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HISTORICAL TSUNAMI DATABASE FOR NEW ZEALAND

A thesis
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of the requirements for the Degree
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at the
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by

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ABSTRACT

New Zealand has suffered relatively few tsunamis compared to many countries around or within the Pacific rim, but has experienced over 30 tsunamis during the last 177 years. The larger events occurred prior to the time when coastal settlements became highly populated. The New Zealand Ministry of Civil Defence is responsible for managing such extreme events, and for this function it is advantageous to have a comprehensive database for rapid appraisal of tsunami warnings. This project therefor aims to extend the existing tsunami events data and to present it in an operational database for The New Zealand Ministry of Civil Defence. In addition from the tsunami database, tsunami runup risk and expected tsunami runup heights for several New Zealand coastal sectors were calculated.

Using existing dates of tsunami events, new reports of tsunami waves were researched from South Island newspaper archives. Additional extra information about the tsunami waves, for example wave height and wave period, was also obtained from the newspapers for existing reports.

The tsunami data, including source mechanism data, was entered into a database spreadsheet in the form of a lookup table using Microsoft Excel. Event sources are divided into key regions as defined by The National Geophysical Data Centre of the National Oceanic and Atmospheric Administration. Tsunami events are divided up into key regions defined by Regional Council authorities. The database will enable The Ministry of Civil Defence to predict tsunami heights around New Zealand by interpolating data from past events.

Tsunami return periods and expected runup calculations were made for various sites around New Zealand. It was found that destructive tsunami waves are most likely to originate from local sources. The most common and largest far-field tsunami waves are from the West Coast of South America.

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Introduction

CHAPTER 1 - INTRODUCTION

1.1 WHAT ARE TSUNAMIS

> From their home on Pukihae Street, situated atop a 30-foot-high sea cliff overlooking Hilo Bay, Kapua Heuer and her family saw the events unreel before them. Kapua was busy preparing for the day's activities when suddenly one of her daughters asked, "Mommy, what's wrong with the water?" They all went to the cliff's edge at the end of the yard and saw that the seafloor was becoming exposed as the water withdrew. Far out at the breakwater the outward flow met an incoming wave, and the whole mass of water rushed towards the shore. Instinctively, Kapua and her daughters stepped back - just in time. As the wave collided with the sea cliff, water splashed over the tops of their coconut trees. Then the crash of the arriving wave mingled with the sound of walls and buildings being crushed as the wave struck downtown Hilo. (Dudley and Lee, 1988)

'Tsunami' is a Japanese word meaning 'Harbour Wave'. Tsunamis may be generated from vertical disturbances in the sea floor, which forces a water column to be displaced from its position. The displacement causes a tsunami wave which will then propagate away from the source, ready to unleash its power on coasts that are in its way. Wavelengths of tsunami can exceed 800 km and their periods are usually 20 - 60 minutes (de Lange and Hull, 1994). Due to their large wavelengths, the water depth to wavelength ratio is very small. This means the waves travel as shallow water waves affected by reflection, refraction, diffraction, and shoaling transformations.

Shallow water waves travel at speeds which are given by $\sqrt{gh}$, where h is the water depth and g is gravitational acceleration (de Lange and Hull, 1994). So for open ocean water depths of 3500 m a tsunami will travel at 185 m/s (670 km/hr), while speeds along coasts tend to be around 100 km/hr. Wave heights in the open ocean tend to be very small (less than 1m) but may reach up to 30m along the coast.

Tsunamis can be a large threat to coastal locations (Figures 1.1 and 1.2). Waves similar to the one that hit Hilo in 1960 can strike with very little or no warning, causing considerable amounts of damage. Even locations that are protected from wind generated waves can be victims of the destructive power of tsunamis (Yeh *et al.*, 1994).

FIGURE 1.1 - Damage from a 35-foot tsunami that struck Hilo in Hawaii on 23 May 1960. Photo from the Pacific Tsunami Museum Archives

FIGURE 1.2 - Areas destroyed by the fires and tsunami of the July 13 1993 at Aonea on Okushiri Island. Taken by Kokusai Kogyo Co. Ltd., Japan - Shown by Tsuchiya and Shuto (Eds), 1995.

1.2 NEW ZEALAND'S TSUNAMI HAZARD

> "Mr Tunnicliffe and Mr Winkfield had heard Mr Hall's shouted warning but had barely moved from the door when the first wave struck. The wall of water picked them up and swept them towards the road, then dumped them on the road as it receded. Below them they saw a scene of devastation. Only one room of the Halls' house was still recognisable." (Grayland, 1978)

The above scene was set at Turihaua, just north of Tatapouri, as two waves, about ten meters in height, brought destruction to homes and caused considerable damage to the Tatapouri Hotel in 1947. Compared to many countries around or within the Pacific rim, such as Japan, Indonesia, or Hawaii, New Zealand has suffered very few destructive tsunamis. However, the larger events occurred prior to the time when coastal areas became highly populated (de Lange, 1983). The same wave events today would cause greater damage and be of considerable concern.

New Zealand tectonic structures, such as the Tonga-Kermadec Ridge (de Lange and Hull, 1994) and the New Zealand continental shelf (de Lange, 1983), help to reflect tsunami energy away from New Zealand. However, some structures may also help to reflect energy towards New Zealand. The Great Barrier Reef can focus tsunami energy on the west coast of New Zealand through reflection (Braddock, 1969).

Historical data of tsunami can be an asset to aid in tsunami prediction and hazard assessment for important ports and cities around New Zealand. Numerical models of various scenarios must be calibrated with data of actual events. Unfortunately the data for New Zealand is limited. Historical tsunami data also enables calculations of tsunami return periods and expected wave heights to be made for New Zealand.

1.3 OBJECTIVES

The main aim of this thesis is to assist the Ministry of Civil Defence with an improved database of the tsunami hazard along the New Zealand coast. To achieve this the following objectives were set:

- Extend the collection of historical tsunami data that was initiated by de Lange (1983). This will aid in the assessment of tsunami hazards for important ports and cities around New Zealand's coast. As de Lange's focus was mainly on the North Island (de Lange and Healy, 1986) data collection will be focused primarily on the South Island.

Reports and articles will be researched mainly by visiting libraries located in Wellington, Christchurch and Dunedin as there is a wealth of information there. Dates of tsunami events from 1840-1996 will aid in the speed of data collection.

- Information about the tsunami events will be entered into a computer database. Event locations and tsunami sources will be divided into key regions. This will enable Civil Defence to see expected tsunami runup around New Zealand by either selecting a region in which an event has just occurred or by selecting a region to see what sources have affected it in the past. This system will be similar to the database of earthquake events and tsunami events created for the Kuril-Kamchatka region (Gusiakov and Osipova, 1993) which enables predictions to be made of tsunami sizes for a given earthquake source and magnitude. Because New Zealand has not suffered as many tsunami, a larger error is introduced.

- Using the data obtained from the first objective, calculations of tsunami wave risk will be made for various important cities and ports located around New Zealand. Risk can be calculated using the exceedance frequency method.

Chapter 2

Tsunami Waves

CHAPTER 2 - TSUNAMI WAVES

Tsunami waves were originally called 'tidal waves'. This is not technically true in that tides are caused by gravitational attraction of celestial bodies, mainly from the sun and moon, acting on large water bodies (Bernstain, 1954; Flemming, 1977). Tsunamis are the result of disturbances in a large body of water, and have nothing to do with celestial attraction. However, it is understandable that they were originally called 'tidal waves' as they frequently manifest as irregular oscillations of the tide. This chapter describes how they are created, their energy, how they propagate, and how they affect the coast.

2.1 - GENERATION OF TSUNAMIS

There are many ways in which a tsunami wave is created. Some of the mechanisms are secondary processes set off by the primary mechanisms. Tsunami waves can be formed from submarine landslides which have been set off by earthquakes instead of being formed from fault movement. The three main mechanisms for the generation of tsunamis are submarine fault movement, submarine landslides, and volcanic activity. Most of these involve large vertical displacements of the sea floor and hence disruption of the water column above.

2.1.1 Submarine Fault Movement

Seismic activity on the sea floor is one of the major causes of tsunami waves. However not all submarine fault movements are mechanisms for tsunami generation. Movement can be either be horizontal, vertical, rotational or a mixture of two or all three.

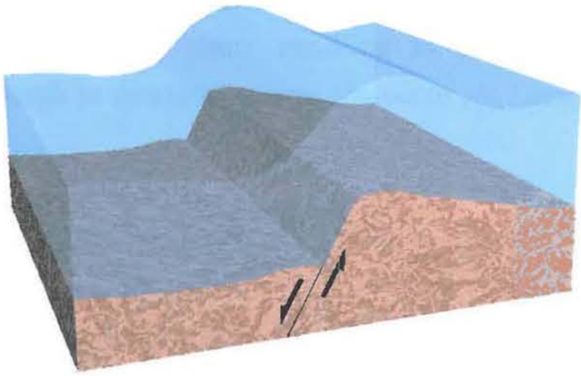

FIGURE 2.1 - Submarine fault movement resulting in tsunami creation. Based on Dudley and Lee, 1988.

Horizontal displacement does not normally lead to disruption of the water column; it is the vertical movement which either forces a column of water up or pulls it down, as shown in Figure 2.1. Dipslip and reverse faults, shown in Figure 2.2, are therefore the major factor controlling tsunami generated from submarine faulting (Iida, 1969); as their fault movement has a greater vertical component than horizontal. Generally only faulting which is shallower than 100 km will produce a tsunami (Iida, 1969).

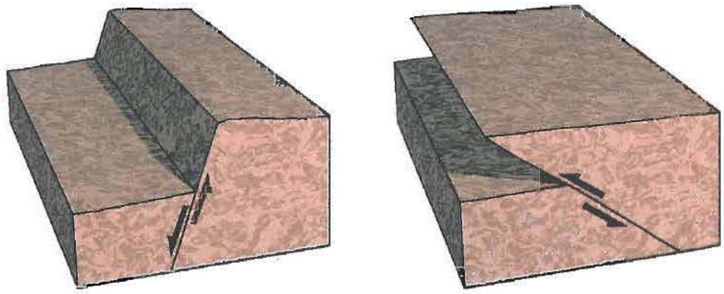

FIGURE 2.2 - Two main fault movements resulting in tsunami creation; Normal faulting (on left) and Reverse faulting (on right). Based on Coch, 1995.

The tsunami waves will radiate out away from the fault in all directions. For long fault zones the tsunami wave energy tends to be greater on the waves which propagate out at right angles to the fault (de Lange and Hull, 1994).

2.1.2 Landslides

Submarine landslides can also produce tsunami waves, as shown in Figure 2.4. Triggering mechanisms for submarine landslides are normally some kind of natural event, for example an earthquake (de Lange and Hull, 1994). Slides normally have to occur near the coast or in estuaries to be of any potential hazard (Jiang and Le Blond, 1994). They tend to produce very little disturbance in the water. However, if the slide is large and the slope is fairly steep, resulting in a fast movement, then water displacement large enough to create a tsunami can occur (de Lange and Hull, 1994).

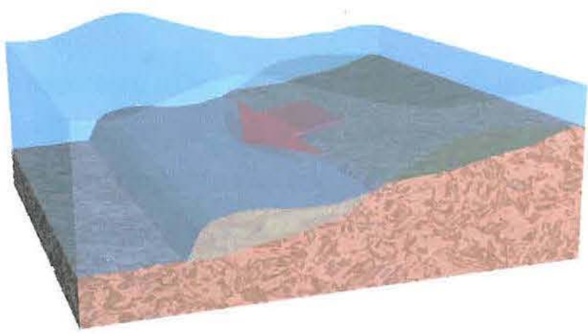

FIGURE 2.4 - Submarine landslide resulting in tsunami. Red arrow shows movement of sea floor. Based on Dudley and Lee, 1988.

Tsunamis can also be generated by terrestrial landslides plummeting into the ocean. The water is displaced as the mass of soil/rock falls in its place, see Figure 2.5. The created wave will tend to radiate away from the coast and not produce a major threat. However if this occurs in a harbor or embayment then the wave can cause damage on the other side. Imamaru, Takahashi and Shuto postulated that the unusually high runups of the tsunami wave which hit Flores Island in 1992 could be explained by local semi-terrestrial landslides although they had no submarine data to support their idea. A large section of a cliff in Kealakekua Bay, Hawaii, fell into the sea in 1951. This resulted in 0.6 m high waves which swept across the shore to the village on the opposite side (Dudley and Lee, 1988).

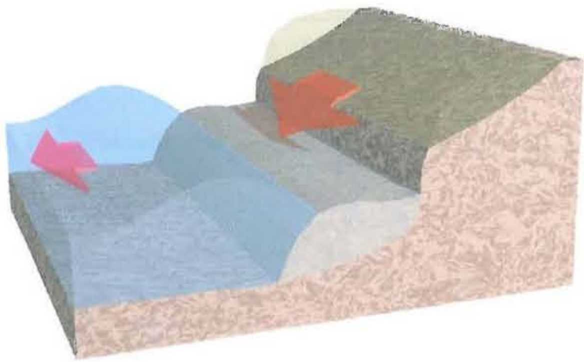

FIGURE 2.5 - Terrestrial landslide resulting in a tsunami. Red arrow shows movement of land slide into sea. Pink arrow shows direction of water surge of tsunami. Based on Dudley and Lee, 1988.

2.1.3 Volcanic Activity

Volcanic eruptions located offshore can sometimes cause tsunami waves. There are many mechanisms by which tsunami waves can be formed from volcanic activity. From examining data on volcanically produced tsunamis, Latter (1981) determined ten different tsunami causing mechanisms and the percentage at which they occur. This is shown in Table 2.1. The three main ones are volcanic earthquakes, pyroclastic flows and submarine explosions.

It is very hard to make estimates of an eruption size (Smith and Shepherd, 1993) and the tsunami characteristics (for example, size) are dependent on the mechanisms duration, orientation and volume of displaced water (de Lange and Hull, 1994). To estimate the hazard of a volcanically generated tsunami we have to consider the mechanisms which are going to be characteristic of the volcano (Tinti and Saraceno, 1991). For example, Smith and Shephard (1993), have studied the Kick'em Jenny volcano located in the Lesser Antilles. They have found that any tsunami causing events from the volcano will probably be from volcanic earthquakes, submarine explosions and caldera collapse.

Volcanoes located within the continental shelf will be of greater concern than ones located outside because their energy can be trapped on the shelf (de Lange and Hull, 1994).

Probable tsunami cause of volcanic origin.	Percentage of total
Earthquakes accompanying eruptions	22
Pyroclastic flows impacting on water	20
Submarine explosions	19
Caldera collapse or subsidence	9
Avalanches of cold rock	7
Base surges with accompanying shock waves	7
Avalanches of hot material	6
Air-waves from explosions	4.5
Lahars (mudflows) impacting on water	4.5
Lava avalanching into sea	1

TABLE 2.1 - Volcanic mechanisms of tsunami generation. Taken from Latter, 1981.

2.1.4 Meteorites

Verschuur (1996), suggests that at the beginning of the Cenozoic era a meteor hit the Earth causing a crater which is 180 km in diameter and 20 km deep. The force of the impact virtually emptied the primal Caribbean sea as it sent huge tsunami waves to the surrounding coasts.

