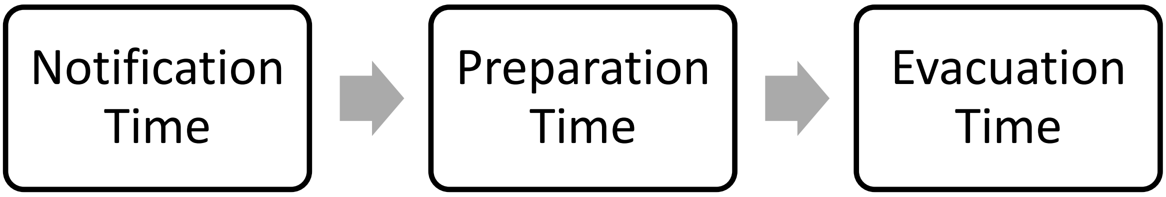
  - Time to arrange methods of transport

- How long it would take to transport 13 000 people out of the danger area
  - Different methods of transport to be used
  - Speed of each method
  - Distance from Te Atatu to a safe area

- How long it would take for the tsunami to reach Te Atatu Peninsula
  - How likely is a successful evacuation?

Main

The answer to this question, that is the time taken from the moment an earthquake strikes to cause a tsunami, can be split up into the time taken for the decision to issue a tsunami warning until regional civil defence authorities to alert residents; the time taken for residents to respond to the warning and start the process of evacuation; and the time taken for people to move from Te Atatu Peninsula to an area of acceptable safety.



Where are we predicting that the earthquake will occur?

Auckland Regional Council contracted NIWA to undertake a modelling-based assessment of tsunami hazard for the Auckland region, which produced a report on how Auckland would be affected by a tsunami.[2]

Three factors affect how New Zealand is affected by tsunamis in the Pacific Ocean:

1. Source location and geometry (of earthquake)
2. Wave transformations that occur when the tsunami crosses the ocean
3. Effects of bathymetry (the measurement of depth of water in ocean) and the geometry of the continental shelf and coastal region.

The Auckland area faces only a few potential sources, on the western coast of South America and the Tonga-Kermadec trench as a more regional source. Tsunamis from the north (Solomon Islands/Fiji Basin or Indonesia) have not caused any significant impact on Auckland historically because of our relative geographical position. Tsunamis lose most of their energy and intensity in moving around the large land masses of southern tip of Asia and Australia.

[2] (Lane, Walters, Arnold, Enright, & Roulston, 2007). Auckland Regional Council Tsunami Inundation Study.

The boundary along South America's west coast is seismically very active and has a relatively high rate of convergence. Large subduction earthquakes (caused by one plate moving bellowing another) have return periods of approximately 50-100 years. The Auckland region has experienced a total of three earthquakes due to the Chilean region in 1868, 1877 and 1960, with the highest wave height of the tsunami reaching 1.5 m. Tsunamis originating from Chile are thus the most plausible tsunami scenario facing Auckland.

However, for two reasons, the scenario involving tsunamis due to seismic activity near Chile can be discounted. Firstly, due to the fact that the wave front must travel across the whole Pacific Ocean to reach New Zealand, the time taken from the earthquake occurring until it first reaches New Zealand shores is approximately 12 hours. This time can be calculated using the depth of the ocean at different stages on the wave's movement, and has been calculated using computer-generated modelling software. Thus, even when a tsunami is confirmed, Te Atatu Peninsula would most likely be able to evacuate in sufficient time and reach high ground.

Secondly, empirical evidence suggests that the tsunami that would affect the Auckland region, with a maximum wave height of approximately 1.5 m, would have a minimal effect on the Auckland region, and more specifically the Te Atatu Peninsula, such that a full-scale evacuation in the least time possible would be unnecessary.

Large subduction zone earthquakes in the Tonga-Kermadec Trench would have a far more extreme impact on the coast. Even though these earthquakes occur less frequently, one cannot dismiss the event of a tsunami occurring due to this trench simply because of its infrequency, because there is no way with today's technology to predict when an earthquake may occur. This means that this threat is the most serious to Te Atatu Peninsula, and thus is the scenario which will be used to assess the success of the evacuation.

How long would it take for the tsunami to reach Te Atatu Peninsula?

