Review of Tsunami Hazard in New Zealand (2013 Update)

Compiled by William Power

GNS Science Consultancy Report 2013/131
August 2013

GNS SCIENCE
TE PŪ AO

Review of Tsunami Hazard in New Zealand (2013 Update)

Compiled by William Power

GNS Science Consultancy Report 2013/131
August 2013

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to the Ministry of Civil Defence and Emergency Management. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of, or reliance on any contents of this Report by any person other than the Ministry of Civil Defence and Emergency Management and shall not be liable to any person other than the Ministry of Civil Defence and Emergency Management, on any ground, for any loss, damage or expense arising from such use or reliance.

The data presented in this Report are available to GNS Science for other use from 13 September 2013.

BIBLIOGRAPHIC REFERENCE

Power, W. L. (compiler). 2013. Review of Tsunami Hazard in New Zealand (2013 Update), *GNS Science Consultancy Report* 2013/131. 222 p.

CONTENTS

EQUATIONS

FIGURES

TABLES

APPENDICES

EQUATIONS

APPENDIX FIGURES

APPENDIX TABLES

EXECUTIVE SUMMARY

In this report we have examined all likely sources of tsunami that could affect New Zealand, and evaluated their potential to generate tsunami, the likely waves produced, and the likely size of tsunami at the New Zealand coast. This review builds on the 2005 *Review of Tsunami Hazard and Risk in New Zealand*, and summarises the current state of knowledge, highlighting the results of new research and changes in scientific understanding between 2005 and 2013. A substantially revised probabilistic hazard model has been constructed for this report, which for the first time estimates the tsunami hazard for all parts of the New Zealand coastline.

This report focuses on quantifying tsunami hazard, i.e., the likely size of tsunami for specified timescales, along with estimates of uncertainty. It does not provide estimates of risk, i.e., expected costs of damage and numbers of casualties. Every effort has been made to assign realistic parameters for seismic tsunami sources in terms of their likely earthquake magnitudes and frequencies, but there are large uncertainties. Our probabilistic method incorporates these uncertainties throughout the analysis, so that the results contain realistic 'error bars'.

The hazard posed by tsunami generated by landslides and volcanic activity has been carefully considered. At this time it has not been possible to quantify the hazard from these sources, though research work towards this goal is being undertaken. For most parts of New Zealand, the hazard posed from these tsunami sources on time frames of up to 2500 years is considered secondary to the hazard from earthquake-generated tsunami. This is consistent with the global experience of tsunami, in which relatively few events in the instrumental era have been attributed to landslide and volcanic sources relative to the number of earthquake-generated tsunami.

The 2011 Tohoku tsunami in Japan illustrates some of the key changes in scientific knowledge since 2005. That event was the latest in a sequence, starting with the 2004 Indian Ocean tsunami and the subsequent 2009 South Pacific tsunami, that were produced by earthquakes substantially larger than had been considered likely to occur at those locations. These earthquakes contradicted previous geophysical assumptions about the maximum magnitudes of earthquakes that could be created on tectonic plate boundaries. There are now far fewer restrictions on possible maximum magnitudes than was previously thought to be the case, and the new probabilistic model attempts to account for this. It is now known that there was a similar tsunami in Japan in AD 869, indicating that the interval between the largest earthquakes there is over a thousand years. The tectonic plates in Japan are converging twice as fast as those around New Zealand, which suggests that the interval between the largest earthquakes on our local plate interfaces could be in excess of two thousand years. The important implication here is that our brief historical record of 200 years can, on its own, provide very little guidance in estimating the magnitude of the largest earthquakes that New Zealand may experience.

To improve estimates of the earthquake potential of subduction plate interfaces around New Zealand, where one plate is pushed below another, we must study the evidence of prehistoric tsunami and earthquakes (paleotsunami and paleoearthquakes) in the geological record, and work with the global community to find new, statistically valid, geophysical estimates.

The movement between the tectonic plates in the Tohoku tsunami was very non-uniform—in some areas the plates moved more than 50 metres whereas in many other areas the movement was much less, typically around 5 to 10 metres. This 'non-uniform slip' has important implications for tsunami, as the distribution of movement between the plates affects the motion of the seabed, which determines the size of tsunami. The probabilistic model in this report attempts to incorporate the effects of this phenomenon to a first level of approximation; this is at the cutting-edge of current science and the analysis represents a first attempt at tackling this important problem.

The greater uncertainty that now exists regarding the maximum size of earthquakes on plate boundaries close to New Zealand, has led to an increase in the estimated hazard from tsunami triggered by local and regional sources. While for most parts of New Zealand the overall levels of tsunami hazard have not changed greatly from the assessed hazard levels in the 2005 report, the estimated hazard has generally increased in those areas most exposed to tsunami from local subduction zones – notably the east-facing coasts of the North Island, and the southwest corner of the South Island.