Thousands of meteorites have been recorded to hit the Earth's surface (Mason, 1962). There are also at least 145 impact craters which have been found scattered around the Earth's surface (Verschuur, 1996). Most of the craters are found on land because any in the oceans will be covered with layers of sediments. One ocean crater which has been found is located off the coast of Nova Scotia and is 45 km in diameter.

Ahrens and Harris (1992), estimate that there are approximately 2000 objects with diameters 1 km and greater which have trajectories which will intersect the Earth's orbit sometime in the future. Table 2.2 shows the expected return period of meteorites of different sizes impacting the oceans and the expected tsunami size. Nuclear explosions could be used to deflect the trajectories of large meteorites away from the Earth's orbit (Ahrens and Harris, 1992; Verschuur, 1996).

Size of impactor	50 m	100 m	300 m	1 km
Type of object: • Iron • Hard stone	 2 m -> 80 m 0.8 m -> 32 m	 7 m -> 280 m 2 m -> 80 m	 40 m -> 1.6 km 25 m -> 1 km	 700 m -> 28 km 200 m -> 8 km
Return period	100 yr.	1,000 yr.	20,000 yr.	200,000 yr.

TABLE 2.2 - Return period and sizes of tsunami waves caused by meteorites of different sizes. Deep water waves -> 1,000 km from impact site. Taken from Varshuur (1996).

2.1.5 Rissaga

Rissaga, also known as 'Meteorological tsunami' (Nomitsu, 1935) are caused by sudden changes in atmospheric pressure affecting the sea level. For every millibar (mB) that the atmospheric pressure drops, the sea level will rise 1 cm (assuming an average sea water density of 1025 kg/m^3). Rabinovich and Monserrat (1996), indicate that not all sudden atmospheric changes result in the formation of a rissaga, certain resonance conditions seem to be needed. Some of the atmospheric conditions include hurricanes, passing pressure fronts, barometric fluctuations and pressure pulses. The tsunami wave which struck New Zealand in 1883 after the Krakatoa eruption was thought to be a rissaga wave caused by atmospheric coupling (de Lange and Healy, 1986).

2.2 - TSUNAMI ENERGY TYPES

Tsunamis generated by explosions, submarine landslides or meteorites do not pose much threat to distant coasts, unless they are very large. The net energy of the wave is dissipated very quickly as it travels away from the source (Dudley and Lee, 1988). Tsunamis created by sea floor faulting can travel very long transoceanic distances with very little loss of net energy (Dudley and Lee, 1988). This poses a threat to not only local coasts but far ones as well.

2.3 - PROPAGATION OF TSUNAMIS

There are three main processes which affect tsunami waves as they travel; reflection, refraction and diffraction. These processes create areas of higher or lower risk by concentrating or dissipating wave energy.

2.3.1 Reflection

Reflection occurs when a wave passes over a sudden decrease or increase in water depth (Camfield, 1980). Some of the waves energy is reflected back from where it came. The amount of energy reflected is related to the steepness of the change in water depth (de Lange and Hull, 1994). The two biggest reflectors are the continental slope and the coast (Nekrasow, 1969).

2.3.2 Refraction

Refraction is the process resulting in changes of direction for both shallow water waves and tsunami waves. Like ocean waves, tsunami travel faster in deep water and slower in shallow water making their trajectory dependent on sea floor bathymetry (Defant, 1961). If a wave front travels into a bay, the edges of the wave will travel slower due to the shallower water. The middle of the wave will travel faster due to the deeper water. Hence, the wave front will start to curve to the shape of the bay (Figure 2.6). By the time the wave front has reached the shore it is nearly parallel (Defant, 1961; Kovach, 1995). Wave energy converges on peninsulas resulting in larger wave heights (Figure 2.6), and diverges along the bay, resulting in smaller wave heights (Bascom, 1959).

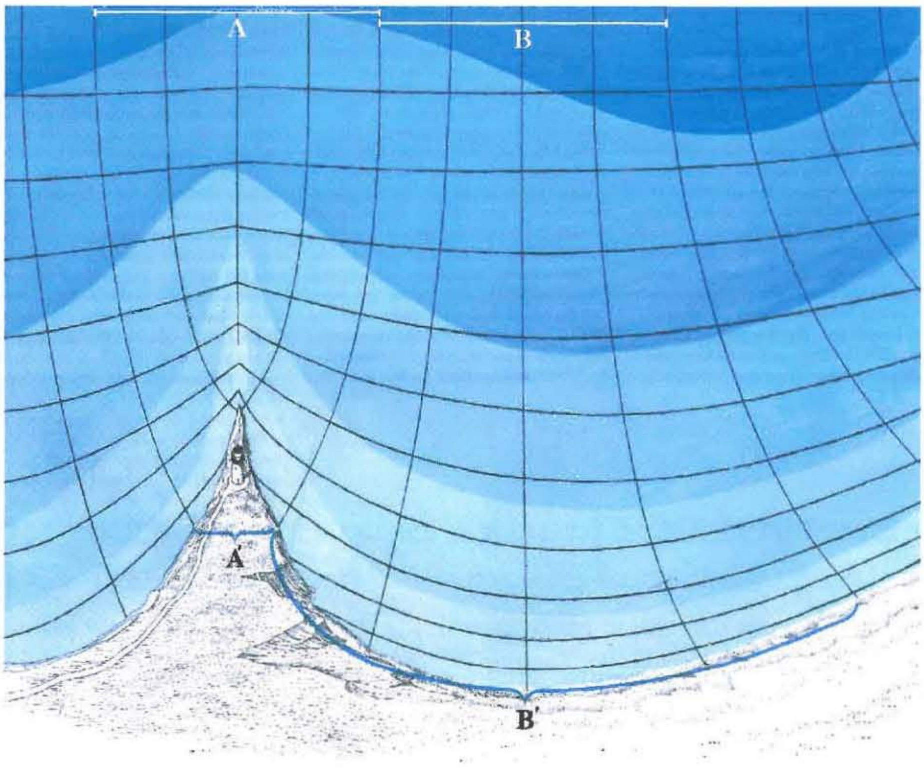

FIGURE 2.6 - Refraction of waves around point and into bay. Horizontal lines represent wave crests and vertical lines divide the waves into equal energy units. Both A and B represent 4 energy units, A is focused on the point while B is dispersed around the bay. Taken from Bascom, 1959.

2.3.3 Diffraction

Diffraction is another process which acts upon both wind driven waves and tsunami waves. As the wave front travels towards a small opening, like a harbor entrance (Figure 2.7), the energy diffracts through it producing waves which radiate away from the other side (Bascom, 1959; Kovach, 1995).

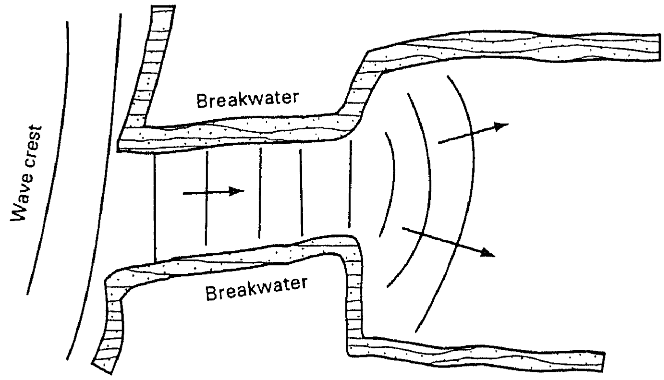

FIGURE 2.7 - Diffraction of waves into a harbor. Lines represent wave crests. Taken from Kovach, 1995.

2.4 - FAR-FIELD AND NEAR-FIELD TSUNAMIS

The location of a tsunami wave source can be very important in determining its potential hazard. Different processes can act on the waves to concentrate or dissipate their energy as they propagate. Based on the location of the source mechanism tsunami waves can be categorized into two groups; far-field and near-field. Warnings of far-field tsunami can be sent to local and regional authorities of endangered coasts through Tsunami Warning Systems (Dudley and Lee, 1988). Near-field tsunami can strike with very little or no warning (Otago Regional Council, 1997).

2.4.1 Far-field Tsunamis

When the source mechanism of a tsunami is generated outside the continental shelf it is known as a far-field tsunami. The two main processes acting on the far-field tsunami are refraction and reflection. Regions of shallow or deep water can refract tsunami waves. Shallow regions focus the wave energy like a lens, while deep regions cause dispersion. Reflection occurs mainly as the wave train of the tsunami reaches the continental shelf (de Lange and Hull, 1994). Due to the more rapid change in water depth, wave energy is reflected away from the shelf and can help in mitigating the destruction caused from the waves.

Hunt (1993) examines the effect of wave amplification of up to 83 (8300%) as the tsunami reaches the continental shelf. No current data indicates that there are any large amplifications of this kind (de Lange and Hull, 1994).

As the tsunami wave travels the vast distances around the Pacific Ocean the Coriolis Effect, caused by the force of the Earth's rotation, can deflect its path of travel (de Lange and Hull, 1994). This can result in a reduction of wave height through dispersion (Tsuji, 1991) or a concentration of energy as the waves crosses the equator (de Lange and Hull, 1994).

2.4.2 Near-field Tsunamis

Tsunami waves created on the continental shelf are known as near-field tsunami (de Lange and Hull, 1997). Refraction still acts on the tsunami causing it to bend around the coast. Refraction can also trap energy on the continental shelf (de Lange and Hull, 1994). Tsunami wave energy reflecting off the continental slope and the coast can also act to trap wave energy on the continental shelf. Diffraction acts as the tsunami enters into harbors and estuaries.

2.5 - EFFECTS OF TSUNAMIS LIKELY ON THE NEW ZEALAND COAST.

Tsunami waves at sea can often go undetected (Bernstein, 1954; Bascom, 1959; Kovach, 1995). Hilo, Hawaii, was being destroyed by huge waves as a captain of a ship looked on in surprise (Bascom, 1959). The waves had passed the ship unnoticed. As tsunami waves approach the shore they slow down, their wavelength compress converting energy into an increase in wave height (Dudley and Lee, 1988). There are many ways in which a tsunami can affect the coast; they depend on the specific site and the event (de Lange and Hull, 1994).

2.5.1 Tidal Oscillations.

Tsunamis very commonly reach the coast as a rapidly rising and falling tide (Dudley and Lee, 1988). This is very common for New Zealand tsunami. For example, tidal oscillations of around 2 m were reported at Whitianga during the 1960 Chilean tsunami. Shoaling characteristics of the wave do not cause it to form a steep wave front which would break to form a bore. Runup will equal the height of the wave (de Lange and Hull, 1994). Due to the long period of the oscillations, wind generated waves can travel on top of the tsunami (Dudley and Lee, 1988; de Lange and Healy, 1986). Potentially, this can cause damage when the wave strikes during a storm surge and/or high tide. The reported tsunami of 1929 at Karamea was during a storm surge. The storm waves, reaching heights of 6 m, would have caused greater damage had the tsunami manifest itself as a tidal fluctuation of 2.5 metres.

2.5.2 Bore

When a tsunami wave breaks offshore, in river mouths or in estuaries, it produces a bore. Kovack (1995), describes a bore as "...a vast wall of sea water weighing millions of tons that crashes inland with destructive power almost beyond belief". The tsunami of March 1947 was described as a "large greenish-grey wall of water" (Otago Daily Times, 1947). Bores are the most destructive (Yeh, 1991). A nearly vertical wall of water is formed as the wavelength of the tsunami compresses and the height increases (Dudley and Lee, 1988). Transfer of momentum is thought to cause large vertical and horizontal turbulence in front of the wave (Yeh, 1991). This occurs infrequently (Dudley and Lee, 1988). However, several have been reported around New Zealand, for example, the two 1947 tsunami waves to strike the Gisborne area. Small bores have also been reported in rivers and estuaries such as the Avon River and Tamaki Estuary. Many bridges have been destroyed or damaged from bores travelling up rivers (de Lange and Healy, 1986).

2.5.3 Harbor Oscillations (seiching)

Seiching of harbors and other partially land-locked bodies of water, can be set off by the trapping of tsunami energy (Dudley and Lee, 1988). If the water bodies' natural frequency, dependent on its size and shape, is equal to the frequency of the tsunami then resonance will amplify the wave height. Seiching may occur for several days once set in motion. After the 1868 Chilean tsunami, tidal oscillations at Port Chalmers continued for a day while oscillations at Nelson started on the 15th of April and continued until the 17th.

2.5.4 Tsunami Runup and Flooding

Flooding can be a major concern during tsunami events. A number of houses around New Zealand have been reported as being flooded as a result of tsunami waves. During the 1960 Chilean tsunami electrical gear at Lyttelton was flooded, causing it to be inoperable for a day (de Lange and Healy, 1986). The Whitianga airport and a camp ground were also flooded during the 1960 Chilean tsunami. The extent of tsunami damage and flooding is measured as either vertical runup or inundation (Morgan, 1984). Runup is the maximum elevation reached by the tsunami wave and is expressed as the vertical height reached by the wave. Inundation is the maximum horizontal distance inland reached by the tsunami wave. Vertical wave heights reported in newspapers were usually relative to still water, mean high water or mean high water spring.

Chapter 3

Tsunami Warning

CHAPTER 3 - TSUNAMI WARNING

3.1 - TSUNAMI WARNING SYSTEMS

Tsunami warning systems are used to alert coastal populations to the impending danger of a tsunami wave. Even though tsunami waves travel at speeds of around 185 ms^{-1}, they are relatively slow compared to seismic waves. This should enable an early warning to be issued to relevant coasts (Okal, 1993). For this reason the Pacific Tsunami Warning Center was set up in 1948 to issue tsunami wave warnings based on seismic data and sea-level measurements (Milburn *et al.*, 1996).

The Tsunami warning system consists of a number of regional centers; a center which is responsible for the whole of the Pacific; seismic stations and tide gauges; data archiving; catalogs and historical data; and a research program (IOC, 1987). The Pacific Tsunami Warning Center, located in Honolulu, is responsible to issue warnings around the Pacific within sixty minutes of a tsunami causing earthquake (IOC, 1987).

3.1.1 How They Work

Seismographs located around the Pacific detect any earthquake waves in a matter of minutes (Dudley and Lee, 1988). If the earthquake Richter magnitude is greater than 6.5, based on earthquake magnitudes of submarine fault movement likely to cause a tsunami, then an alarm is set off. Data from the seismographs is then sent to Honolulu where within half an hour the epicenter of the earthquake is located (Dudley and Lee, 1988). This is done through two algorithms, one using short periods and the other long periods, which independently calculate the epicenter (Talandier, 1993).

If the earthquake magnitude is large enough to create a tsunami wave and the epicenter is near the ocean then a tsunami watch is established (Dudley and Lee, 1988). The five nearest tidal stations to the epicenter are informed to keep watch for any tidal anomalies (Dudley and Lee, 1988). If the tide gauges do not reveal anything of major concern then the tsunami watch is called off.

However, if the tide gauges do reveal tsunami waves then a tsunami warning is established with the evacuation of threatened coasts (Dudley and Lee, 1988). Any vessels near the coast are requested to head out to sea where they will be safe (Dudley and Lee, 1988). In Hilo, Hawaii road signs indicating the route to be taken during evacuations help to reduce any confusion during such times (Dudley and Lee, 1988).

Along with tsunami watches and tsunami warnings the Pacific Tsunami Warning Center can send out tsunami dummies and tsunami information bulletins (Ministry of Civil Defence, 1996). Tsunami dummies are used to check the systems communication and transmission times. Tsunami information bulletins are used to inform of a non-tsunamigenic earthquake.