There are three main earthquake-prone areas that we have identified that could cause tsunamis that would directly affect the Te Atatu Peninsula. These areas are highlighted in red zones in Figure 1 below. The furthest from New Zealand is the South American western coastline, with the border of the Pacific and Nazca plates and Tonga-Kermadec Trench being the next two zones that are of threat to New Zealand.

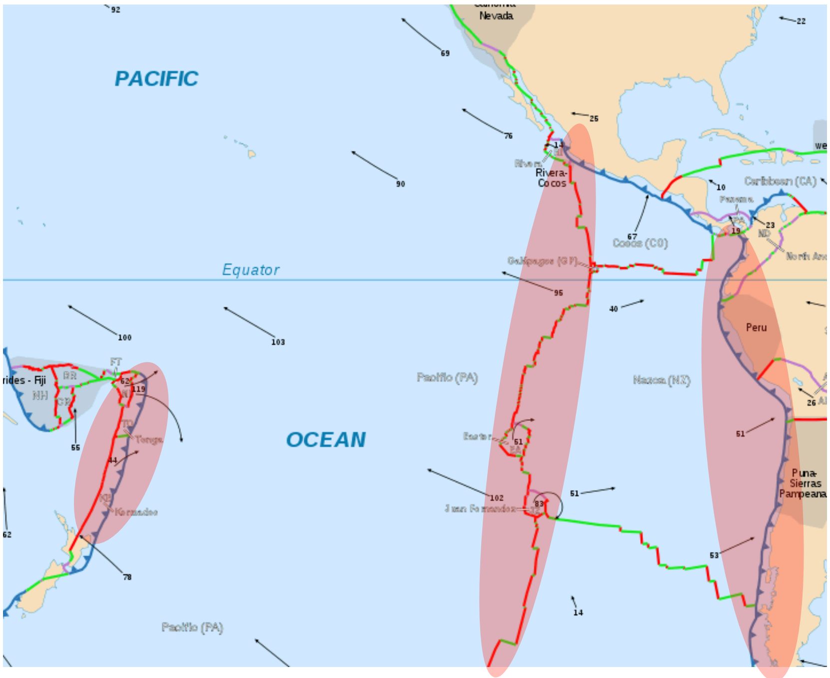


Figure 1. The plate boundaries highlighted in red are areas which are likely to cause a severe tsunami that would hit Te Atatu Peninsula.[3]

The furthest likely epicentre just off the coast of Chile will take roughly 13 hours to reach Te Atatu Peninsula. The next closest epicentre, at the border of the Pacific and Nazca plates, will produce a tsunami that will take roughly 7 hours to reach Te Atatu Peninsula, which is shown in Figure 2. Because these two times of tsunami warnings are large, we have excluded them from the calculations based on the assumption that our evacuation time for tsunamis that give us lesser timespans, for example from the Tonga-Kermadec Trench, will apply to these long-range tsunamis.

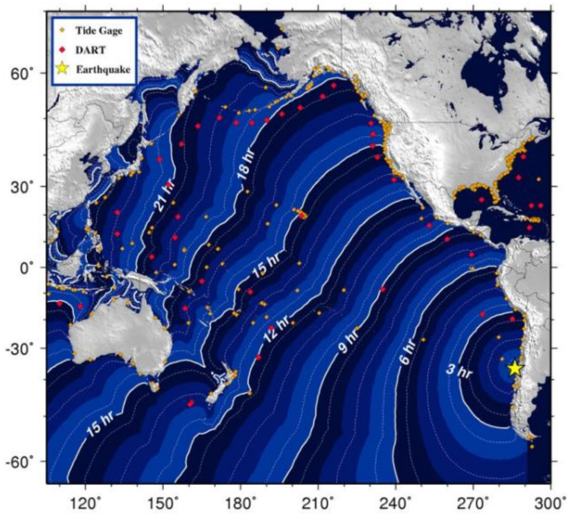


Figure 2. Travel times of tsunami originating in South America[4]

[3]Tectonic Plates Boundaries detailed.. Retrieved October 1, 2011. http://mapsof.net/uploads/static-maps/tectonic_plates_boundaries_detailed.png

There are two locations of high activity which are around Kermadec Island and Tonga. Figure 3 displays the locations of earthquakes in this area over the past 100 years. It can be seen that there are 2 main concentrated areas. In calculating the time for evacuation as per the problem, we calculated the time taken for a tsunami to reach the Te Atatu Peninsula for each of these earthquake zones to provide a point of reference, so that the evacuation times could be evaluated as to their chance of success if a tsunami were to hit the Auckland region.

