When engineering isn't enough – planning for immediate evacuation in Wellington Region following major subduction zone earthquakes

2013 NZSEE Conference

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ABSTRACT: Despite decades of building strengthening and more robust building codes, there exists a significant residual risk to the people of Wellington Region from a major earthquake and tsunami event on the offshore subduction zone. Strong shaking will result in widespread damage displacing people from homes and other structures, and will also trigger (self) evacuation of the designated tsunami evacuation zones. Modelling of damage to structures and tsunami self-evacuation indicates that up to 116,000 people could be displaced immediately following the event. Many will be able to return to their homes following the tsunami all-clear but for the immediate interim, safe shelter will be required.

1 INTRODUCTION: EVACUATION DUE TO EARTHQUAKE DAMAGE OR TSUNAMI THREAT

1.1 Evacuation triggers

For many natural perils, evacuation by citizens occurs prior to event impact. In these situations warnings are provided by authorised agencies or experienced as natural phenomena, and the public either choose to, or are requested to, evacuate in a timely fashion to prevent casualties and reduce loss. Perils that typically provide warning triggers include: cyclones, floods, distant and local tsunami, and wind storms with associated coastal inundation (storm surge). However, earthquakes do not provide pre-impact evacuation triggers. This lack of warning prior to impact results in damaging earthquake events generating post-event, rather than pre-event, evacuation (Wright & Johnston 2010). An intensely felt and damaging earthquake experienced in coastal population centres produces a complex set of circumstances when considering evacuation behaviour, because the public must consider immediate damage to structures and the threat of a local-source tsunami in their decision-making (Leonard et.al. 2012).

1.2 Decision to evacuate post-earthquake

Decision-making for immediate post-earthquake evacuation can be considered to be driven primarily by structural damage, i.e. is the structure uninhabitable. Other structural considerations may influence the decision to evacuate such as loss of utility services. However, as was seen in Canterbury following the recent earthquake events, many citizens choose to remain in their residences after loss of utility networks. Other considerations for evacuation are non-structural such as fear of aftershocks, desire to be near friends or family in other locations, loss of employment or other income. These non-structural issues are discussed in greater detail in Wright & Johnston (2010). However, for the purposes of this paper, discussions regarding immediate evacuation following a major Hikurangi Margin subduction zone event off of East coast North Island, New Zealand (Figure 1), focus on post-earthquake evacuation triggered by structures being rendered uninhabitable or tsunami self-evacuation.

1.3 **Decision to evacuate due to potential tsunami threat**

For evacuation purposes, tsunami can be characterised by the potential warning time available. Distant source tsunami are those which provide adequate warning time for official public alerting processes to be applied and for the public to respond. In New Zealand, distant source tsunami are those that have at least three hours of travel time from source to the arrival of the first wave anywhere on New Zealand shores. Local source tsunami are those which occur offshore of areas at-risk and if generated by a major earthquake (as opposed to a submarine landslide or volcano) will be experienced as strong shaking by those at-risk.

Local-sourced tsunami can arrive on-land within minutes and typically include arrival times ranging from a few minutes up to one hour from tsunami generation. These locally sourced tsunami events, due to the short arrival time, do not usually allow for official public alerting activities, and so evacuation must be triggered by the public understanding and acting on the natural warning of shaking that is long (one minute or more) or strong (so strong that a person cannot stand). The key message for the public is that the shaking is the best warning possible.

A third class of tsunami can be described as regional; that the source is distant enough not to create a natural warning for the population at risk, but also close enough to create difficulties for officials in terms of time available to generate and distribute warnings which allow for timely evacuation. These types of events are potentially the most problematic for officials charged with public alerting (Leonard et. al. 2012).

2 **WELLINGTON REGION EARTHQUAKE AND TSUNAMI RISK FROM A MAJOR HIKURANGI MARGIN SUBDUCTION ZONE EVENT**

2.1 **Subduction zone event**

This paper discusses the challenges associated with evacuation triggered by a major subduction zone event impacting Wellington Region, i.e. a local tsunami. The Pacific Plate is subducting beneath the Australian Plate to the east of the North Island, creating a dynamic zone of activity capable of generating very large earthquakes (Wallace et. al. 2009). The Hikurangi Margin section of the plate boundary runs roughly parallel to the eastern coast of the Wairarapa district of Wellington (Figure 1).