1.0 INTRODUCTION

1.1 SCOPE OF THIS REPORT

Following the disastrous tsunami in the Indian Ocean on December 26, 2004 the New Zealand Government resolved to consider the risk of such events in New Zealand. The Ministry of Civil Defence & Emergency Management commissioned a report from the Institute for Geological and Nuclear Sciences (now GNS Science) to answer this question. The report "Review of Tsunami Hazard and Risk in New Zealand" was compiled by Kelvin Berryman and completed in 2005.

In the period between 2005 and 2012 much research has been undertaken on the subject of New Zealand's tsunami hazard. A new report was commissioned by the Ministry of Civil Defence & Emergency Management to update the findings of the original 2005 report with this new information. The new report builds upon the findings and structure of the original. Like the original it represents the work of many scientists, and it directly incorporates material from the original report where the present understanding is unchanged.

This report is a synthesis of available data on the hazard of distant, regional and local tsunami in New Zealand. It includes summaries of geologically and historically derived information on the occurrence of tsunami, and of numerical modelling studies. A revised probabilistic model of tsunami hazard has been developed for this report which incorporates new information on tsunami sources resulting from studies since 2005. It also differs from the 2005 hazard model by developing hazard estimates for the entire coast, not only the major cities.

Estimates of expected casualties and damage costs have not been included in this report. It is anticipated that the Riskscape project (see Section 2.4.4.2) will use the tsunami hazard model developed here to produce revised estimates of tsunami risk.

1.2 CONTRIBUTORS

Many people have worked on this project. The project also draws heavily on the 2005 report, particularly in the area of tsunami sources. The following researchers are acknowledged for their contribution to writing the following chapters of this report:

Introduction (2013 update): William Power[1]

Tsunami Impacts: Stefan Reese[2, 3]

Historical and pre-historical tsunami databases: Kate Clark[1]

Tsunami Modelling: Xiaoming Wang[1], William Power[1]

Tsunami Sources (2013 update): Laura Wallace[1, 4], William Power[1], Joshu Mountjoy[2]

Probabilistic Modelling: William Power[1], Joshu Mountjoy[2]

Discussion and Conclusions: William Power[1]

[1] GNS Science
[2] NIWA
[3] SwissRe
[4] University of Texas

The following are additionally acknowledged for their scientific contribution to this report in the following areas:

Tsunami Sources: Philip Barnes[2], Kelvin Berryman[1], Nicola Litchfield[1], Andy Nicol[1], Martin Reyners[1], Aggeliki Barberopoulou[1], Stuart Fraser[1, 5]

Probabilistic Modelling: Christof Mueller[1], Stuart Fraser[1,5], Biljana Lukovic[1]

The following are additionally acknowledged for their contributions to the 2005 report on which this report draws:

Warwick Smith[1], Mark Stirling[1], David Heron[1], Gaye Downes[1], Ursula Cochran[1], Willem de Lange[6], James Goff[1, 7], Scott Nichol[8], Roy Walters[2], Terry Webb[1], Russell Robinson[1], John Beavan[1], Rob Langridge[1], Geoffroy Lamarche[2], Arne Pallentin[2], Mauri McSaveney[1], Nick Perrin[1], Ian Wright[2], Alistair Barnett[9], Doug Ramsay[2], Jim Cousins[1], Andrew King[1].

Project management was provided by: Ursula Cochran[1] and Hannah Brackley[1], and document editing and preparation by: Eileen McSaveney[1] and Kat Hammond[1]. Reviewing was performed by Emily Lane[2], David Burbidge[10] and Kenji Satake[11].

1.3 STRUCTURE OF THE REPORT

In this Chapter 1 we briefly describe the structure of the report, what tsunami are, how they are generated, and what damage they can do. Chapter 2 describes the impacts of tsunami and how they may be quantified to evaluate tsunami risk. In the following chapter on historical and paleotsunami (Chapter 3) we present the current state of knowledge about tsunami that have occurred in our relatively recent recorded history and earlier tsunami that have left evidence in the form of sedimentary deposits.

Chapter 4 describes techniques for numerical modelling of tsunami, and summarises modelling work that has been done for New Zealand. Chapter 5 on Tsunami Sources characterises the set of possible causes of tsunami, whether generated by earthquake, landslide, volcano or bolide impact, and whether this occurs close to New Zealand or far overseas.

A nationwide model of tsunami hazard was developed for this report. The model, the input data it uses, and the results it produces are the subject of Chapter 6. Finally in Chapter 7 there is a discussion about the findings of the report and conclusions are drawn, including a series of recommendations for further research.