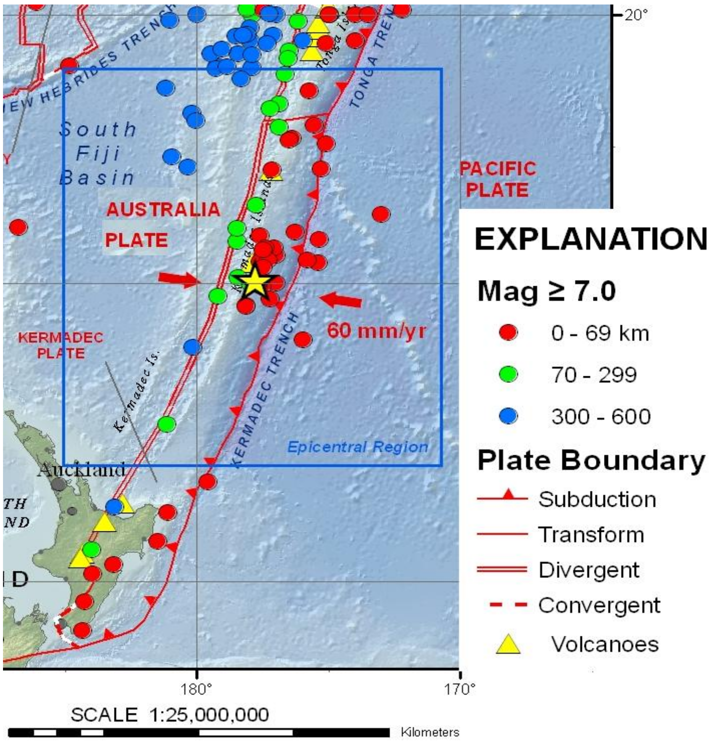


Figure 3. Past earthquake locations on the Tonga-Kermadec Trench in the past 100 years [5]

Using Google Earth, it can be seen that the distance from Kermadec Island to Te Atatu is 1100 km, to an accuracy of 2 significant figures. The distance from Tonga to Te Atatu is 2000km, which is slightly greater than that of Kermadec Island.

[4] Tsunami Travel Time. Retrieved October 1, 2011. http://wcatwc.arh.noaa.gov/2010/02/27/725245/06/ttvu725245-06.jpg

[5] Past earthquake locations. Retrieved October 1, 2011. http://feww.files.wordpress.com/2008/10/kermadec-trench-usgs.png

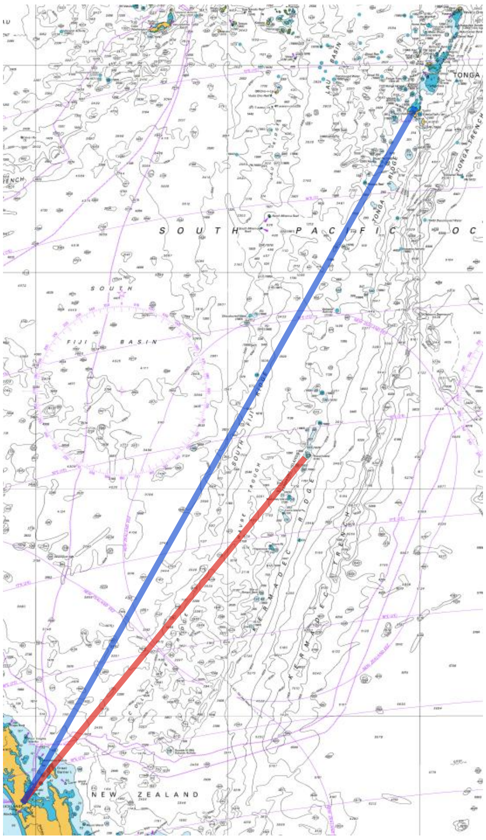


Figure 4. Depth chart of Pacific Ocean north east of New Zealand [6]

The blue and red lines represent the paths the tsunami would take from Kermadec Islands and Tonga respectively. The average depth was calculated for each route. The red line on Figure 4 corresponds to a continuous depth of 1800m and the blue line to one of 2100m.