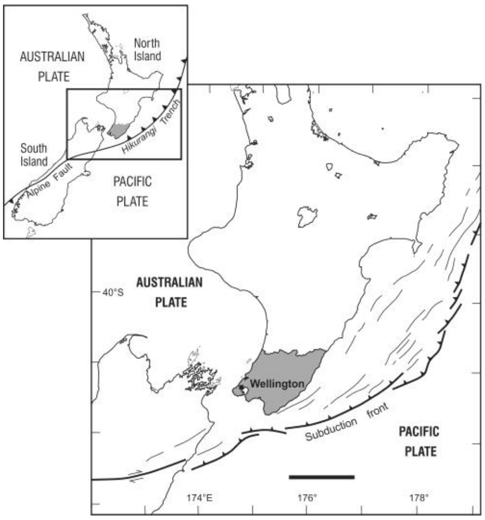

Figure 1 The offshore Hikurangi margin subduction zone

This section of the plate boundary is now thought to be capable of generating a range of event magnitudes including very large earthquakes (>M_w 9) similar to the 2011Great Tohoku earthquake which generated a devastating tsunami in Japan. The average return period for very large events on the Hikurangi Margin is not well defined; however, it is estimated to be at least 300 years (Wallace et. al. 2009), but could be much longer than that. In this paper we consider a very large, yet credible, event of M_w 8.9 on the Wellington portion of the subduction zone, capable of generating extreme shaking of intensities MM9-MM10. People should consider the shaking as a natural warning for potential tsunami and act accordingly. Shaking of this intensity is also expected to generate significant damage to buildings and infrastructure.

2.2 Methodology for mapping evacuation zones in Wellington

It is recognised that there are many sources for damaging tsunami in Wellington Region, and that each source can produce a range of different events. Modelling all possible tsunami waves offshore and translating wave heights offshore into onshore inundation zones that can be used for tailor-made, event-specific evacuation zones is not possible or affordable based on current resources, data and understanding of the multitude of potential tsunami sources for the region. For this reason, a pragmatic and cautionary approach has been applied to generate an evacuation zone which envelopes all possible maximum events. The methodology used to create the evacuation zones, using a GIS-based attenuation rule applied to probabilistically-determined wave-heights at the coast, is described in detail in Leonard et al. (2009). It also provides for two lesser evacuation zones.

No one event is expected to reach the boundary of the evacuation zone in all locations, due to wave orientation, attenuation, wave period and other influences: therefore, this method will always produce over-evacuation. However, it is considered this approach is the safest and most reasonable given the uncertainty inherent in tsunami generation and behaviour, and the infrequency of major events. This evacuation zone, which applies to all felt major earthquakes and should be evacuated based on natural ground shaking warnings without waiting for any official notification, is described and mapped by authorities as “the Yellow Zone”. The methodology used to generate this zone has been validated against recorded maximum inundation in the Tohoku tsunami, March 2011. The validation showed that for a 35m run-up value, the zone successfully encompassed the recorded inundation extent (Fraser & Power, in press).

The methodology also allows for smaller areas to be evacuated based on official warnings for distant source tsunami, when time, monitoring and expertise allows estimation of smaller wave heights and lesser inundation. For these events officials can advise the public whether to evacuate the Red Zone (basically a near-shore marine and beach exclusion zone for smaller, distant events) or the Orange Zone (a larger zone based on maximum distant events, which in most locations are smaller than potential inundation from local tsunami, but still include considerable on-land threat and inundation). Figure 2 shows examples of evacuation zones within Wellington Region. It can be seen that the Yellow Zone encompasses the Red and Orange Zones, therefore when a natural tsunami warning is experienced the public response should be to evacuate all zones (Leonard et. al. 2009).