Because tsunami waves act as shallow water waves, due to their long wavelengths, they travel at speeds equal to $\sqrt{gh}$. Using this equation we can calculate the time taken for a wave to travel across the Pacific Ocean by only knowing the ocean depth, h, and the gravitational constant, g. This can provide us with the expected time that the tsunami wave will strike any location around the Pacific. This is a very important part of the warning system as evacuation procedures can be started with the areas who are the first to be effected (Dudley and Lee, 1988).

3.1.2 False Alarms

The main problem with the warning system is that of false alarms. Not all large submarine earthquakes result in disturbances of the sea floor which will then create a tsunami. If the focal point is deep within the crust then there will be very little sea floor displacement. In 1986 the Tsunami Warning System issued warnings around the Pacific after the Aleutian earthquake. In Hawaii all coastal areas were evacuated. Unfortunately, the wave turned out to be insignificant, the warning was false. This cost Hawaii millions of dollars (Milburn *et al.*, 1996). It is estimated that every time a false alarm is issued in Hawaii, and the coasts evacuated, it could cost $30 million (Okal, 1994). Not only are false alarms expensive, they also destroy the integrity of the warning system (Milburn *et al.*, 1996). In 1960, people didn't take the tsunami warning seriously after two previous warnings in 1952 and 1957 resulted in insignificant waves (Dudley and Lee, 1988).

3.1.3 Real Time Tsunami Reporting Systems

A system, known as TREMORS, has been established for the French Polynesia region. The system includes; a teleseismic event detector, an event locator and a software algorithm to proved real time assessment of seismic moment, M_0 (Okal, 1994). The following process is used (Talandier, 1993):

- Earthquakes are detected by the teleseismic detector.
- Location of the epicenter is found using the locator. The locator uses two independent algorithms based on short waves and long waves.
- Distance information is used to estimate a window of arrival times.

- The software algorithm then uses the arrival times to calculate the mantle magnitude, M_m.
- Seismic moment, M_o, is calculated from M_m.
- From the data the algorithm then calculates tsunami risk for Polynesian sites.

Risk confirmation can be made through T waves and/or historical references. Tidal gauges help to indicate whether a tsunami watch or tsunami warning should be established. Real time transmissions of M_m are made to important international organisations.

Bottom pressure recorders are also very useful in real time tsunami reporting. The can be used to measure tsunami waves, as small as 0.5 cm, in ocean depths of up to 6 km (Eble *et al.*, 1991). The data are then fed to a surface buoy by using an acoustic modem (Figure 3.1). The surface buoy, made out of fiberglass and foam, then proceeds to transmit the data to a satellite (Milburn *et al.*, 1996). This system allows tsunami wave data to be collected in quasi real time (close to but not quite real time). The bottom pressure recorders can be deployed for a period up to 12 months before their battery supply runs out.

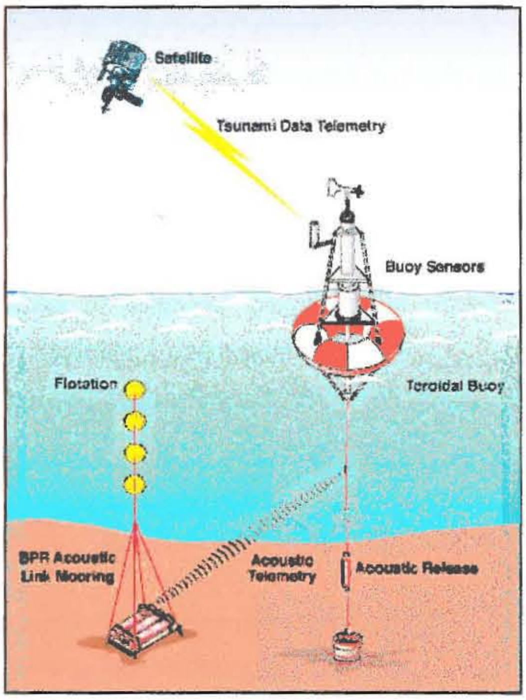

FIGURE 3.1 - Setup of the prototype real time tsunami reporting system. Taken from Milburn *et al.*, 1996.

With a network of real time systems set up around the Pacific the number of false alarms could be reduced, and the speed and accuracy of tsunami warnings would be improved (Milburn *et al.*, 1996).

3.2 - TSUNAMI WARNING SYSTEM FOR NEW ZEALAND

New Zealand is part of the Pacific-wide Tsunami Warning System (IOC, 1987). The Pacific Tsunami Warning Center has a direct link to Civil Defence in Wellington, 24 hours a day, to issue tsunami dummies, tsunami information bulletins, tsunami watch's and tsunami warnings (Ministry of Civil Defence, 1996).

If a tsunami watch is established then information is announced to:

- Regional councils and territorial authorities
- Civil Defence Commissioners
- New Zealand Police National Headquarters
- New Zealand Police Wellington, for Police Districts
- New Zealand Defence Force
- Maritime Safety Authority of New Zealand
- Ministry of Civil Defence
- Secretary of Civil Defence
- Department of the Prime Minister and Cabinet
- National Institute of Water and Atmosphere Research Ltd
- any other appropriate organisation

If a tsunami warning has been sent the Director of Civil Defence will (Ministry of Civil Defence, 1996):

- Issue a tsunami warning to Regional councils and territorial authorities of affected areas and also to Civil Defence Commissioners.
- Inform Ministry of Civil Defence, Secretary of Civil Defence and Department of the Prime Minister and Cabinet.
- Provide advice for public broadcast to Radio New Zealand Ltd, IRN News and Sport, and TVNZ Ltd.

  Inform: New Zealand Police National Headquarters
  New Zealand Police Wellington, for Police Districts
  New Zealand Defence Force
  New Zealand Fire Service
  Civil Aviation Authority of New Zealand
  Maritime Safety Authority of New Zealand
  New Zealand Industrial Supplies Office

Ministry of Transport
Electricity Corporation of New Zealand Ltd
Transit New Zealand
Telecom New Zealand Ltd
Department of Social Welfare
Meteorological Service of New Zealand Ltd
Institute of Geological and Nuclear Sciences Ltd
National Institute of Water and Atmosphere Research Ltd

A system such as TREMORS could not be set up effectively for New Zealand because our empirical database of tsunami runup is insufficient. Accurate estimations of tsunami risk relative to seismic moment requires a large number of events to calibrate the TREMORS runup algorithm, which New Zealand does not have.

Chapter 4

Tsunami Database

CHAPTER 4 - TSUNAMI DATABASE

4.1 ARCHIVE SEARCH

The aim of this archive search is to further the information collected by de Lange and Healy (1986) on historical tsunamis around New Zealand coasts. In order to establish a database for tsunami runup predictions at various New Zealand coastal sites. As can be seen from Figure 4.1, many of the tsunami reports are for the North Island (76), and only a few are from the South Island (45). For this reason, research was predominantly based on South Island newspapers, especially the West Coast as there are only a few tsunami reports for that region.

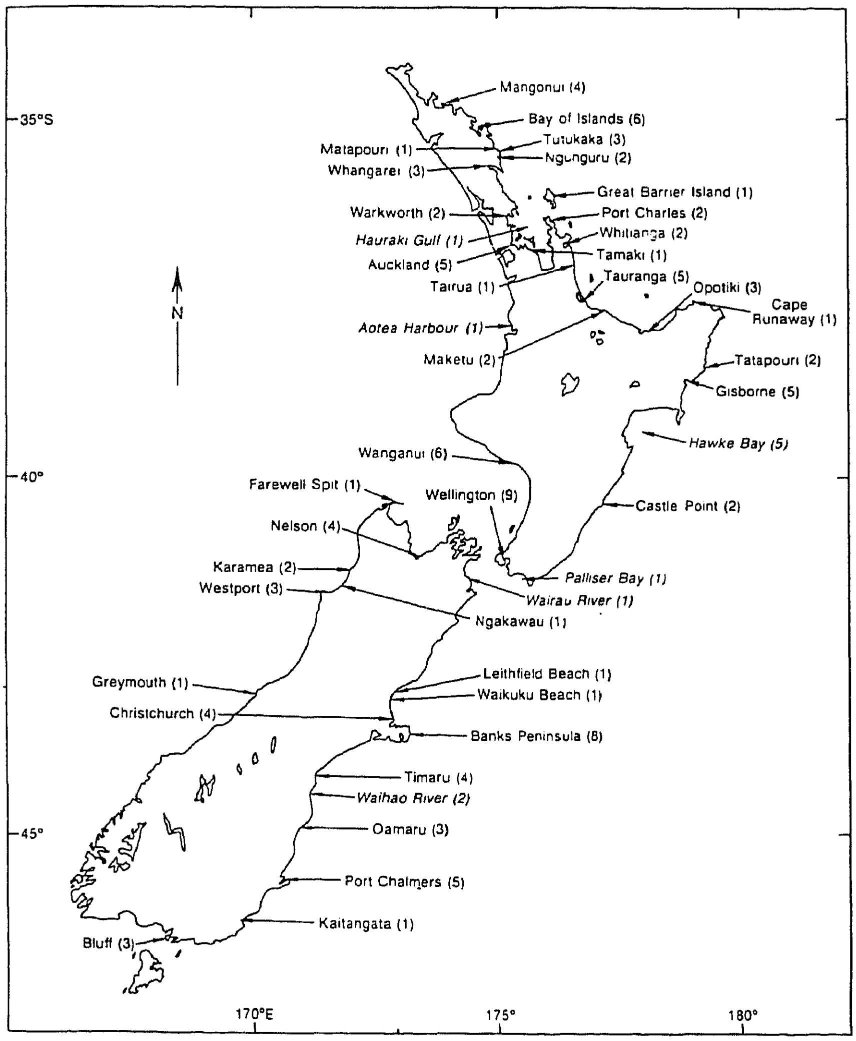

FIGURE 4.1 - Locations of historical tsunami reports around New Zealand. Taken from de Lange and Healy, 1986.

4.1.1 Method

Data was mostly found by searching through microfilms of old newspapers, or from the actual newspaper itself. No substantial information was found in museums. Some information was found in history books, but compared to the newspaper reports it was superficial. Using a list of the tsunami event dates from de Lange and Healy (1986) the corresponding newspapers, if available, were found on microfilm or in paper form. However, not all of the dates were available in either form. This was limiting to the search. Newspapers looked at were:

- Southland Times
- Kaikoura Star
- Nelson Evening Mail
- Greymouth Evening Star
- News (Westport)
- West Coast Times
- Lyttelton Times
- Otago Witness
- The Nelson Examiner
- Otago Daily Times
- The Southland News
- The Gisborne Herald

To find a report of an event in the newspaper, it was necessary to search from the day of occurrence to several days after. Early papers did not have the advantage of electronic communication. News travelled slowly. Often it was 4 to 6 days after the event that news reached the newspaper's office, or slightly quicker for local events. As technology advanced, news travelled much faster, reducing the number of days taken for information to reach the newspaper's office. Today information on an event will normally reach the newspaper the same day it occurs.

4.1.2 Results

From the newspapers searched it became apparent that there were very little reports of any tsunami waves along the west coast of the South Island. Nelson also seems to escape any effects of a tsunami wave. Many of the newspaper reports indicated that there were no unusual tidal occurrences at Nelson. New reports of tsunami waves were found for the following locations:

Autumn 1820:	Otara	Orepuki beach	
Aug 1868:	Waitangi Otago Heads Invercargill	Port Charles Dunedin Bay Riverton	Akaroa Taieri River Campbelltown
May 1877:	Thames Kaiapoi	Pigeon Bay Jackson's Head	Westport
1926-29:	Tologa Bay		
Mar 1947:	Kaiti Beach		

May 1960:	Ahipara	Russell	Great Mercury Island
	Tryphena	Mercury Cove	Mercury Bay
	Opotiki	Tokomaru Bay	Tolaga Bay
	Tatapouri	Clifton Domain	Riversdale
	Ngawi	Little Akaloa	Okains Bay
	Brighton	Taieri Mouth	Taylors Point
	Colac Bay	Fortrose	Stewart Island
	Bluff		
May 1986:	Lyttelton.		
Oct 1986:	Auckland		
May 1987:	Deep Cove		
Jun 1993:	Auckland		
Oct 1994:	Marsden Point	Auckland	Tauranga
	Gisborne	Napier	Wellington
	Lyttelton	Pegasus Bay	

Extra data were also found for some locations that were already mentioned in the results found by de Lange and Healy (1986). These locations are listed below:

Aug 1868:	Wellington	Lyttelton	Oamaru
	Timaru		
May 1877:	Lyttelton	Oamaru	Port Chalmers
Mar 1947:	Turihaua Point	Murphys Beach	Pouawa Beach
	Wainui Beach		
Nov 1952:	Tutukaka		
May 1960:	Gisborne	Napier	Lyttelton
	Oamaru	Dunedin	

For a summary of the new reports and extra data listed above refer to Table 4.1. For a more detailed summary refer to Appendix 1.

4.1.3 Discussion

Newspapers have often reported that no unusual tidal observations were recorded in Nelson during tsunami events. This suggests that Nelson escapes the effects of tsunami waves. The west coast region of New Zealand also seems to be unaffected by most of the tsunami events. This is probably due to the coast being only directly exposed to the Tasman sea. For tsunami waves created in the Pacific Ocean to have any effect they will have to be reflected off Australia or refracted around New Zealand (Braddock 1969).