The velocity of the tsunami is given by the equation:

$$v = \sqrt{gd}$$

Where v = velocity
g = gravity
d = depth

Taking the average depth:

$$v_{red} = \sqrt{9.81 \times 1800}$$
$$= 132\, ms^{-1}$$

$$v_{blue} = \sqrt{9.81 \times 2100}$$
$$= 144\, ms^{-1}$$

Time from Kermadec island $\frac{1.1\times10^6}{132} = 8333s = \mathbf{139\ minutes}$

Time from Tonga = $\frac{2.0\times10^6}{144} = 13889s = \mathbf{231\ minutes}$

How long would it take for the notification to reach the regional civil defence?

Tsunami forecasting technology uses seismic parameter estimates and tsunami measurements to sort through a pre-computed generation/propagation forecast database and select an appropriate, linear combination of scenarios that most closely matches the observational data. Thus when an underwater earthquake occurs, a tsunami can be predicted and a warning issued almost immediately. The only shortcoming of such a system is that there is no

[6] NZ Chart 202, Land Information New Zealand. Retrieved October 1, 2011. http://www.linz.govt.nz/hydro/charts/nz202-chart-catalogue/acknowledge.aspx?chart_num=14605

definitive way of knowing whether an underwater earthquake will cause a tsunami, so there are more often false tsunami warnings that arise. This is, however, an acceptable consequence of the rapidity of sensing.[7]

Table 1 analyses the best possible timeline for the speed of communication between the start of the earthquake and tsunami wave, and the time that notification reaches alert sirens, media and the general public.

Process		**Best possible (minutes)**
MCDEM	PWTC message received (time since earthquake)	10
	Interaction National Duty Officer & National Controller	5
	Interaction National Duty Officer/National Controller & Scientific advisors	10
	Compile and send message	15
Total for this part of the process		**40**
CDEM Groups	MCDEM message received and receipt confirmed	30
	Local assessment & warning/response activation	30
Total including CDEM process		**100 minutes**

Table 1. Estimates of the best possible time frames needed to activate a regional response from the moment the earthquake strikes[8]

Note:

- MCDEM – Ministry of Civil Defence and Emergency Management
- CDEM – National Civil Defence and Emergency Management

The Pacific Tsunami Warning Centre (PWTC) has a group of dedicated seismologists and specialists, who can only "issue the first earthquake information within 10-20 minutes"[3], that is a warning in the event of a serious earthquake that could lead to a tsunami would arrive at New Zealand Civil Defence at a minimum of 10 minutes after propagation of the wave.

There is then another 30 minutes lost in the MCDEM in assessing, evaluating and deciding on the next course of action before regional civil defence authorities are alerted. Once the message is received at the Auckland Civil Defence, the message must be confirmed and an action plan set in place, which would total another hour. The total notification time, thus, would come to **100 minutes**.

[7] (Tsunami Forecasting) (n.d.). Retrieved October 1, 2011, from http://nctr.pmel.noaa.gov/tsunami-forecast.html

[8] (Webb, 2005). Review of New Zealand's preparedness tsunami hazard, comparison to risk and recommendations for treatment.