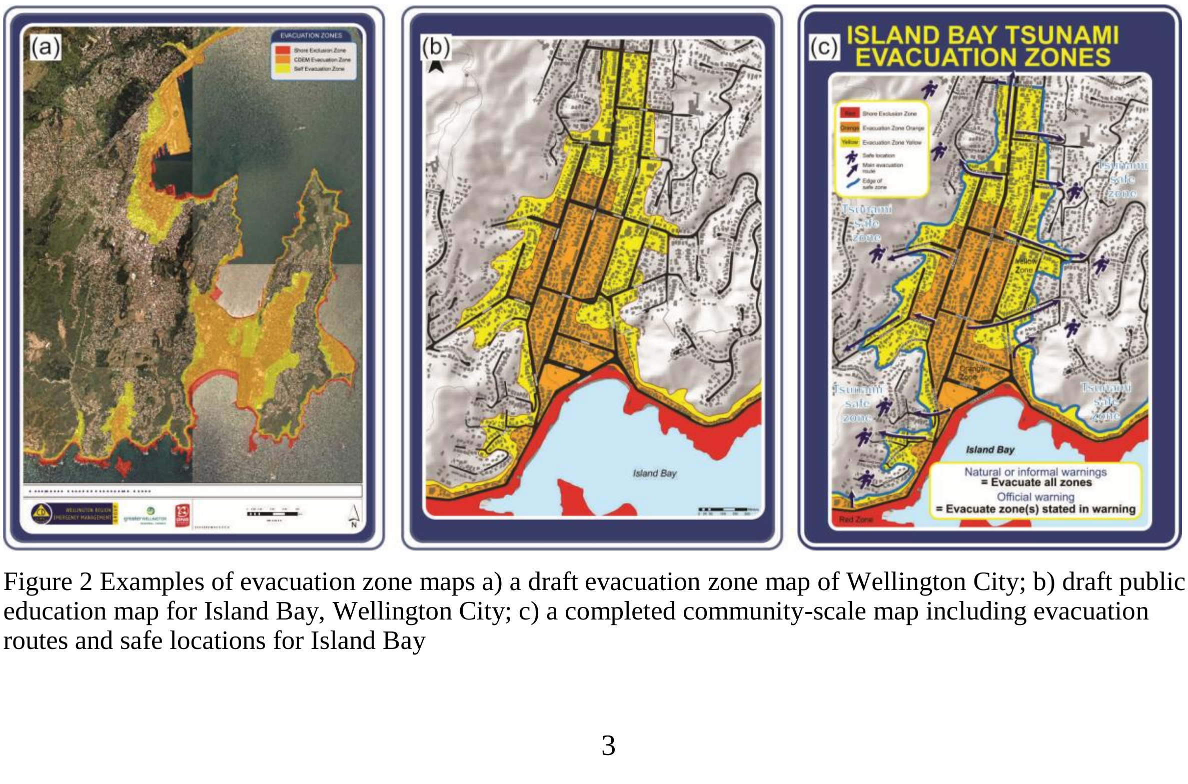

Figure 2 Examples of evacuation zone maps a) a draft evacuation zone map of Wellington City; b) draft public education map for Island Bay, Wellington City; c) a completed community-scale map including evacuation routes and safe locations for Island Bay

2.3 Public education; zones, warnings and response

Public education regarding earthquake risk and tsunami evacuation zones comes under the domain of Civil Defence Emergency Management (CDEM) officials. Wellington has recently amalgamated all CDEM units within councils to form a region-wide body responsible for disaster planning and response. Community engagement including meetings and exercises, and publications and resources covering earthquake and tsunami preparedness (including maps of the evacuation zones and information about official and natural warnings) are provided by the Wellington Region Emergency Management Office (WREMO). Their responsibilities also include planning for and coordinating post-event welfare provision, as well as liaison with communities, emergency responders and the national CDEM body prior to and during events.

3 ESTIMATING NUMBERS OF EVACUEES FOR A SUBDUCTION ZONE EVENT IMPACTING WELLINGTON REGION

3.1 Method for estimating sheltering needs

Estimation of immediate Wellington Region evacuee numbers for a major (M_w 8.9) event requires several inputs:

- The time of event, as this affects population distribution;
- The number of buildings within the tsunami evacuation Yellow Zone and their expected occupancy rates;
- Information on the construction type, age and quality of the buildings in Wellington Region and how they will perform when subjected to shaking intensity MM9-10; and,
- Assumptions regarding self-evacuation rates in response to the natural ground shaking warning provided by the earthquake.

We estimate the maximum possible number of evacuees to allow those charged with planning for evacuation and sheltering to consider credible worst-case scenarios as well as lesser events. Therefore, because the majority of the coastal buildings of the Region are residential, the night-time census of population will be used to maximise the numbers of people potentially within the tsunami evacuation zone. The population residing within the Yellow Zone at night has been determined as 80,210 (Table 1).