[5] Massey University
[6] Waikato University
[7] University of New South Wales
[8] University of Auckland
[9] Barnett & McMurray Ltd
[10] Geoscience Australia
[11] Earthquake Research Institute, University of Tokyo

1.4 WHAT IS A TSUNAMI?

A tsunami is a natural phenomenon consisting of a series of waves generated when a large volume of water in the sea, or in a lake, is rapidly displaced. Tsunami are known for their capacity to violently inundate coastlines, causing devastating property damage, injuries, and loss of life. The principal sources of tsunami are:

- large submarine or coastal earthquakes (in which significant uplift or subsidence of the seafloor or coast occurs)
- underwater landslides (which may be triggered by an earthquake, or volcanic activity)
- large landslides from coastal or lakeside cliffs
- volcanic eruptions (e.g., under-water explosions or caldera collapse[12], pyroclastic flows[13] and atmospheric pressure waves)
- meteor (bolide) splashdown, or an atmospheric air-burst over the ocean.

In a tsunami, the whole water column from the ocean floor to its surface is affected, the initial disturbance creating a series of waves radiating outwards, until the waves either dissipate or collide with a shoreline. Tsunami waves can arrive at nearby shores within minutes, or travel across the deep ocean basins at speeds in excess of 500 kilometres per hour (km/hr). Very large sources (disturbances) are required to cause tsunami that are damaging at great distances from the source. For example, the 1960 magnitude[14] (M) 9.5 Chile earthquake, which had a rupture length of several hundred kilometres, produced a 25 metre (m) high tsunami locally, over 10 m in Hawaii, and nearly 4 m in New Zealand. On the other hand, tsunami that are generated locally do not need such a large source to be large and damaging at nearby shores. For example, the 1947 M7.1 earthquake off Gisborne affected 120 km of coastline, with a tsunami of 10 m maximum height occurring along tens of kilometres of coast north of Gisborne.

The amplitude of tsunami waves[15] in deep water is generally less than one metre, producing only a gentle rise and fall of the sea surface that is not noticed by ships, nor able to be seen by aircraft, although new satellites with sea-surface elevation technology can detect large tsunami in the deep ocean. When tsunami waves reach shallower waters, their speed decreases rapidly from their deep-ocean values, and at the same time their height increases

[12] CALDERA COLLAPSE refers to the formation of a large depression when the underlying magma chamber of a volcano collapses during or following an eruption or explosion. The collapsed caldera is a crater-shaped depression which may be many hundreds of square kilometres in area, and many hundreds of metres deep. The collapse needs to occur suddenly to cause a tsunami.

[13] A PYROCLASTIC FLOW is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano at hundreds of km/hr, and can have temperatures greater than 500°C. In a coastal setting, such flows cause tsunami when they enter the sea. Pyroclastic flows can also occur from underwater volcanoes.

[14] The MAGNITUDE of an earthquake is a measure of its energy. There are several methods for estimating the magnitude, which often give slightly different results. At present the most widely used form of the magnitude is the moment magnitude M_w. In this report M is used to signify an approximate generic magnitude in situations where there is significant uncertainty; this is often the case when discussing earthquakes that occurred before the instrumental era.

[15] TSUNAMI HEIGHT (m) is the vertical height of waves above the tide level at the time of the tsunami (offshore it is approximately the same as the AMPLITUDE). It is far from constant, and increases substantially as the wave approaches the shoreline, and as the tsunami travels onshore.The term "WAVE HEIGHT" is also often used, but there is a potential ambiguity as many scientists define WAVE HEIGHT as the peak-to-trough height of a wave (approximately twice the amplitude). Note that this is a change in terminology from the 2005 Tsunami Hazard and Risk Review, intended to bring greater consistency with international usage of these terms.

(as the front of each wave slows down and the back of the wave, which is moving faster, catches up on the front, piling the water higher). A tsunami wave that is only half a metre high in the open ocean can increase to a devastating 10 m high wave travelling at 10-40 km/hr at impact with the shore.

Tsunami waves differ from the usual waves we see breaking on the beach or in the deep ocean, particularly in the distance between successive waves, because tsunami waves occupy the whole ocean depth and not just the top few tens of metres as in storm waves. Both of these factors contribute to the huge momentum of water in a tsunami at the coast. The distance between successive tsunami waves (called wavelength) can vary from several kilometres to over 400 km, rather than around 100 metres for normal waves at the beach. The time between successive tsunami wave crests (called period) can vary from several minutes to a few hours, rather than the few seconds usual for beach waves. Hence, when tsunami waves reach the shore, they continue to flood inland over many minutes, and then the waves may retreat over as many minutes, before the arrival of the next wave. The waves may come in at irregular intervals, often without complete withdrawal of the inundating water from previous waves due to retardation of the outflow and impoundments. The first wave to arrive may not be the largest wave.