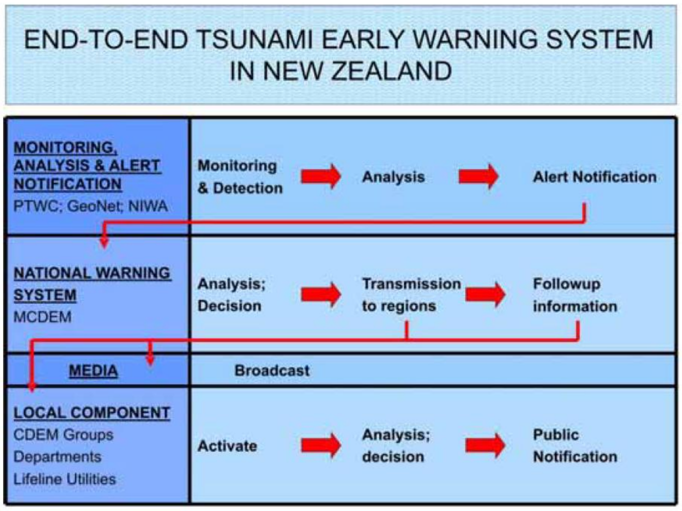


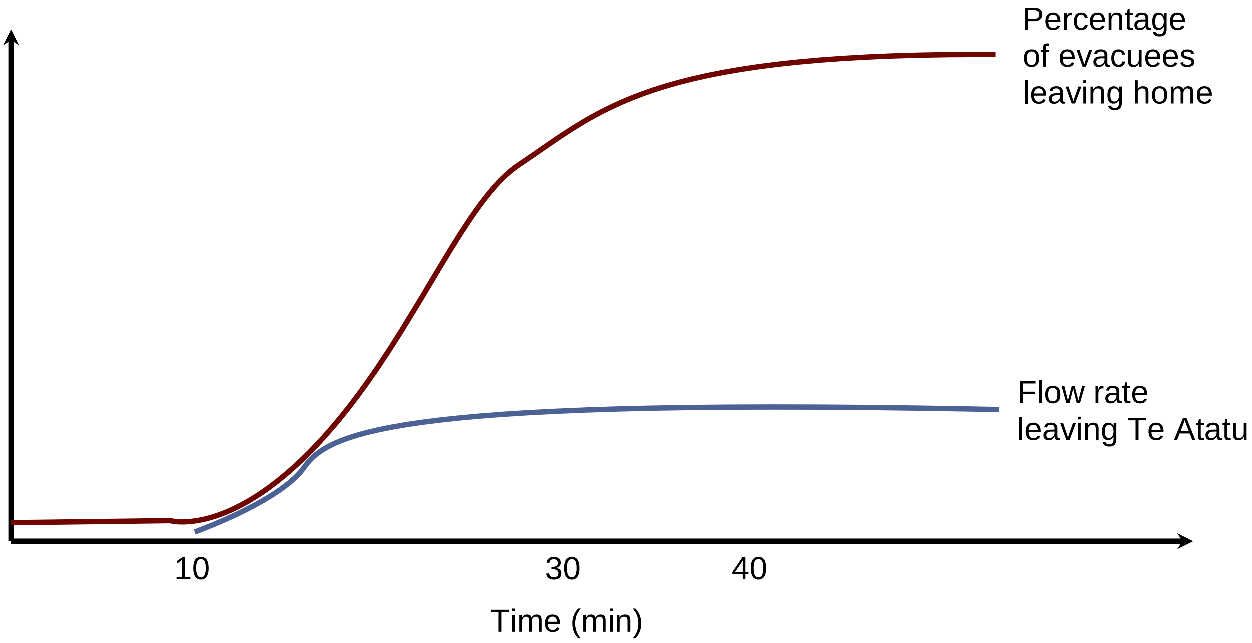
Figure 5. End-to-end Tsunami Early Warning System in New Zealand[3]

How long would it take for people to prepare to leave their households, if they stopped for belongings and pets etc?

After the alarm sounds there will be a short period of 10 minutes until the first permanent residents start to leave their homes.

This is an average for the entire population taking into account those of all state and mobility.

After this time there is an exponential growth of people leaving followed by a followed by a steady flow which tails off. This is depicted by the graph.



Because of congestion the amount of people that can leave at any one time is limited, so after 25 minutes flow rate is constant

This information is based on a study of evacuation behavior for a tsunami by T.Charnkol and Y.Tanaboriboon.[9]

How long would it take to physically evacuate from Te Atatu Peninsula?

To evacuate Te Atatu Peninsula, we can use several different methods of transport, including cars, buses and helicopters. These methods would have to transport people out of Te Atatu peninsula to a safe location.

We considered boats as a form of transport; however, any area able to be accessed by water within the harbour is in danger from the tsunami. The lack of docking facilities on the Peninsula also makes this unfeasible. [1]

<u>Helicopters:</u>

The NZ Air Force is in possession of 33 helicopters [3] and the Auckland Rescue Helicopter Trust has 2 stationed in Auckland. [4] These would have to be used throughout the country – however, considering that Te Atatu is an especially vulnerable area in terms of both lack of road access and proximity to the harbour, and that many of these helicopters will originate from Auckland, we consider it reasonable to assume that 4 helicopters would be used to evacuate people from Te Atatu. There are many parks and reserves around Te Atatu Peninsula [1] where these helicopters could land, and they could evacuate those who do not have cars (along with buses).