EYear	ETime	EDate	ELocation	EH	ERunup	EWaves	EPeriod	ESpecificDamage
1820			Otara	*10.00*	10.00			1 - Lives
			Orepuki Beach	*10.00*	10.00			1 - Lives
1868		15-Aug	Port Charles	1.80	1.80	1		
		15-Aug	Wellington				5	
		15-Aug	Lyttelton					2 - Shipping
		15-Aug	Akaroa	1.20	1.20	1		
	0800	15-Aug	Oamaru	6.10	6.10		4	
	0500	15-Aug	Timaru	3.10	3.10	>1	12	
	0900	15-Aug	Otago Heads	1.50	1.50	>1		
	1800	15-Aug	Dunedin Bay	*1.00*	1.00	1		
		15-Aug	Taieri River	*3.00*	3.00	1		
	0800	15-Aug	Invercargill	1.50	1.50	>1	30	
	0800	15-Aug	Riverton	0.90	0.90	>1		
	Morn	15-Aug	Campbelltown	0.90	0.90	>1		
1877	1600	11-May	Thames	0.90	0.90	2-5		
		11-May	Kaiapoi	0.90	0.90	1		
	0700	11-May	Lyttelton	0.90	0.90	>1		
		11-May	Pigeon Bay	1.25	1.25	1		
	0800	11-May	Oamaru					
	Early	11-May	Port Chalmers	0.50	0.50	>1		
		11-May	Jackson's Head	*2.00*	2.00	1		
	1430	11-May	Westport	1.80	1.80	>1		
1926			Tolaga Bay	6.35	6.35	3		3 - Jetty
1947		25-Mar	Kaiti Beach	*4.00*	4.00	1		3 - Houses
		25-Mar	Turihaua Point					1 - House
	0840	25-Mar	Pouawa Beach	*6.00*	6.00	1		
		25-Mar	Murphys Beach	4.65	4.65	1		1 - Pumkins, Fence
		25-Mar	Wainui	*5.00*	5.00	2		5 - House
1952	1930	5-Nov	Tutukaka	0.91	0.91	>1	10	
1960		23-May	Ahipara	*1.00*	1.00	>1		
		23-May	Russell	*1.00*	1.00	1		1 - Flashing beacon
		23-May	Great Barrier Is.	*1.50*	1.50	>1		
		23-May	Great Mercury Is.					
		23-May	Mercury Cove	*3.00*	3.00			
	2100	23-May	Mercury Bay	2.32	2.32	>20	40	
	Early	24-May	Opotiki	1.52	1.52	1		
	0500	24-May	Tokomaru Bay	3.05	3.05	1		1 - 27m of wooden sea wall
	2030	23-May	Tolaga Bay	*2.00*	2.00	20+	15	5 - Camp ground
		23-May	Tatapouri	2.74	2.74	1		
	2030	23-May	Gisborne	5.49	5.49	>1	20	
	0330	24-May	Napier	3.05	3.05	>1	40	1 - Gas main; 3 - Footbridge, Many boats
	Morn	24-May	Clifton Domain	*4.00*	4.00	1		4 - Sea Wall; 5 - House
	Morn	25-May	Riversdale	*1.50*	1.50	1		
	Night	24-May	Ngawi	*1.50*	1.50	>1		
	Night	23-May	Lyttelton	4.35	4.35	>1		3 - House; 5 - 2 Houses, Hotel
		23-May	Little Akaloa	*3.00*	3.00	1		1 - Shed; 3 - Woolshed; 4 - House
	0230	24-May	Okains Bay	3.05	3.05	1		1 - Bridge; 2 - House
	2100	23-May	Oamaru	3.65	3.65	>1	60	
	0740	23-May	Taylors Point	0.60	0.60			
	0325	24-May	Dunedin	0.60	0.60	1		
		23-May	Brighton	*1.00*	1.00	>1		3 - Large dingy, wooden jetty
	Morn	23-May	Taieri River	1.50	1.50	2-5		1 - 35ft launch; 3 - Fishing launch
	1700	24-May	Fortrose	*1.50*	*1.50*	>1		
		24-May	Bluff	*0.50*	*0.50*	>1	23	
	Early	23-May	Colac Bay	*1.00*	*1.00*	>1		
	Night	23-May	Stewart Is.	1.22	1.22	>1		
1982		Dec	Auckland	0.10	0.10			
1986		7-May	Lyttelton	0.40	0.40			
1986		Oct	Auckland	0.10	0.10			
1987		20-May	Deep Cove	3.00	3.00	1		1 - Wharf
1993		Jun	Auckland	0.10	0.10			
1994		6-Oct	Marsden Point	0.10	0.10			
		6-Oct	Auckland	0.10	0.10			
		6-Oct	Tauranga	0.10	0.10			
		6-Oct	Gisborne	0.10	0.10			
		6-Oct	Napier	0.10	0.10			
		6-Oct	Wellington	0.10	0.10			
		6-Oct	Lyttelton	0.10	0.10			
		6-Oct	Pegasus Bay	0.10	0.10			

TABLE 4.1 - New data collected from the archive search.

The west coast of the South Island is sparsely populated. Reports of historical tsunamis were mainly reliant on visual observations. If the waves were small and occurred at night, then it is highly likely that they would have gone undetected. Due to this there may have been several tsunami waves which have gone unnoticed. However, the west coast of the North Island is more populated, and there are still very few reports. This would suggest that the absence of reports is due to the absence of tsunami waves affecting the west coast.

4.2 - DATABASE

The information on the tsunami events collected for this thesis from the archive search and also the information from de Lange and Healy (1986) was entered into a computer database. This will aid Civil Defence in estimating expected tsunami runup around New Zealand.

4.2.1 Method

The database used was in the form of a 'look up table' created with Microsoft Excel. Each column represents a field and each row (excluding the header rows) represents a record. The first two rows (header rows) include the name of each field. The spreadsheet has been split into two vertical components, this is so the field names can be visible even after scrolling down through the records.

4.2.2 Database Fields

The database uses the following fields:

EYear Year the tsunami event affected New Zealand.

ETime Time of the first tsunami wave to strike (24 hour time) in NZST. If no time was given in the reports then the cell is left blank. If the exact time was not given then the following abbreviations were used:

Early	- Early morning	0000-0600
Morn	- Morning	0600-1200
After	- Afternoon	1200-1800
Night	- Night	1800-0000

EDate Date of the tsunami event. If no date was given in the reports then the cell was left blank.

ELocation Location affected by the tsunami wave.

ERegn Regional Council region which the location is within, numbered from 1-17. See Figure 4.2 for location of the different regions.

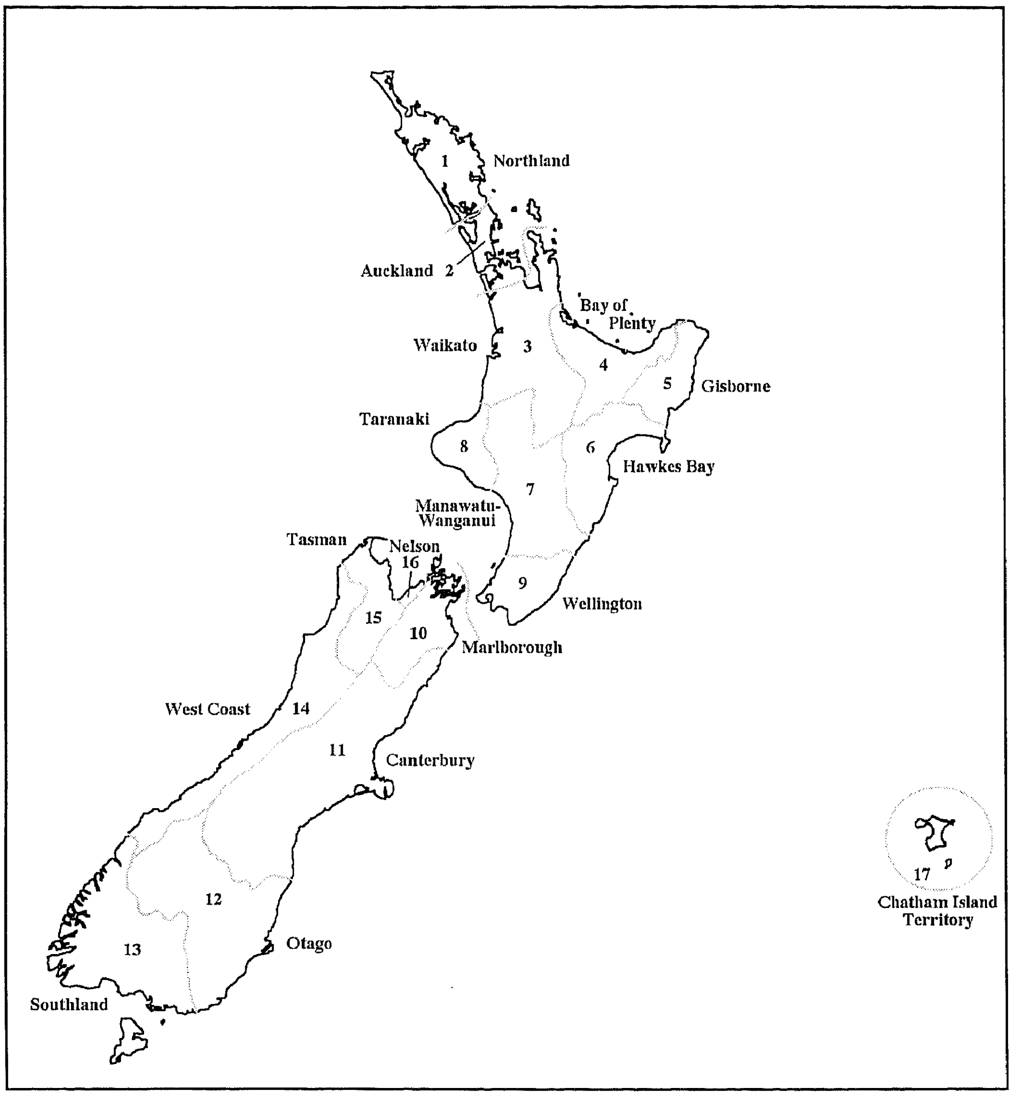

FIGURE 4.2 - Regional Councils of New Zealand. Adapted from Kelly and Marshall, 1996.

EH Maximum height of the tsunami waves relative to still water or mean sea level (underlined). When wave heights were not given the heights were estimated (shown in italics on the database) from wave heights of adjacent locations and/or from the following assumptions:

Large Wave	-	3.0 m
High Wave	-	2.0 m
Extra Tidal Oscillations	-	1.5 m
Unusual Wave	-	1.0 m
Small Wave	-	0.5 m
Seiching	-	0.5 m
Minor Tidal Oscillations	-	0.2 m
Slight Tidal Oscillations	-	0.1 m

ERunup Maximum vertical runup of the tsunami waves relative to still water or mean sea level (underlined).

EWaves Number of waves observed. The number of waves has been divided up into the following categories:

>1	-	More than one wave, but number not specified.
2-5	-	Two to five waves.
6-10	-	Six to ten waves.
11-20	-	Eleven to twenty waves.
20+	-	More than twenty waves.

If the number of waves was not specified then the number, where possible, was estimated from duration and period of oscillations. If no periods and duration's were given, the following assumptions were made:

Oscillations	-	>1
Several	-	2-5
Sequence	-	6-10
Series	-	6-10

EPeriod Minimum period between waves.

ESpecificDamage Specific damage caused by the tsunami wave. The type of damage is represented by the following numbers:

1	-	Destroyed or lost.
2	-	Severely damaged.
3	-	Damaged.
4	-	Slightly damaged.
5	-	Flooded

STime Time of the event which created the tsunami in UTC.

SDate Day in which the event created the tsunami.

SLocation Location where the tsunami was created. Location is either entered as a place name or as longitude and latitude.

SRegn

Region where tsunami was created as defined by The National Geophysical Data Center of the National Oceanic and Atmospheric Administration. Boundaries of regions are based on frequency of occurrence of tsunami creation, geophysical relations, risk in distant areas, and political justification. The region codes are as follows:

80 - Hawaii.
81 - New Zealand and South Pacific Islands.
82 - New Guinea and Solomon Islands.
83 - Indonesia.
84 - Philippines.
85 - Japan.
86 - Kuril Islands and Kamchatka.
87 - Alaska (including Aleutian Islands).
88 - West Coast of North and Central America.
89 - West Coast of South America.

60 - Indian Ocean.
50 - Mediterranean Sea.
70 - Southeast Atlantic Ocean.
71 - Southwest Atlantic Ocean.
72 - Northwest Atlantic Ocean.
73 - Northeast Atlantic Ocean.

SCause

The type of event which created the tsunami. The following abbreviations were used:

SlideEQ - Tsunami created from submarine landslide set off by an earthquake.
Slide - Tsunami created from submarine landslide.
Quake - Tsunami created from seafloor faulting.
Rissaga - Rissaga wave created from atmospheric coupling.
Land - Tsunami created from a terrestrial landslide.

SMag

If the tsunami was created from sea floor faulting, then this field equals the magnitude of the accompanying earthquake. If the tsunami wave was created from some other mechanism then this field is left blank.

Refs

References used for the creation of this database.

1 - de Lange and Healy, 1986.
2 - New data found for this thesis, shown in Appendix 1.

Comments

Comments on source, damage or tsunami event.

4.2.3 Querying Instructions

Making a query on one of the fields using the Autofilter function can be done through the following steps:

- Click on the arrow (▼) located on the second row of the header of the field to be queried. This will bring up a menu with a list of all the records for that field plus a few extra commands listed below:

All	Shows all the records of the field (no query).
Custom...	Allows the user to customize the query.
Blanks	Shows all records which are blank.
NonBlanks	Shows all records which are not blank.

- Select either one of the record values or one of the extra commands.

If the Custom command is selected, then the window shown in Figure 4.3 will be shown (may vary slightly for different versions).

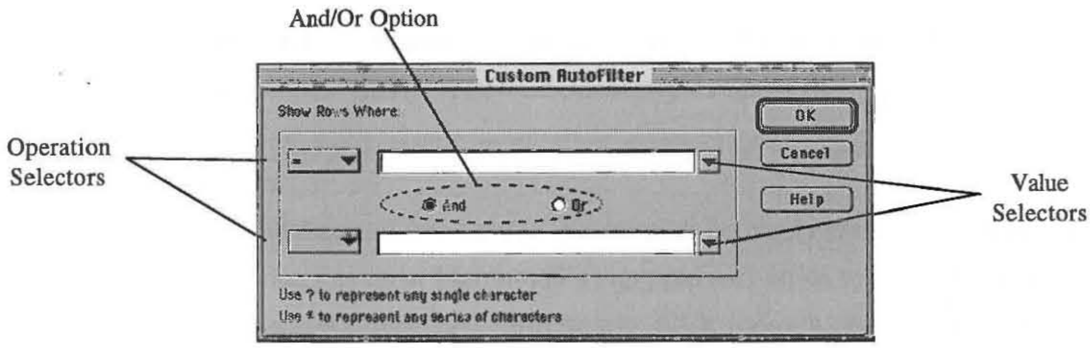

FIGURE 4.3 - Window shown while creating a Custom Autofilter.

The Operation Selector determines whether the shown records will be = (equal to), > (greater than), < (less than), >= (greater than or equal to), <= (less than or equal to) or <> (not equal to) the value selected in the Value Selector. The And/Or Option selects whether a record is shown if both operations are true (AND), or whether only one of the operations has to be true (OR). When the custom query has been entered, the **OK** button will perform the query. The **Cancel** button is used to return to the spreadsheet without running a query. The **Help** button is used for assistance on Custom Autofilters.

4.2.4 Results

From the historical data (shown in Table 4.2) we can see that half of the tsunami events have been caused from local sources and half from far-field sources. Far-field tsunami have mostly been generated around the West Coast of South America (region 89) or around the South Pacific Islands (region 81). While the remainder of the tsunami have been generated from sources distributed around the following regions:

- Indonesia, region 83.
- Japan, region 85.
- Kuril Islands and Kamchatka, region 86.
- Alaska (including Aleutian Islands), region 87.
- West Coast of North and Central America, region 88.

Source region	Number of tsunami
81 - New Zealand (local)	17
81 - South Pacific Islands	6
83 - Indonesia	1
85 - Japan	1
86 - Kuril Islands and Kamchatka	2
87 - Alaska (including Aleutian Islands)	1
88 - West Coast of North & Central America	1
89 - West Coast of South America	4

TABLE 4.2 - Number of tsunami waves created from different regions. Total number of far-field tsunami waves equals 16.

4.2.5 Discussion

Using an Excel spreadsheet allows for the database to be easily transferred between PC and Macintosh computers as most Macintosh's can read and write to PC formatted disks. Microsoft Excel is a widely used program, nearly all of today's computers come with it installed. This means the database spreadsheet can be readily transferred from computer to computer without installing any special software. However, to function as designed, the spreadsheet does require a version of Excel which supports Autofilters.