Table 1 Night-time Population of Wellington Region by building type including break-down of tsunami evacuation Yellow Zone population

Building Use	Region Buildings	Region People	Yellow Zone Buildings	Yellow Zone People
Dwelling	182,139	421,463	36,110	68,553
Apartment	923	15,582	319	5626
Hotel/Motel	175	4361	59	1855
Rest-home	629	5501	19	616
Hospital/Clinic	88	6895	5	111
Non-residential	10,162	7788	3900	3449
Total	194,116	461,590	40,412	80,210

In recent years we have modelled damage to buildings and estimated casualties for large Wellington Region earthquakes, including losses and casualties from subsequent tsunami where appropriate, in a variety of client and publically-funded projects. In brief, our modelling procedure was to:

- Create an earthquake scenario (e.g. M_w 8.9 subduction zone earthquake)

- Estimate the shaking intensity pattern over the Wellington Region using the MMI attenuation model (Dowrick & Rhoades 2005).
- Estimate the damage state of each building using fragility functions linking the shaking intensity with expected levels of damage in various types of building (Spence et al., 1998; Cousins, 2010),
- Evacuate people from the tsunami Yellow Zone in response to the strong shaking (temporary evacuation for most),
- Given the seabed dislocation, model the generation and propagation of a tsunami (Cousins et. al. 2009),
- Estimate water depths throughout the built-up areas (Cousins et al 2009), and then
- Re-estimate the damage state of each building in the city using fragility functions linking the depth of inundation with expected levels of damage in various types of building, and finally
- Using the most severe of the damage state results from earthquake and tsunami, decide how long each building would be uninhabitable.

The modelling relied on six defined damage states (DS) based on how structures are expected to perform when subjected to severe shaking or inundation, viz. None (DS0), Light (DS1), Moderate (DS2), Heavy (DS3), Severe (DS4), and Collapse (DS5). Buildings in damage states 3, 4 and 5 were deemed to be uninhabitable for varying lengths of time.

The assets models were taken from RiskScape, a risk modelling package being developed jointly by GNS and NIWA (Institute of Geological and Nuclear Sciences, and National Institute of Water and Atmospheric Research) (King et. al. 2009; Reese et. al. 2010).

Wellington Region is known to have a relatively high earthquake hazard; therefore many commercial and public buildings have stricter earthquake resistant requirements than other parts of New Zealand. However, these rules have been tightened over the decades and older buildings are typically not built to the standard of newer structures. It can be expected with such strong shaking, that despite Wellington's strict seismic building code, some older or less well-built buildings, or buildings on less stable soils will suffer damage of a sufficient severity as to render them uninhabitable. Tsunami damage to coastal buildings will also be significant (Cousins et. al. 2009).

3.2 **Evacuation compliance rates**

The best-case scenario in terms of public safety and a well-prepared population is 100% understanding of the natural ground shaking warning coupled with 100% evacuation in a timely manner to areas outside all evacuation zones. However, this is worst case scenario in terms of planning and response for traffic management (pedestrian or vehicle assisted), provision of emergency shelter, and assisted evacuation for those with limited mobility or other impairments. For the purpose of this paper we assume an optimistic 100% evacuation rate. It is very difficult to achieve this value but we know from the Great Tohoku earthquake in Japan that 96% of people who previously resided in the inundated area survived, despite confusion over official warnings conflicting with natural warnings and over-optimism regarding tsunami seawall protection (Fraser et. al. 2012a)

The other consideration for determining evacuation numbers is those displaced by at least heavy damage to buildings (DS3 to DS5). Modelling as summarised above indicates that 24,333 buildings, accommodating 57,310 people, will be rendered uninhabitable (Table 2). These figures include 21,451 people located within buildings in DS3-5 that are also located within the Yellow Zone, resulting in those residents having two reasons to evacuate. When we account for this, we determine that 35,859 people will be immediately displaced due to heavy building damage outside the Yellow Zone. In addition to this figure, 80,211 people are displaced due to self-evacuation of the Yellow Zone regardless of building damage, resulting in a total of 116,070 displaced people. Table 3 outlines the contribution to total evacuee numbers of displacement due to damage and displacement due (initially) to tsunami self-evacuation.