<u>Response time:</u>

We assume that these helicopters are stationed in the general Auckland region – i.e. within 15km of Te Atatu [1]. Given that helicopters have a flight speed of 120 nautical miles per hour (222.24km/hr) [5], it would take them about 4 minutes to reach Te Atatu. This does not include response time of helicopters and crew after they hear of the earthquake – for rapid-response helicopter crews such as the Westpac Rescue helicopters, this should be under 10 minutes. We will treat the total time for 2 helicopters to reach Te Atatu Peninsula as 15 minutes.

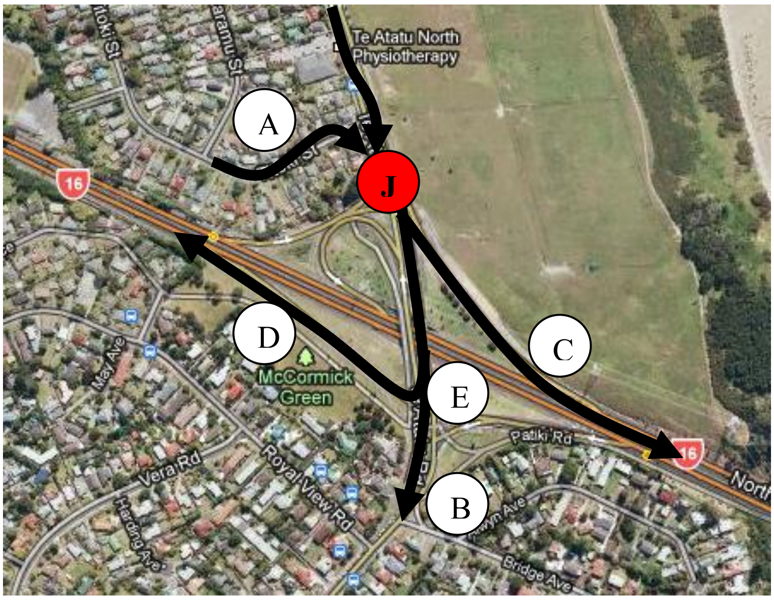
<u>Transport speed:</u>

The helicopters can carry 10 people in one load [4]: 2 crew and 8 passengers. They will need to load the passengers, fly them to safety, unload and return. We will take an approximate safe distance as 5km inland, which will take the helicopters 1.5 minutes each way. If we also take a loading and unloading time of 5 minutes each, then one helicopter can transport 8 people to safety in 13 minutes.

In total, the helicopters can transport 2.46 people per minute from the peninsula.

[9] Retrieved October 1, 2011. http://www.iatss.or.jp/pdf/research/30/30-2-09.pdf

Road transport



Te Atatu Rd is the only road leading out of Te Atatu Peninsula (taking the boundary of the peninsula as the motorway). Traffic feeds into it at various points (the last being Titoki St, A), and exits the peninsula onto the southern section of Te Atatu Road (B) or the motorway (C and D).

The problematic error in terms of congestion is marked by point J. This is the point at which cars must change lanes to exit the motorway and travel down route C. The motorway onramp is a substantial point for the evacuation procedure as long as a car reaches the motorway it can then travel north to safety. The area of maximum congestion that will be most impeded and affected will be the area between J and the motorway i.e. the length of the motorway onramp. Cars across all three lanes of Te Atatu Road may all wish to exit at this point and hence will most notably decrease flow rate as three lanes must funnel cars into one. This is the area that we have modelled as contributing most significantly to delays within Te Atatu Rd. This will be addressed in the following mathematical model.

We have also assumed that the traffic lights at point E are overridden so they don't prevent the flow of cars south along Te Atatu Rd.

Car

Car Modelling

For our mathematical model for the flow rate of cars we assumed that there would be a total of 5000 cars that will be travelling.