Using an Excel spreadsheet does have its limitations. It is not possible to only display a select number of fields without copying them to a new spreadsheet. This should not pose a major problem, merely a slight inconvenience. The biggest limitation of the Autofilter command is that it cannot do OR searches between fields. For example, the user will not be able to search for the following queries:

wave height > 3 m OR **wave period** < 20 min

location = Christchurch OR **source region** = 81

Data of historical tsunami are very limited. Some of the records in the database have empty fields and/or estimated values. Many newspaper reports were often very brief. Some reports only state information like the following:

> "The tide has been receding again today." - (The Southland News, August 18, 1868)

> "At Ahipara waves ran up a tidal creek" - (The Otago Daily Times, May 25, 1960)

From this it is very hard to obtain information like maximum runup, maximum wave height, period between waves ... etc. Early data of tsunami waves were mainly reliant on eye witness accounts and observations. Tide gauges were not as readily available as they are today. Events had to be fairly major before being observed, especially if they occurred at night.

The ideal database for New Zealand would be similar to the historical tsunami database for the Kuril-Kamchatka region. The database is subdivided into an earthquake database and a tsunami database, both of which cover a period from 1737 to 1990 (Gusiakov and Osipova, 1991). There are nearly 8000 earthquake reports and 124 tsunami reports. The database is linked together with a graphical interface designed to increase the speed of data recovery.

If the tsunami wave affects the coast as an irregular tidal oscillation, like a fast rising and falling tide, then the maximum vertical runup will equal the height of the wave (Houston and Garcia, 1974). If the wave reaches the coast as a bore or surge then it is possible that the runup height can be greater than that of the wave height (Camfield, 1980). There are many equations used to calculate the predicted runup of a tsunami wave on a beach. However, for this database, the maximum tsunami runup is estimated as being equal to the maximum tsunami wave height for the following reasons:

- Many of the waves affected the coast as tidal oscillations.
- There is insufficient data to calculate maximum runup without introducing considerable error.
- Many of the wave heights were already estimates so that it was not possible to justify the pseudo-accuracy of any runup predictions.

Chapter 5

Tsunami Risk

Chapter 5 - Tsunami Risk

Using the historical data, estimations of tsunami return periods and expected runup heights can be made for various sites around New Zealand, tsunami source regions and New Zealand as a whole. Maximum expected runup heights were calculated for time periods of 100, 50, 20 and 10 years. Return periods were calculated for tsunami runup heights of 10, 6, 3 and 1.5 m.

5.1 - Method

To do this, construction of the tsunami height exceedance frequency distribution was made for each location. This is the same method used by Pelinovsky, Yuliadi, Pratseya and Hidayat (1996) to calculate the tsunami risk for the central part of Sulawesi Island. This method can also used to calculate return periods of floods (NERC, 1975). The following steps were used:

- Maximum runup height, *H,* for each event is listed in descending order, an example, Location X, is shown in Table 5.1, using maximum runups of 10, 7.4, 3.5, 3.5, 1.5, 1.5, 0.2, 0.2, 0.2 and 0.2m.

Number of tsunamis exceeding or equal too runup, *H*.

Runup, *H*	*N*	*f* (*N*/100)
10.0	1	0.01
7.4	2	0.02
3.5	4	0.04
2.4	6	0.06
0.2	10	0.10

Number of events each year.

Table 5.1 - Maximum runup heights and exceedance frequencies for location X.

- The number of waves, *N*, exceeding and including *H* is calculated.
- The frequency, *f*, of tsunami runup of height *H* expected each year is calculated by dividing *N* by the period which the historical data covers. The New Zealand data dates back to 1820 giving a period of 177 years. However, for this example we will use a period of 100 years.

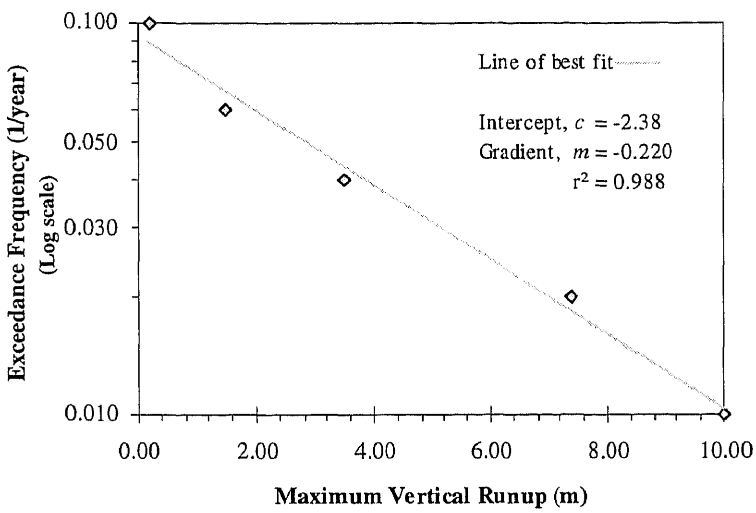

FIGURE 5.1 - Theoretical example of exceedance frequencies of waves at a location X.

- Maximum runup heights, *H*, and exceedance frequency, *f*, is then plotted on a semi-log graph. The gradient, *m*, and intercept, *c*, of the line of best fit, as shown in Figure 5.1, is used with the following equation to determine the Poisson curve which best fits the data:

$$f = e^{mH+c}$$

- The equation is used to estimate the expected frequency for any wave height. To calculate the return period for a wave height the reciprocal of *f* is taken (*1/f*).
- To determine how well the data points fit the line of best fit the r^2 value is used. If $r^2 = 1$ then the data fits perfectly, if $r^2 = 0$ then the data does not fit at all (Wild and Seber, 1993).
- The equation shown above can be rearranged in terms of return period (1/f) so that the expected tsunami height for a given period can be calculated. The rearranged equation is shown below:

$$H = \frac{\ln(P^{-1}) - 1}{m}$$

For example, for the data plotted in Figure 5.1 above, location X can expect a 10.1 m tsunami every 100 years, a 7.0 m tsunami every 50 years and a 2.8 m tsunami every 20 years.

5.2 - RESULTS

5.2.1 Sites Around New Zealand

Return periods for 10 m, 6 m, 3 m, and 1.5 m runups were calculated for various coastal cities and ports around New Zealand, shown in Figure 5.2, and also for New Zealand as a whole (calculated from maximum runup of each source event). The results are shown in Table 5.2, for return period calculations and exceedance graphs of each site refer to Appendix 3.

CITY/PORT	Lat, Long	10m	6m	3m	1.5m
Whangarei Harbour	35.80S, 174.40E	3.5 M	43 399	1 612	311
Auckland Port	36.85S, 174.77E	1.4 M	18 406	732	146
Tauranga District	37.67S, 176.20E	344 895	8 364	514	127
Gisborne Harbour	37.87S, 178.02E	557	179	77	50
Napier District	39.50S, 176.90E	1 535	351	116	67
Wanganui	39.95S, 174.98E	3 257	625	181	97
Wellington Port	41.28S, 174.78E	26 919	1 490	170	57
Lyttelton Port	43.62S, 172.75E	373	131	59	40
Timaru	44.40S, 171.25E	5 021	715	166	80
Port Chalmers	45.82S, 170.62E	50.7 M	162 627	2 192	255
New Zealand		53	22	12	9

TABLE 5.2 - Return periods (in years) of tsunami runup heights of 10, 6, 3 and 1.5 m. (M = million years).

Calculations were also made for the maximum expected runup heights in 100 years, 50 years, 20 years and in 10 years. These are shown in Table 5.3.

CITY/PORT	Lat, Long	100 years	50 years	20 years	10 years
Whangarei Harbour	35.80S, 174.40E	0.47			
Auckland Port	36.85S, 174.77E	1.15	0.50		
Tauranga District	37.67S, 176.20E	1.24	0.49		
Gisborne Harbour	38.67S, 178.02E	3.94	1.50		
Napier District	39.50S, 176.90E	2.59	0.71		
Wanganui	39.95S, 174.98E	1.56			
Wellington Port	41.28S, 174.78E	2.27	1.31	0.04	
Lyttelton Port	43.62S, 172.75E	4.99	2.35		
Timaru	44.40S, 171.25E	1.96	0.54		
Port Chalmers	45.82S, 170.62E	0.85	0.37		
New Zealand		12.99	9.74	5.45	2.20

TABLE 5.3 - Expected tsunami size (m) to strike in 100, 50, 20 and 10 years. Blanks indicate the waves are too small to be detected.

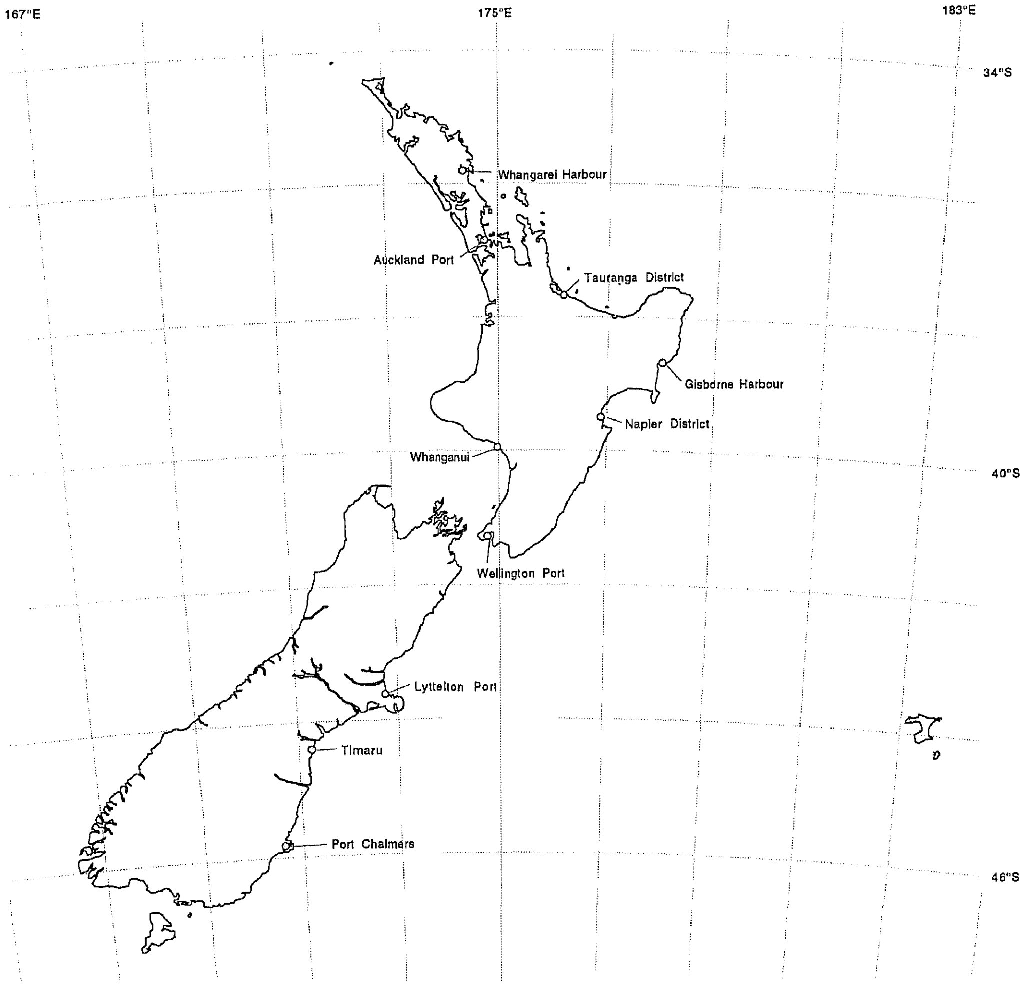

FIGURE 5.2 - Locations of sites around New Zealand used for return period calculations.

5.2.2 Tsunami Source Regions

Most of the tsunami events have been generated from local sources. Tables 5.4 and 5.5 show the return periods and expected tsunami sizes for both locally generated tsunami and far-field tsunami.

SOURCE REGION	10m	6m	3m	1.5m
Local	63	30	17	13
South Pacific Islands	462 540 M	40.9 M	37 209	1 122
Indonesia	* - At most runup of 1.8 m in 177 years.			
Japan	* - At most runup of 0.1 m in 177 years.			
Kuril Islands and Kamchatka	181 248	8 325	826	260
Alaska	* - At most runup of 1.25 m in 177 years.			
West Coast of North & Central America	* - At most runup of 0.4 m in 177 years.			
West Coast of South America	170	95	61	49
Far-field	233	86	41	28

TABLE 5.4 - Return periods (in years) of tsunami waves from local or far-field sources for heights of 10, 6, 3 and 1.5 m. * indicates only one recorded tsunami event.

SOURCE	100 years	50 years	20 years	10 years
Local	11.72	8.04	3.17	
South Pacific Islands	0.46	0.17		
Kuril Islands and Kamchatka	0.26			
West Coast of South America	6.36	1.59		
Far-field	6.60	3.80	0.11	

TABLE 5.5 - Expected tsunami runup heights (m) from local and far-field sources to strike in 100, 50, 20 and 10 years. Blanks indicate that the waves were too small to be detected.

5.3 - RESULTS AND DISCUSSION

5.3.1 Accuracy of Method

The Poisson exceedance frequency distribution is based on the assumption that the events will be random events in time and not related to each other (NERC, 1975; Kite, 1977). Although the tsunami events are related to natural processes we can assume that they are random because the processes are extremely complex.

In Table 5.3 and 5.5 the blank squares of expected tsunami size for return periods of 10 and 20 years is due to limitations in the exceedance frequency distribution. Each equation will have a return period for the wave of height 0 m. Any return periods entered into the equation which are below this value will return expected wave heights which are negative. For example, the equation for Auckland has a return period of 31.5 years for a wave height of 0 m. If we try to calculate expected wave heights for 10 and 20 years the results will be negative. This indicates that the wave heights are too small to be calculated.

The r^2 values, from the lines of best fit, can show how well the Poisson distribution curve equations of exceedance frequency fit the data. A value of 1 shows that the data is represent perfectly by the line of best fit. While a value of 0 shows that the data does not follow any trend which can be estimated by a line of best fit. Exceedance frequency calculations for both sites around New Zealand and tsunami source regions have r^2 values ranging from 0.721 - 0.995. Most of the values lie between 0.912 - 0.995. This suggests that the Poisson distribution predicts the exceedance frequencies very well. The exceedance frequency graph for Napier, Figure 5.3, has a low r^2 value of 0.721. The data points do not lie on or near the line of best fit. However, the exceedance frequency graph for Timaru, Figure 5.4, has a high r^2 value of 0.995. The data points lie very close to the line of best fit showing a very good correlation.

The number of data points for each exceedance frequency graph can also affect the accuracy of the return period estimates. However, the data available for some locations was very limited. Timaru, Wanganui and Whangarei only have 3 or 4 tsunami events recorded over the 177 year period. This obviously introduces uncertainty and reduced confidence. The tsunami source region 86, Figure 5.5, has only 2 data points, giving an r^2 value of 1. This does not represent how well the data points correlate to the line of best fit. Clearly, the more data points, the more accurate the prediction will be. The Wellington exceedance graph, Figure 5.6, contains 8 points, and gives a better indication of how well the data points fit the line of best fit.