Table 2 Numbers of people in buildings in various damage states – damage due to shaking and tsunami for all of Wellington Region including the tsunami evacuation Yellow Zone

Building Use	DS_0 None People (n)	DS_1 Light People (n)	DS_2 Moderate People (n)	DS_3 Heavy People (n)	DS_4 Severe People (n)	DS_5 Collapse People (n)
Dwelling	116,903	154,877	97,252	38,095	4137	10,185
Apartment	4951	4662	3647	1951	164	206
Hotel/Motel	1053	1694	822	519	141	132
Rest-home	1561	2008	1318	562	32	21
Hospital/Clinic	3888	2211	729	67	0	0
Non-residential	2322	2820	1634	852	90	66
Total	130,678	16,8272	10,5402	42,046	4654	10,610

Table 3 Numbers of people in buildings in various damage states, for buildings OUTSIDE the tsunami evacuation (Yellow) zone and numbers of people INSIDE the Yellow Zone who are assumed to have self-evacuated.

Building Use	DS_0	DS_1	DS_2	DS_3	DS_4	DS_5	Yellow Zone
Dwelling	100,265	134,445	84,663	29,201	3231	1088	68,556
Apartment	3623	3399	2080	788	57	8	5626
Hotel/Motel	684	991	418	272	141	0	1855
Rest-home	1447	1630	1299	456	32	21	617
Hospital/Clinic	3846	2168	703	67	0	0	111
Non-residential	1234	1689	918	414	54	29	3446
Total	111,099	144,322	90,081	31,198	3515	1146	80,211

4 IMPLICATIONS FOR PUBLIC SHELTERING REQUIREMENTS

4.1 Immediate evacuation needs

This paper is largely focussed on immediate evacuation; that is, the 24 hour period following the subduction zone earthquake. Many of those who self-evacuate the tsunami evacuation Yellow Zone may be able to return to their homes following the official tsunami "all-clear" providing the homes are in lesser damage states (including undamaged) and still inhabitable. If the earthquake occurs at night, there is added complexity for those seeking safe shelter as it is likely there will be electricity outages, interruption to communications and limited visibility due to lack of lighting and debris dust. Identification of safe locations (and ideally earthquake-resistant) shelter at these locations prior to a strong earthquake will allow communities to plan and test through exercises, evacuation practicality, accessibility and time required. The WREMO is already assisting communities with this process. However, because the process is relatively young, with the focus so far having been on mapping evacuation zones and community identification of routes and safe locations, widespread evacuation drills are yet to be held.

4.2 **Evacuation safe location options**

There are a number of options open to those displaced due to tsunami self-evacuation or building damage:

1. Relocate to friends or family in a less damaged building within the Region
2. Relocate to paid accommodation, where facilities are able to operate, within the Region
3. Relocate to the nearest high ground, (for coastal self-evacuees with no other safe location previously identified)
4. Relocate to a public shelter (these are unlikely to be operational for receiving evacuees for some hours following the earthquake)
5. Relocate to a designated tsunami vertical evacuation shelter or safe location (with some resources, e.g. water available)
6. Leave the region and use Option 1 or 2.

Some of these options are likely to be severely limited due to the expected damage to transport infrastructure following such intensive shaking with resulting landslides and liquefaction across the region in weaker soils or unstable slopes (Brabhaharan 2000). Wellington Region does not currently designate vertical evacuation shelters in planning for tsunami response; however, findings from recent research undertaken in Japan indicate these can be effective in saving lives in locations which either have limited access to higher ground or are so densely populated that congestion prevents people reaching safety in a timely manner (Fraser et. al. 2012b). The scale of the displaced population in Wellington Region is such that due consideration must be given to facilitating with communities a range of safe location options that best meet local needs.

5 CONCLUSION

Up to 116,000 people could be immediately displaced following a major subduction zone earthquake off the east coast of Wellington Region. This number of evacuees resulting from a single event has not before been experienced in New Zealand and reinforces the current planning being undertaken by WREMO to identify tsunami safe locations and by councils throughout the region to undertake seismic strengthening. Engineering solutions cannot reduce all risk to the population. Therefore, consideration of vertical evacuation options, further roll out of tsunami evacuation route planning with communities, and conducting physical evacuation exercises should be considered as priorities for those charged with overseeing disaster preparedness in the Wellington Region.

6 ACKNOWLEDGEMENTS

This research is supported by the Wellington It’s Our Fault project and Natural Hazard Research Programme Core Funding. Thank you to Russ Van Dissen for reviewing this paper.

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