The total population required to be evacuated from Te Atatu is 13,000. The average family size was taken to be 2.6 (11). Dividing 13,000 by 2.6 we obtained 5000 cars. We assumed that every family would take only one car due to the psychological trait of families in sticking together, particularly at times of crisis. To check this figure we found the average number of cars per 1000 people to be 733 (12). This means that the total number of cars in Te Atatu can be modeled as 13000x0.733=9529. This figure is greater than 5000, thus our assumption of one car per family is plausible.

Speed of car traffic flow:

To estimate the flow speed of traffic along Te Atatu Rd, we used a mathematical model designed to simulate traffic patterns during emergency evacuations, NETVACI. [6] This model takes the speed of traffic to be:

$$U(t) = UF \times (1 - \frac{K(t)}{KJ})$$

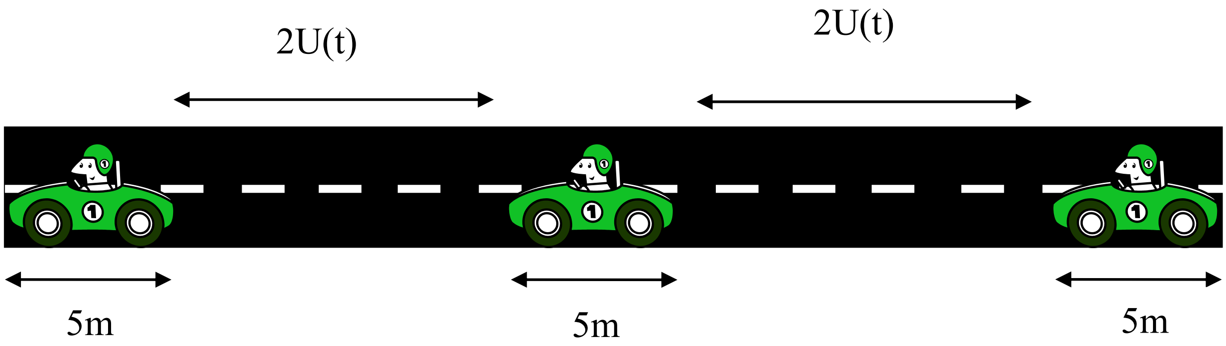
In this formula:

- U(t) is the average speed of traffic
- UF is the free-flowing speed of traffic (i.e. speed limit)
- KJ is the jam density per lane of traffic (the vehicle density required to completely stop traffic)
- K(t) is the actual traffic density per lane, defined by
- VM(t) is the number of vehicles moving on the road
- LD is the length of road
- LQT(t) is the length of the road section creating congestion
- We also take the average length of a car to be 5m

Our values for these variables are: $K(t) = \frac{VM(t)}{LD - LQ(t)}$

UF = Legal speed limit = 50km/hr = 13.89m/s
KJ = 250 cars per mile per lane [7] = 0.155 cars per metre
LD = distance from central Te Atatu Road to motorway = 1896m [1]
LQ(t) = distance from Titoki street to motorway = 275.86m [1]

To calculate VM(t), we must know both the length of a car and the average following distance between cars. We assume that drivers obey the legal guideline of 2s between cars. [8] This means that the following distance is 2 x U(t), or twice the average traffic speed.



Therefore: total length of the road = (5 x number of cars) + (following distance x (number of cars -1))

$$5VM(t) + 2U(t) \times (VM(t) - 1) = 1896$$

$$VM(t) = \frac{1896 + 2U(t)}{5 + 2U(t)}$$

Inserting all of the known values into the formulae:

$$K(t) = \frac{1896 + 2U(t)}{(5 + 2U(t))(1896 - 275.86)}$$

$$U(t) = 13.89 \times (1 - \frac{1896 + 2U(t)}{0.155(5 + 2U(t))(1896 - 275.86)}) = 13.89 - \frac{104.62 + 0.11036U(t)}{5 + 2U(t)}$$

$$2U(t)^2 - 22.67U(t) + 35.17 = 0$$

$$U(t) = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{22.67 \pm \sqrt{232.5555}}{4}$$

$$U(t) = 1.85ms^{-1}(6.66km/hr) \;\; or \;\; 9.48ms^{-1}(34.13km/hr)$$

To decide between these two values, we assumed that the flow of traffic would be similar to that during peak rush hour. Surveys carried out by Transit NZ indicate that this occurs in the morning; in the most recent survey, the average travel speed in morning peak traffic was 36km/hr. [9] This is similar to the figure of 34.13km/hr, giving independent confirmation.