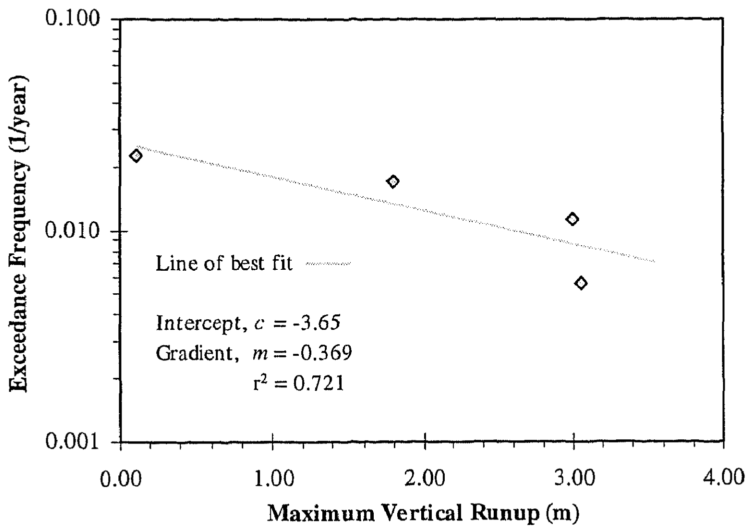

FIGURE 5.3 - Exceedance frequency distribution of tsunami runup heights for Napier. The r^2 value is only 0.721 showing that the data is not very well correlated with the line of best fit.

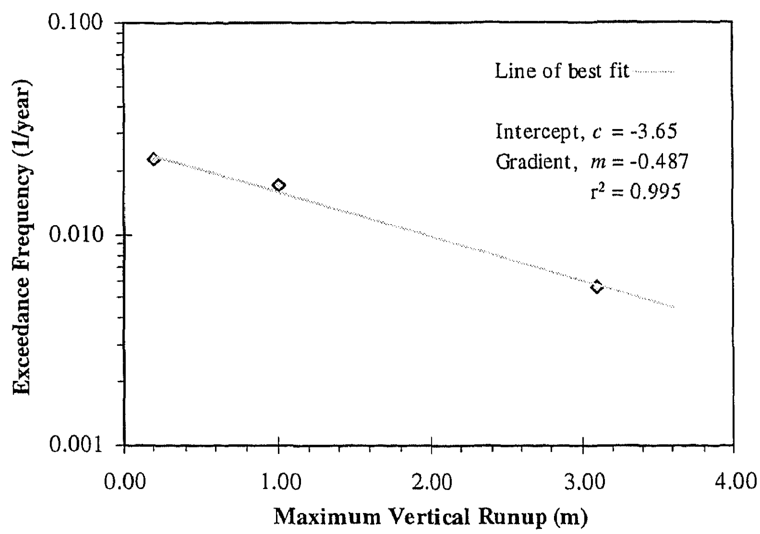

FIGURE 5.4 - Exceedance frequency distribution of tsunami runup heights for Timaru. The r^2 value is 0.995 showing that the data is very well correlated with the line of best fit.

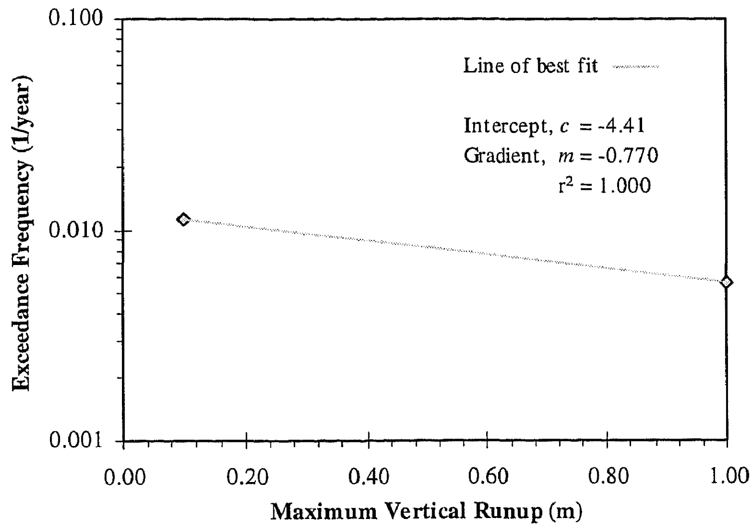

FIGURE 5.5 - Exceedance frequency distribution of tsunami runup heights from source region 86. There are only two data points. This means that the r^2 value will equal 1, which will mean nothing as there are not enough data points for correlation.

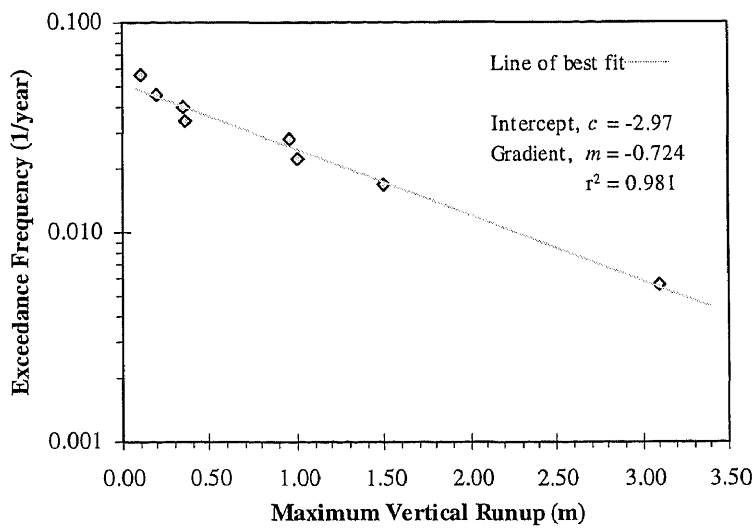

FIGURE 5.6 - Exceedance frequency distribution of tsunami runup heights for Wellington. There are 8 data points which provides us with a much better estimation of return periods. Data can be seen to follow the line of best fit.

5.3.2 Results

Tables 5.2 and 5.3 show that Lyttelton is most at risk of being struck by a significant tsunami wave (3 m or more). It is likely that every 60 years Lyttelton can expect a tsunami runup of 3 m. Port Chalmers is the least likely to be affected by a significant tsunami wave. It can be expected that there will be a runup of 3 m every 50.7 million years.

Table 5.4 and 5.5 show that a tsunami of significant size is most likely to be generated from local sources, such as the two 1947 tsunamis in the Gisborne area. Every 17 years a local tsunami of significant size can be expected somewhere in New Zealand. Past local tsunami have mostly affected the Gisborne, Hawkes Bay, Wellington and Canterbury regions. Tsunamis from local sources tend to be larger than ones generated from far-field sources. However, far-field tsunami, such as the 1868 Chilean tsunami, tend to affect more of New Zealand. Far-field tsunami of a significant size are expected most from the West Coast of South America (region 89). New Zealand can expect a 3 m tsunami from this region every 61 years.

5.3.3 Application

Expected tsunami heights can be added to expected storm surge heights to determine coastal setback. For example, if the expected life span of a house (design life) is 100 years, then setback can be calculated from the maximum expected tsunami height in 100 years and maximum expected storm surge in 100 years. This gives an elevation of how high the house must be to survive expected storm surges and tsunami runups which might affect the coast in the next 100 years. This also accounts for storm surges and tsunami waves affecting the coast at the same time (worse case scenario). The elevation can then be transformed into a horizontal distance inland using the topography of the location.

For example, Figure 5.7 shows the maximum storm surge and runup heights of 0.8 m and 10.1 m expected for Location X in the next 100 years. This gives an elevation of 10.9 m. If the average slope is 20° (1:2.75) then the house would have to be at least 30 m away from the sea to be safe.

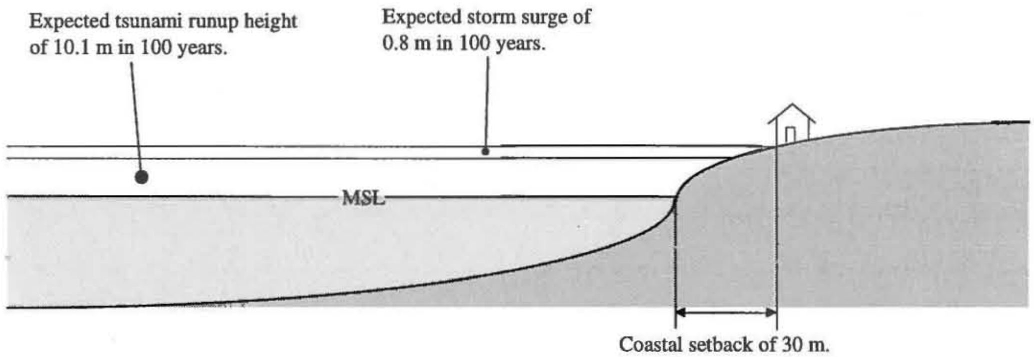

FIGURE 5.7 - Coastal setback for a house in Location X.

5.4 - SUMMARY

Through using the exceedance frequency distribution, return periods and expected tsunami runup heights were calculated for various locations throughout New Zealand. Return periods and exceedance frequencies were also calculated for tsunami source regions and New Zealand as a whole. Correlation of event data fits well with the Poisson distribution. Lyttelton was the most at risk Port of being affected by a tsunami wave of significant size and Port Chalmers was the least at risk Port. Expected tsunami runup heights can be used to calculate the coastal setback. This can help to minimize the damage done to coastal structures. To increase the accuracy of the of the exceedance frequency a large number of reported tsunami events is needed for each location.

Chapter 6

Summary and Conclusion

CHAPTER 6 - SUMMARY AND CONCLUSION

The three objectives for this thesis were to: (i) extend the current tsunami data shown by de Lange and Healy (1986), (ii) create a database of all the data, and from that to (iii) calculate the tsunami risk for various locations around New Zealand. The database was extended by addition of 8 new tsunami events and 36 new tsunami reports for locations around New Zealand of existing tsunami events. However, there is still room for further research.

In summary, the findings and achievements of this thesis through the tsunami data, the tsunami database and the return periods were:

- Tsunami data for New Zealand is limited.
- Data from de Lange and Healy, 1986, has been updated to include tsunami events from 1981 - 1997 and also the 1820 tsunami.
- Local tsunami waves are the most destructive and the most likely to cause damage around New Zealand.
- The most destructive and common far-field tsunami waves will probably originate from the West Coast of South America (region 89).
- Major far-field tsunami, for example the 1868 Chile tsunami, affects most of New Zealand, unlike a local tsunami which tends to only affect a small section of coast, such as the two 1947 Gisborne tsunami waves.
- New Zealand can expect a significant (> 3 m) far-field tsunami every 41 years and a significant local tsunami every 17 years.
- Expected tsunami heights can be added to expected storm surge heights to estimate coastal setback.
- Lyttelton and Gisborne are the most susceptible to tsunami waves of destructive potential.

The archive search was mainly though historical newspaper held in the Alexander Turnbull Library in Wellington and the Hocken Library in Dunedin. The Christchurch and Dunedin Museums were also visited. Locations which were not visited due to time restrictions were the National Achives and Museums located in other areas around New Zealand.

The lookup table database created using Microsoft Excel is simple and effective. It would have been possible to create a database with a graphical interface., but for the purpose of this thesis a lookup table was adequate. It would also be useful to construct an internet web page database.

Using the available data from the database, return periods and expected runup heights have been presented for various sites around New Zealand. The only limitations were due to lack of available data. Some sites, such as Nelson, only had one report of a tsunami event. This made it impossible to calculate expected runup and return periods.

The main problem for this thesis was limited time and money resources available for the archive search. The following recommendations are made for further studies:

- Extending the archive search even further by: visiting locations not visited for this thesis and searching through newspapers not used for this thesis.
- Find the exact date and source of the Tolaga Bay tsunami around 1926-29 and the 1820 tsunami.
- Find tsunami events missed by this thesis.
- Create a web page for the tsunami database.
- Evaluate storm surge heights for important sites around New Zealand to be added to expected tsunami heights in the evaluation of coastal setback.

Appendix 1

Additional Tsunami Data

APPENDIX 1 - ADDITIONAL TSUNAMI DATA

SUMMARY NOTES OF TSUNAMI REPORTS
(Additional to previous de Lange and Healy, 1986, information)

EARTHQUAKE AROUND 1820

TIME	
MAGNITUDE	
EPICENTRE	
RELIABILITY INDEX	0.75

This tsunami event was originally found reported in MacIntosh, 1985. The report stated that in the early 1800's a huge wave engulfed and killed a large number of Maoris at Otara. The same is also reported for Orepuki Beach. The Southland Daily News (sometime around 1936) reports of tsunami waves around 1820 wiping out many hundreds of Maoris at Orepuki Beach.

SOURCES:

MACINTOSK (1985)

SOUTHLAND DAILY NEWS

Around 1936

EARTHQUAKE OF AUGUST 13TH, 1868

TIME	1645
MAGNITUDE	8.5
EPICENTRE	18.5S 71.0W
RELIABILITY INDEX	1

Wellington - Unusual tide oscillations occurred every five minutes.

Lyttelton - A wave 20 feet (6.1 m) high, which came up with great rapidity, was reported in Lyttelton harbour. The shipping suffered serious damage.

Akaroa - It was reported that the tidal wave was 4 feet (1.2 m).

Timaru - The tide was reported to rise 10 feet (3.1 m) five times in a hour.

Oamaru - Unusual rise and fall of tide many times between 8 am and 12 pm was reported by a correspondent at Oamaru. At 12 pm, 2 feet (0.61 m) of water flowed into the Government shed and boats were swept up the Creek. In six minutes the sea had risen a total of 11 feet (3.35 m), before falling away again. At daybreak a boat which was 400 feet (121.9 m) from shore and would normally be in 11 feet (3.35 m) of water, was left grounded for a few minutes. A man in the boat got out and walked over to the anchor, which he had dropped sometime ago, and picked it up. Eye witnesses observed the rapid rise and fall of the tide. They estimated that it had fallen about 20 feet (6.1 m) in just a few minutes and rose just as fast. Five oscillations in 20 minutes were observed. There was heavy surf, even though there was no wind.

Otago Heads - Observations of rising and falling tides similar to those at Oamaru were also made in Otago Heads. At 9 am, half an hour after the flood tide had set in, the water rose 5 feet (1.5 m) to the normal high water mark. For 2 minutes it remained stationary at this level, then fell just as rapidly. The tide then reached 7 knots at the lower Red buoy. Two buoys which had been strongly anchored came adrift. The waters in Port Chalmers continued to quickly rise and fall. A watchman, appointed by the Harbour Master to record changes, observed the water ebbing 17 inches (0.43 m) in two minutes.

Dunedin Bay - During the dining hour, when the tide should have been falling, it started to rise rapidly. The vessel s.s. Keera which was hauled up on a beach near Pelichet Bay needed to be moved another 25 feet (7.62 m) to be safe from the rising water.

Taieri River - There was a great rise and fall of the water. A boat was pulled from its moorings near East Taieri Bridge and washed down stream by the retreating water. It was recovered before it reached the breakwater.

Invercargill - A wave was reported at 8 am on Saturday 15th in the New River Estuary. The wave was estimated to be from three to 5 feet (1.5 m), running from the Heads up to the Jetty. This gave the appearance that the tide was full rather than at half flood were it should have been. Half an hour later the water ebbed very rapidly for about the same time. A new wave came in with less velocity. This continued until around noon. Mr Hart noted strong currents on Saturday morning while in a dingy. After coming ashore he followed the receding water 200 feet (60.9 m). He then had to swiftly retreat 180 feet (54.8 m) as the water began to rise rapidly. The slope of the ground was about 1/200 ($\approx 0.3°$).

Riverton - Waves were reported to have raised the water level 3 feet (0.91 m) at 8 am on Saturday morning. On one side of the estuary cattle had to run from the waves, some even had to swim to high ground.