New Zealand's location astride a plate boundary means that it experiences many large earthquakes. Some cause large tsunami. New Zealand's coasts are also exposed to tsunami from submarine and coastal landslides, and from island and submarine volcanoes. In addition, tsunami generated by large earthquakes at distant locations, such as South America, or western North America and the Aleutians in the north Pacific Ocean, can also be damaging in New Zealand.

Tsunami with run-up heights[16] of a metre or more have occurred about once every 10 years on average somewhere around New Zealand, a similar frequency to Hawaii and Indonesia, but about one third that in Japan. Smaller tsunami occur more frequently, the smallest of which are only detectable on sea-level recorders.

New Zealand can expect tsunami in the future. Some coasts are more at risk than others because of their proximity to areas of high local seismic activity, or exposure to tsunami from more distant sources. No part of the New Zealand coastline is completely free from tsunami hazard.

[16] TSUNAMI RUN-UP (m), a measure much used in tsunami-hazard assessment, is the elevation of inundation above the instantaneous sea level at the time of impact at the farthest inland limit of inundation. This measure has a drawback in that its relationship with the amplitude of the waves at the shore depends markedly on the characteristics of waves and on the local slopes, vegetation, and buildings on the beach and foreshore areas, so it is highly site-specific.

1.5 WHAT DAMAGE DOES A TSUNAMI DO?

Tsunami damage and casualties are usually from four main factors (see also Table 1.1 and further discussion in Chapter 2):

- Impact of swiftly-flowing torrent (up to 40 km/hr), or travelling bores[17], on vessels in navigable waterways, canal estates and marinas, and on buildings, infrastructure and people where coastal margins are inundated. Torrents (inundating and receding) and bores can also cause substantial erosion both of the coast and the sea-floor. They can scour roads and railways, land and associated vegetation. The receding flows, or "out-rush", when a large tsunami wave recedes are often the main cause of drowning, as people are swept out to sea.
- Debris impacts—many casualties and much building damage arise from the high impulsive impacts of floating debris picked up and carried by the in-rush (inundating) and out-rush (receding) flows.
- Fire and contamination—fire may occur when fuel installations are floated or breached by debris, or when home heaters are overturned. Breached fuel tanks, and broken or flooded sewerage pipes or works can cause contamination. Homes and many businesses contain harmful chemicals that can be spilled.
- Inundation and saltwater-contamination by the ponding of potentially large volumes of seawater will cause medium- to long-term damage to buildings, electronics, fittings, and to farmland.

[17] Tsunamis often form bores in harbours, man-made waterways, and in coastal rivers and streams. A bore can be a smooth or turbulent, non-breaking step-like increase in water height resulting in wall-like change in water levels from normal to some higher level. They can travel 3 or more kilometres up a river with the water many metres above the normal level, sometimes well over the bank height, causing damage to bridges and wharves, and causing water to flood nearby flat areas.

Table 1.1 Summary of damage that can be caused by tsunami waves.

People and animals	**Built environment**	**Natural environment**	**Shipping**
• Washed off feet • Drowned, especially in out-wash • Injured by debris or impact with structures • Skin may be removed by the "sand-blast" effect of suspended particles • Injury/illness due to contact with contaminated water	• Damaged by inundation and deposition of sand • Damaged by floating debris (including cars and boats) • Wooden buildings floated and damaged • Reinforced concrete buildings damaged (with on-land water levels of 4m+) • Reinforced buildings badly damaged (with on land water levels of 10m+) • Coastal wharves, coastal defences (seawalls/gabions) and bridges damaged or destroyed • Riverside wharves and bridges damaged or destroyed 3 km or more upstream by bores • Walls, fences, road surfaces, power/telegraph poles damaged or destroyed • Oil spills from overturned vehicles, heaters or floated storage tanks, with consequent fire danger • Aqua-culture rafts, etc. damaged • Sewerage systems obstructed, or damaged, with consequent contamination	• Erosion or deposition • Trees snapped or uprooted • Long-term sea-water contamination effects (salt) • Sewage contamination • Fish and shellfish thrown ashore, with consequent contamination • Disturbance, siltation, contamination of the near shore marine environment with subsequent reduction in fish stocks	• Ship and boat damage by impact with wharves, breakwaters or other boats • Ship and boat damage by complete withdrawal of water, or too rapid a return of water to allow floating • Ships and boats torn from moorings and thrown on shore • Buoys moved • Channels altered by scouring and deposition • Shipping lanes littered with floating debris • Oil spills from overturned boats and wharf installations with consequent fire danger • Port and marina docking facilities and breakwaters