The total time take can be determined by the time taken for the last car to travel the total sum of the length of all 5000 cars and the following distances divided by the speed:

$$t = \frac{d}{v_{ave}} = \frac{(5000 \times 5 + 4999 \times 2 \times 9.47986)}{9.47986} = 12635.2684s = 3.5098hr$$

5000 Cars with 2.6 people per car means 13,000 people

Thus, 13,000 people are moved in (3.509369x60) minutes

Rate of evacuation for cars = 61.74 people per minute per lane

<u>Bus Transportation</u>

During an emergency evacuation, buses can play an important role in supplying a means of transportation for who don't have working cars. Thus, out of the three lanes going out from Te Atatu we have decided to allocate one lane specifically for buses. One lane will also be going back towards Te Atatu to allow the buses to return and pick up more passengers.

We have deemed the Pak N Save at 202 Lincoln Road, Henderson as a safe drop-off zone for passengers. This is 5.3km from Central Te Atatu. [1] A further assumption we have made is that 20 buses would be available to be mobilized to serve this cause. These buses would be from neighboring areas or from the immediate local Te Atatu region.

We take the capacity of a bus to be 90 people. [10]

The legal speed limit is 50 km/h and due to the nature of the bus lane, the actual traffic rate in this lane would be rather close so we modelled it at 45km/h.

Furthermore, we assumed drop off time + load time = 8 minutes

Travel time + load time + drop off time = 22.133 mins

22.13 minutes / 90 people = 4.067 people per minute per bus

20 buses means rate of evacuation = 4.067x20=81.34 people per minute

This assumes 20 buses running in a constant loop of picking up, leaving Te Atatu, dropping off and returning to Te Atatu.

Buses are a suitable transport mechanism for those that do not have a car, may not feel comfortable driving in such a high-pressure situation, must accompany an elder or other citizen that cannot ride in a car i.e. Alzheimer's patient or perhaps do not have petrol in their car.

We are also assuming a delay of 20 minutes between the time of the siren and the time of arrival of the first buses. This time is due to the fact that all 20 must reach a central localised spot before departing and time is required to co-ordinate these buses.

<u>Transport systems:</u>

t= time taken for evacuation through a combination of 2 lanes of cars, 2 lanes of buses and helicopters

Method of transport	People evacuated per minute
Helicopter	2.46
Car	123.48
Bus	81.34

If h is the number of people evacuated by helicopter,
c is the number of people evacuated by car, and
b is the number of people evacuated by bus:

$$h = 2.46(t-5)$$
$$c = 123.48t$$
$$b = 81.34(t-10)$$

The time taken for people to get their property ready and mobilise for evacuation is ten minutes and this has already been addressed. Thus, the 15 minute delay time for helicopters to arrive from the siren will only effectively diminish the rate of evacuation by helicopter by 5 minutes (15-10) . By a similar logic, the delay time for the rate of evacuation by buses will be delayed effectively by only 10 minutes (20-10)

Therefore to figure out t:

123.84t+81.34(t-10)+2.46(t-5)=13,000

81.34t+2.46t+123.84t=13825.7

t= 66.6 minutes

Total time for the physical transportation phase of the evacuation is 66.6 minutes

Conclusion

In conclusion, the total time it would take to evacuate all 13000 people from Te Atatu Peninsula is 177 minutes. This includes the 110 minute time required for notification and preparation. This also incorporates the minimal 10 minutes that it takes people to ready their belongings and get prepared to leave in the various transport mechanisms i.e. car, bus and helicopter. This means that the total evacuation time after notification is 67 minutes.

If the tsunami's epicentre originates near Kermadec island, the time taken for the wave to reach Te Atatu is 139 minutes. This, tragically, means the entire population could not be successfully evacuated and a number of citizens would not leave the area in time before the initial strike of the tsunami.

However, if the epicentre is located either around Tonga or along the Chilean Coast, the evacuation time is sufficient to allow the entire population to escape safely.

This means that there is a definite need in the future to develop and continue to improve our safety procedures for these natural disasters as loss of human life is intolerable.

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