Cambelltown - Located near Bluff (Hochstetter and Petermann, 1864). During the morning the tide set in with great strength, rising rapidly. At around 7 am the tide was full, 3 hours earlier than normal. The water level then proceeded to rise and fall 2 feet (0.61 m) repeatedly until just after 12 noon. It then set out with great violence for half an hour before resuming normal oscillations.

Port Charles - A runup height of 1.8 m was reported along wide an extra high tide.

SOURCES:

OTAGO DAILY TIMES
17th August 1868

THE SOUTHLAND NEWS
18th August 1868

THE SOUTHLAND TIMES
17th August 1868

NOAA'S NATIONAL GEOPHYSICAL DATA CENTER

EARTHQUAKE OF MAY 10TH, 1877

TIME	0059
MAGNITUDE	8.3
EPICENTRE	21.5S 71.0W
RELIABILITY INDEX	1

This tsunami was also reported in Sydney and Newcastle, Australia.

Westport - A wave was reported at 2:30 pm and 6 pm on Friday 11th. The water rose 6 feet (1.8 m) in three minutes. Oscillations continued on Saturday, but only slightly.

Grahamstown - Grahamstown, now known as Thames. A 3 foot (0.91 m) wave was noticed travelling up the Thames River (now known as the Waihou River) on Friday 11th. At 4 pm on the same day, it flowed in suddenly, but not very high, ebbing just as quickly. It rose again at about 7 am Saturday 12th.

Jackson's Head - The s.s. Wellington reported that they had encountered a very heavy tidal wave 3 miles (5 km) west of Jackson's Head. The stern of the steamer nearly dipped under water and was driven back almost half a mile (about 850 m).

Oamaru - On the 11th of May, the water in the bay started to rise at around 8 am (low water). In 10 minutes it had reached one foot below high water.

Lyttelton - From 7 am till 1 pm the water had been rising and falling, sometimes rising 3 feet (0.91 m) in a few minutes and falling just as fast.

Pigeon Bay - It was reported that Pigeon Bay felt the effects of a tidal wave on May 11th. The water rose 12 inches (0.3 m) above normal high water. The report does not say what stage the tide should have been at. Due to the unusual tide a yacht was washed up into a bush.

Port Chalmers - The first noticeable disturbance was reported at day break by fishermen. The tide receded rapidly, and then it just as rapidly flowed several feet up the bank. An hour later the tide receded again until the water was well below the spring tide low water mark. It had not been this low since the 1868 disturbance. At 9 am, which was at low water, the tide ebbed, and then returned. It continued to rise and fall 7 - 18 inches (0.18 - 0.46 m). The tide would sometimes rise 15 - 20 inches (0.38 - 0.51 m) in half as many minutes. The ebb was nearly as great. The water in the harbour became very turbid. One of the oscillations was measured. The rise was 15 inches (0.38 m) in eight minutes, and the fall was about 9 inches (0.22 m) in eight minutes. Strong ebb flows were reported at Hobart Town Point.

Kaiapoi - Maximum runup of 0.9 m was recorded.

SOURCES:

THE NELSON EVENING MAIL

12th May 1877

OTAGO DAILY TIMES

12th May 1877

14th May 1877

EARTHQUAKE AROUND 1926-29

TIME	
MAGNITUDE	
EPICENTRE	
RELIABILITY INDEX	1

Tolaga Bay - Three large tridal waves were reported running into the bay damaging a unfinsihed jetty. The wave was around 11 feet (3.35 m) above high water spring.

Source:

WHITE-PARSONS, 1944

EARTHQUAKE OF MARCH 25TH, 1947

TIME	2032
MAGNITUDE	6.0
EPICENTRE	38.9**S** 178.24**E**
RELIABILITY INDEX	1

Kaiti Beach - Water rose to the base of the Cook monument. Houses along the road suffered some structural damage.

Turihaua Point - A house was destroyed. The owners had a miraculous escape.

Gisborne - There were three waves reported, at 12 feet (3.66 m) each. Several smaller variations in water level were observed later that morning.

Pouawa Beach - The first tsunami wave was seen at 8:40 am. The wave was reported to be a large greenish-grey wall of water. The second wave was smaller than the first.

Wainui Beach - It was reported that if the wave had been 2 feet (0.61 m) higher it would have caused major damage. The report also indicates that the houses near the beach suffered. As the wave receded it met the second incoming wave about 50 yards (45.72 m) in front of a house. This caused water to cascade high into the air.

Murphys Beach - 12 feet (3.66 m) of water flooded the low-lying land. The receding wave swept a 15 acre paddock of pumpkins out to sea, and demolished a fence which was bordering the beach.

SOURCES:

OTAGO DAILY TIMES
27th March 1947

THE GISBORNE HERALD
26th March 1947

EARTHQUAKE OF NOVEMBER 4TH, 1952

Time	1658
Magnitude	8.25
Epicentre	52.75N 159.5E
Reliability Index	1

Tutukaka - After 9 pm on the 5th of November a 3 foot (0.91 m) wave was seen every 10 minutes.

SOURCE:

THE SOUTHLAND TIMES
7th November 1952

EARTHQUAKE OF MAY 22ND, 1960

TIME	1911
MAGNITUDE	8.5
EPICENTRE	41.0S 73.5W
RELIABILITY INDEX	1

Reports show that the hardest hit areas were tidal estuaries of rivers and streams south of Dunedin.

Great Barrier Island - It was reported that tidal waves were surging across the roads at Tryphena.

Great Mercury Island - Water was reported to be bubbling and whirling.

Mercury Cove - Sandbanks which were normally covered by deep water were exposed in minutes.

Mercury Bay - On 23 May 1960 at 9 pm the water receded, returning 20 minutes later to a height which covered the road and wharf. The tide surges continued for four days, occurring every 40 minutes. A 28 foot boat, the 'Mermaid', broke free from her moorings and was carried 2 miles (3.22 km) up the river. Also a 38 foot boat was swept up onto the road. A 2 foot (0.61 m) wave was report in at around 2 am on Tuesday morning. On Thursday 26th near Pah Point the water height reached 4 feet (1.22 m) above the highest spring tide (19 feet, 5.69 m, from the low tide mark). The flood and ebb flows were estimated to be 12 and 18 knots respectively. A large flat rock, 20x10x6 feet (6.1x3x6 m), from Pah point was swept away and still has not been found.

Russell - A flashing beacon was washed away by a tidal wave.

Ahipara - Waves ran up a tidal creek.

Taieri Mouth - The deck house of the Kiwaka, a 35 foot commercial pleasure craft, was completely destroyed as it was forced under the estuary bridge. The Matarua, a smaller fishing launch, was damaged as it was bashed against the beams of the bridge. Even heavy ropes, which were tying down boats, snapped. The rise in sea level was estimated to be about 5 feet (1.52 m). Dingys and other rowing boats dotted the estuary. Another major surge occurred at high tide (2 pm). The surge reached a height of about 5 feet (1.52 m) as it flowed up the estuary as a bore.

Brighton - Similar disturbances to those at Taieri were also noted here. Mrs A. R. Merrilees described the anomalies as "like the whole ocean rushing in". A surge moved up the Brighton stream, over-turning a small wooden jetty and damaging a large dingy by dropping it onto a rock.

Oamaru - Surges of 7 - 12 feet (2.1 - 3.66 m), lasting 20 minutes occurred approximately every hour. Surges were small at first, but built up with time. Smaller surges would come in over top of the larger surges. The biggest surge was between 4 am and 5 am, and then another at 8 am. A continuous swirling of water was reported at the harbour entrance, yet outside and inside the harbour was as smooth as glass.

Dunedin - At about 3:25 am a 1 - 2 foot (0.3 - 0.61 m) rise and fall in sea level occurred for 30 minutes.

Lyttlelton - Three houses in Charteris Bay were worst affected by the tsunami wave. One was lifted off its foundations, the other two were badly flooded. The ground floor of the Wheat Sheaf Hotel was flooded to a depth of 3 feet (0.91 m). Most damage was done on Monday night/Tuesday morning. On Tuesday afternoon there was a double tide.

Okains Bay - Early on Tuesday 24th, a tidal wave about 8 - 10 feet (2.43 - 3.05 m) high was reported. The wave destroyed the main bridge and crashed through the house of Mr B. Bartrum. The roaring of the water woke him up at 2:30 am, he then fled for high ground as the water was swirling around him.

Little Akaloa - The house of Mr O. Gilbert, which is 50 yards (45.72 m) from the seafront, was moved back 4 inches (0.1 m) on its foundations. Also, one of his farm sheds collapsed and a side of his wool shed was damaged.

Gisborne - At 1 am on Tuesday morning (24th) the tidal waters were reported to surge 18 feet (5.48 m) in 10 minutes. They then receded just as fast. During the day the riverbed was exposed as the tide drained away. This enabled fishermen to walk out and collect flounders which had been stranded from the receding water.

Clifton Domain - An abnormally high tide swept into Clifton Domain on Tuesday morning. The roadway was littered with debris. Fortunately at that time of year the camp was empty. A seawall which was 10 feet (3.05 m) above mean high water was pushed over by the wave. The camp owners house was flooded by seawater.

Tatapouri - Mr Hall reported water level drops of 9 feet (2.74 m) in around 1.5 minutes. The sea also reached the top of the retaining walls.

Tokomaru Bay - A large tidal surge of 8 feet (2.44 m) above normal high water mark struck the bay at around 5 am on Tuesday 24th. Ninety feet (27.4 m) of protective sea walling (wooden) was damaged.

Opotiki - A small sea craft was hit by a 5 foot (1.52 m) bore in the river estuary early on the 24th (Tuesday). No damage to shore properties or structures. Tide marks left on the waterfront indicate that there were some surges during the night. Some damage might have occurred if sea levels had still been high from storm surges.

Tolaga Bay - Surging of the sea started at 8:30 pm. The peak of the surge was over by 5:30 am. The campgrounds were flooded to a depth of 1 foot in the cook house. From 4 am there were consistent surges every quarter of an hour. Surges started easing at 9 am with the out going tide.

Napier - The first wave began at 3:30 am and was 4 feet (1.22 m) high. The wave heights steadily increased until 5 am when a 10 foot (3.05 m) wave swept through Napier's inner harbour. The period between waves is at least 40 minutes.

Ngawi - Three whales, around 20 feet in length, were washed up at Ngawi (west of Cape Palliser lighthouse) due to surging seas on the night of 24th May.

Riversdale - During the morning of 25th May the sea was reported to rise several feet higher than normal and then recede beyond the normal low water mark.

Taylors Point - A runup of 0.6 m was reported.

Fortrose - Larger waves than normal were reported at 5 pm 24th May.

Bluff - The tide on the 24th was reported to fluctuate every half an hour along with normal tide oscillations (every six hours). Between 12:15 pm and 3 pm (normally slack water) the tide rose and fell seven times.

Colac Bay - Early on Tuesday morning tidal surges hit Colac Bay. The surges covered the beach road with debris.

Stewart Island - The worst disturbances were reported to on the night of the 23rd. Debris and Kelp were deposited exceptionally high up the foreshore. During each surge, the height of the water was only 2 feet (0.61 m) under the main wharf decking. The tide would fall 5 feet (1.52 m) and rise 4 (1.22 m).

SOURCE:

OTAGO DAILY TIMES

25th May 1960

THE GISBORNE HERALD

24th May 1960
25th May 1960

NOAA'S NATIONAL GEOPHYSICAL DATA CENTER

EARTHQUAKE OF DECEMBER 19TH, 1982

Time	1744
Magnitude	7.7
Epicentre	Kermadec Islands
Reliability Index	1

Auckland - Runup of less than 0.1 m was reported at the Auckland Port.

SOURCE:

DE LANGE AND HULL, 1994

EARTHQUAKE OF OCTOBER 20TH, 1986

Time	0646
Magnitude	8.3
Epicentre	Kermadec Islands
Reliability Index	1

Auckland - Runup of less than 0.1 m was reported at the Auckland Port.

SOURCE:
DE LANGE AND HULL, 1994

EARTHQUAKE OF MAY 7TH, 1986

Time	2247
Magnitude	7.7
Epicentre	17.8S 101.6W
Reliability Index	1

Lyttelton - Runup of 0.4 m is reported.

SOURCE:
NOAA's National Geophysical Data Center

LANDSLIDE OF MAY 20TH, 1987

Reliability Index	1

Deep Cove - A 3 m tsunami wave was created in the Doubtful Sound after a slip entered the water. A 17 m launch was thrown into a wharf, which was demolished.

SOURCE:
MALONEY, 1995

EARTHQUAKE DURING JUNE 1993

Time	
Magnitude	
Epicentre	Kermadec Islands
Reliability Index	1

Auckland - Runup of less than 0.1 m was reported at the Auckland Port.

SOURCE:
DE LANGE AND HULL, 1994

EARTHQUAKE OF OCTOBER 4TH, 1994

Time	1323
Magnitude	8.3
Epicentre	Kuril Islands
Reliability Index	1

Runup of less than 0.1 m was reported at Marsden Point, Auckland Port, Tauranga, Gisborne, Napier, Wellington, Lyttelton and Pegasus Point.

SOURCE:
DE LANGE AND HULL, 1994

Appendix 2

Tsunami Database

APPENDIX 2 - TSUNAMI DATABASE

EYear	ETime	EDate	ELocation	ERegn	EH	ERunup	EWaves	EPeriod	ESpecificDamage	STime	SDate	SLocation	SRegn	SCause	SMag	Refs	Comments
1820			Otara	13	10.00	10.00			1 - Lives							2	Source and exact year unknown, around 1820.
1820			Orepuki Beach	13	10.00	10.00			1 - Lives							2	Source and exact year unknown, around 1820.
1843		8-Jul	Wanganui	7	0.50	0.50				0515	8-Jul	Wanganui	81	Slide-EQ	7.8	1	Unusual water movement (seiching) in the Wanganui River.
1845	1300	5-Jul	Wanganui	7	1.00	1.00	1				5-Jul	Wanganui	81			1	Double tide.
1848		16-Oct	Wellington	9	0.36	0.36				1410	15-Oct	Lower Wairau V.	81	Quake	7.1	1	Rose .3m above normal sprinf tide.
1855		23-Jan	Wellington	9	3.55	3.55	20+	20	5 - Houses	0941	23-Jan	West Wairarapa	81	Slide	8.0	1	
1855		23-Jan	Nelson	16	2.00	2.00				0941	23-Jan	West Wairarapa	81	Slide	8.0	1	Wave reported.
1855		23-Jan	Wairau R.	10	6.00	6.00	1			0941	23-Jan	West Wairarapa	81	Slide	8.0	1	Gigantic wave swept over beach, then ebbing and flowing.
1855		23-Jan	Palliser Bay	9	9.10	9.10	1			0941	23-Jan	West Wairarapa	81	Slide	8.0	1	Some heights of 10.3m reported.
1855	Night	23-Jan	Avon River	11	1.25	1.25	1			0941	23-Jan	West Wairarapa	81	Slide	8.0	1	Small bore in Avon R.
1856		Mar	Waihao R	11	3.00	3.00	1				Mar					1	Source unknown.
1868	0900	15-Aug	Mangonui	1	1.50	1.50				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Observed on 15-17 Aug. Max rise on 15 between 9am-2pm.
1868		15-Aug	Russell	1	1.50	1.50	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Water rushed above normal spring tide.
1868		15-Aug	Great Barrier Is.	2	2.90	2.90	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Rosalie Bay, tide rose 2m > NHW. Tryphena Har., boat lifted 1.5m > NHW.
1868		15-Aug	Tamaki Est.	2	1.50	1.50	2-5			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Bore on upper reaches of estuary, then 1.2-1.5m water flucuations.
1868		15-Aug	Orewa	2	1.80	1.80				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Unusually high tide.
1868		15-Aug	Port Charles	3	1.80	1.80	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868		15-Aug	Opotiki	4	1.80	1.80	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	A bore raced up the river.
1868	0400	15-Aug	Cape Runaway	4	3.00	3.00	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	3m wave between 4-5am.
1868		15-Aug	Napier	6	1.80	1.80	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Wreck exposed by receeding water.
1868	1100	15-Aug	Castlepoint	9	0.60	0.60	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Extra high tide at 11am. Normal high tide occured at 2pm.
1868		15-Aug	Wellington	9	1.50	1.50		5		1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1,2	1.5m Variations in water level.
1868	0800	15-Aug	Nelson	16	1.50	1.50				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	1.2m bore at 8am, flucuations continued until the 17th. Max=1.5m.
1868	1000	15-Aug	White's Bay	10	1.50	1.50				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Water reached the door of the telegraph office at 11.30am.
1868	0300	15-Aug	Kaiapoi	11	1.20	1.20	6-10		2 - Several ships	1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Seven bores, first largest (at 3am). Small waves during day.
1868		17-Aug	Christchurch	11	0.50	0.50	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Small wave noticed in Avon R.
1868	0330	15-Aug	Lyttelton	11	7.60	7.60	2-5	75	2 - Shipping	1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1,2	Buoy with 200kg anchor moved >800m. Tide .3-.4m > usual for 3 days
1868		15-Aug	Akaroa	11	1.20	1.20	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868	0400	15-Aug	Pigeon Bay	11	3.05	3.05	2-5	40	1 - 2 jetties & a fence.	1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	2 jetty's and a fence was removed. Tide flucuations for rest of day.
1868		15-Aug	Okains Bay	11	3.95	3.95	1		1 - Bridge	1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	A bridge 3.2km from the coast was washed away.
1868		15-Aug	Little Akaloa Bay	11	3.00	3.00				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Water flooded 170m (horizontally) past NHW.
1868	0800	15-Aug	Oamaru	11	6.10	6.10		4		1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1,2	After the 1.5m wave was a sudden drop of 3.6m in 5min.
1868	0500	15-Aug	Timaru	11	3.10	3.10	>1	12		1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1,2	Strong whirlpools formed in harbour.
1868	0900	15-Aug	Otago Heads	12	1.50	1.50	>1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868	1000	15-Aug	Port Chalmers	12	0.30	0.30				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	After initial .3m rise, water continued to fluctuate all day.
1868	1800	15-Aug	Dunedin Bay	12	1.00	1.00	1			1646	13-Aug	18.5S 71.0W	89	Quake	8.5	2	The water rose inundating about 25m inland.
1868		15-Aug	Taieri River	12	3.00	3.00	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868	0800	15-Aug	Bluff	13	1.50	1.50				1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Water rushed in between 8-9am. Water receeded 0.5m at 11am.
1868	0800	15-Aug	Invercargill	13	1.50	1.50	>1	30		1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868	0800	15-Aug	Riverton	13	0.90	0.90	>1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868	Morn	15-Aug	Campbelltown	13	0.90	0.90	>1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	2	
1868		15-Aug	Westport	14	1.50	1.50	1			1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	One bore between 1.2-1.5m.
1868		15-Aug	Chatham Is.	17	10.00	10.00	2-5		1 - Life, settlements	1645	13-Aug	18.5S 71.0W	89	Quake	8.5	1	Flooding 6.4km inland. Settlements destroyed, stones of 500kg moved.

TABLE A2.1 - Tsunami database records for 1820 - 1868

EYear	ETime	EDate	ELocation	ERegn	EH	ERunup	EWaves	EPeriod	ESpecificDamage	STime	SDate	SLocation	SRegn	SCause	SMag	Refs	Comments
1877	0500	11-May	Manowaora Bay	1	2.70	2.70			5 - House	0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Creek bed dry but tide was very high. A house was flooded in .3m water.
1877		11-May	Waitangi	1	3.00	3.00	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	The boat Iona was swept above high tide mark.
1877		11-May	Russell	1	1.80	1.80	6-10			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Tide ebbed and flowed 7 times.
1877	1200	11-May	Paihia	1	2.40	2.40	2-5			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	At noon tide dropped 1.2m in 10min, then rose 1.9m by 12:25pm.
1877	1600	11-May	Wairoa Bay	1	*2.00*	2.00	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Inundation of 9m, two boats left high and dry.
1877		11-May	Te Wharau	1	*1.50*	1.50	2-5			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Tide ebbed and flowed 7 times during the 11th.
1877	1700	11-May	Bay of Islands	1	2.50	2.50		20		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	2.5m rise in a few minutes, then ebbing and flowing every 20min.
1877	0700	11-May	Warkworth	2	1.80	1.80	2-5	60		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Wave at 7, 9 & 10am and 12:45pm. Wave heights 1.8, 1.5, 1.5 and 1.2m.
1877		11-May	Auckland	2	0.20	0.20				0059	10-May	21.5S 71.0W	89	Quake	8.3	1	0.2m flucuation recorded.
1877	1600	11-May	Thames	3	0.90	0.90	2-5			0060	10-May	21.5S 71.0W	89	Quake	8.3	2	Bore in the Thames River, tide flowed at 4pm and at 7am on the 12th.
1877		11-May	Port Charles	3	3.60	3.60	20+	20	1 - Wharf	0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Tide ebbed and flowed 20min all day. Ave height =2.5m, Max=3-3.6m.
1877	0800	11-May	Tauranga	4	1.80	1.80	2-5			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Tide flucuated of .3m sevral times during day, continued on the 12th.
1877	1200	11-May	Gisborne	5	2.40	2.40	6-10	80	1 - Small Punt	0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Disturbances continued till 14th. Bore reported in river at 12:30pm.
1877	2300	10-May	Napier	6	*3.00*	3.00		30		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Watt's Wharf completely flooded.
1877	0700	11-May	Wellington	9	1.50	1.50	20+	7		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	A bore was reported in a narrow channel.
1877		11-May	Kaiapoi	11	0.90	0.90	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	2	
1877		11-May	Waimakariri R.	11	*1.00*	1.00	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	A wave was reported.
1877		11-May	Avon River	11	0.90	0.90	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	0.9m rise in Avon River.
1877	0700	11-May	Lyttelton	11	0.90	0.90	>1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1,2	At 7am water rose above high water mark, then feel exceedingly low.
1877		11-May	Pigeon Bay	*11*	1.25	1.25	*1*			0059	10-May	21.5S 71.0W	89	Quake	8.3	2	
1877	0700	11-May	Akaroa	11	2.50	2.50	11-20	20		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	7am first wave. Waves every 20min, still noticable at noon.
1877		*11-May*	Timaru	*11*	*1.00*	1.00	1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Wave observed, no details.
1877	0800	11-May	Oamaru	12	3.00	3.00				0059	10-May	21.5S 71.0W	89	Quake	8.3	1,2	Small variations until noon. Max disturbance 2.5-3.0m.
1877	Early	11-May	Port Chalmers	12	0.50	0.50	>1			0059	10-May	21.5S 71.0W	89	Quake	8.3	1,2	0.15m rise in 7min.
1877	1000	11-May	Kaitangata	12	1.20	1.20	2-5	60		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	.5m bore, then a 1.2m rise, then feel in 20min. River rose hourly until 2pm.
1877	0900	11-May	Bluff	13	1.50	1.50	2-5	60		0059	10-May	21.5S 71.0W	89	Quake	8.3	1	Waves every hour from 9am till noon. Flucuation of 1.2m-1.5m.
1877		11-May	Jackson's Head	14	*2.00*	2.00	1			0060	10-May	21.5S 71.0W	89	Quake	8.3	2	A steamer was forced back 850m and its stern was nearly dipped under water.
1877	1430	11-May	Westport	14	1.80	1.80	>1			0059	10-May	21.5S 71.0W	89	Quake	8.3	2	
1883	2200	28-Aug	Mangonui	1	*1.50*	1.50	6-10			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Large waves occured at 4 am on the 29th.
1883	0900	29-Aug	Russell	1	*1.50*	1.50	6-10			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Waves continued from the 29th - 30th
1883		29-Aug	Warkworth	2	1.20	1.20	1			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Wave reported in Mahurangi estuary.
1883	0800	29-Aug	Auckland	2	1.80	1.80	1			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Water rose 1.8m in 30min, then dropped to normal in 30min.
1883		29-Aug	Thames	3	*1.50*	1.50	1			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Tide became full during edd flow.
1883	Morn	29-Aug	Coromandel	3	0.90	0.90	2-5			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Wave was seen at low tide, then tidal flucuations.
1883	0400	29-Aug	Whitianga	3	1.80	1.80	2-5			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	The water rose 1.8m during ebb flow.
1883		29-Aug	Tairua	3	1.80	1.80	1			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	A rise and fall of 1.8m was observed.
1883	1500	30-Aug	Maketu	4	0.90	0.90	1			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	A 0.9m bore swept up the Kaituna River
1883	0200	29-Aug	Gisborne	5	0.90	0.90	2-5			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Two waves, one at 2 am and another at 2 pm (both 0.9m).
1883	Night	28-Aug	Lyttelton	11	1.80	1.80	2-5			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	The largest drop in water level was at 7:30 am on the 29th.
1883	Night	29-Aug	Timaru	11	*1.00*	1.00	2-5			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Waves were observed during the night of 29th.
1883	0000	28-Aug	Port Chalmers	12	0.60	0.60	11-20			0259	27-Aug	16.7S 105.4E	83	Rissaga		1	Waves began at 12am on the 28th till around 3 pm.

TABLE A2.2 - Tsunami database records for 1869 - 1883

EYear	ETime	EDate	ELocation	ERegn	EH	ERunup	EWaves	EPeriod	ESpecificDamage	STime	SDate	SLocation	SRegn	SCause	SMag	Refs	Comments
1891		22-Jun	Aotea Harbour	3	*3.00*	3.00	2-5			1840	22-Jun	Waikato Heads	81	Quake		1	Harbour agitated Also a large waves was reported entering the harbour.
1897		21-Sep	Wellington	9	*1.00*	1.00	1			0714	21-Sep	Wellington	81	Quake		1	Unusual wave reported.
1904		8-Aug	Manawatu	9	*3.00*	3.00	2-5			2250	7-Aug	Cape Turnagain	81	Quake	7.5	1	Large waves reported in the Wanganui River
1904		8-Aug	Wanganui	9	*3.00*	3.00	2-5			2250	7-Aug	Cape Turnagain	81	Quake	7.5	1	Large waves reported in the Manawatu River
1913		22-Feb	Westport	14	1.50	1.50	1			0108	22-Feb	41.8S 171.5E	81	Quake	6.8	1	
1913		22-Feb	Ngakawau	14	1.50	1.50	1			0108	22-Feb	41.8S 171.5E	81	Quake	6.8	1	Seiching in river.
1922		11-Nov	New Brighton	12	0.10	0.10	2-5	3		0433	11-Nov	28.5S 70.0W	89	Quake	8.3	1	In 15 min tide changed direction several times, max Δtide=0.1m
1922		12-Nov	Timaru	11	*0.20*	0.20				0433	11-Nov	28.5S 70.0W	89	Quake	8.3	1	Minor oscillations on 12th and 13th.
1922		12-Nov	Port Chalmers	12	0.20	0.20				0433	11-Nov	28.5S 70.0W	89	Quake	8.3	1	Flucuations of .2m on the 12th and 13th.
1922		25-Dec	Leithfeild Beach	11	0.40	0.40	1			0334	25-Dec	43.0S 173.0E	81	Quake	6.3	1	Reported that beach subsided, water then rose (max of 0.4m)
1922		25-Dec	Waikuku Beach	11						0334	25-Dec	43.0S 173.0E	81	Quake	6.3	1	Large fissures opened up, water rose through them.
1922		25-Dec	Lyttelton	11	*0.50*	0.50				0334	25-Dec	43.0S 173.0E	81	Quake	6.3	1	Reports of seiching.
1922		25-Dec	Castlecliff Beach	11	*3.00*	3.00	6-10			0334	25-Dec	43.0S 173.0E	81	Quake	6.3	1	Sudden sequence of large waves and strong tide recession.
1923		4-Sep	Wellington	9	*0.10*	0.10	2-5			0259	1-Sep	32.25N 135.5E	85	Quake	8.2	1	Slight flucuations on the evening of the 4th and the morning of the 5th.
1926			Tolaga Bay	5	6.35	6.35	3		3 - Jetty							2	Source and exact year unknown but between 1926-29.
1929		16-Jun	Karamea	14	2.50	2.50	1			2247	16-Sep	41.8S 172.2E	81	Quake	7.8	1	Storm surges at the time would have made it hard to detect tsunamis.
1931		3-Feb	Wairoa	6	3.00	3.00	1			2317	2-Feb	39.7S 176.7E	81	Quake	7.8	1	3m wave on the Wairoa river after the earthquake.
1931		3-Feb	Waikokopu	6	*2.00*	2.00	2-5			2317	2-Feb	39.7S 176.7E	81	Quake	7.8	1	The water receded 3 times.
1931		3-Feb	Waikari River	6	15.00	15.85	1		1 - Woolshed	2317	2-Feb	39.7S 176.7E	81	Quake	7.8	1	Caused locally from rotational slumping on opposite side of the estuary.
1932		15-Sep	Wairoa	6	*3.00*	3.00	1			1355	15-Sep	38.9S 177.55E	81	Quake	7.0	1	Might refer to Napier EQ in 1931.
1947		25-Mar	Tatapouri	5	10.00	10.00	2-5		1 - Cottage; 2 - Hotel	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1	Two waves greater than 10m. Hotel structuraly damaged.
1947		25-Mar	Kaiti Beach	5	*4.00*	4.00	1		3 - Houses	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	2	Water rose to the base of the Cook monument.
1947		25-Mar	Turihaua Point	5	10.00	10.00	2-5		1 - House, Furniture; 5 - House	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1,2	Two waves greater than 10m.
1947	0840	25-Mar	Pouawa Beach	5	*6.00*	6.00	1		1 - House, 2 Bridges; 2 - Bridge	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1,2	
1947		25-Mar	Murphys Beach	5	4.65	4.65	1		1 - Pumkins, Fence	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1,2	Land inundated 4m.
1947		25-Mar	Manunga Beach	5	7.00	7.00	2-5		2 - House	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1	Wave 6-7m high, house swept of foundations.
1947		25-Mar	Uawa River	5	*2.00*	2.00	2-5			2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1	Bores travelled up to 3km up river.
1947		25-Mar	Wainui	5	*5.00*	5.00	2		1 - Surf Club; 3 - Carivan; 5 - House	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1,2	Surf club destroyed and caravan deposited on top of a fence.
1947	Morn	25-Mar	Gisborne	5	4.00	4.00	6-11		5 - Houses	2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1,2	Dredge swept away, but later recovered, houses flooded.
1947		25-Mar	Mahia Peninsula	6	*1.00*	1.00	2.5			2032	25-Mar	38.9S 178.24E	81	Quake	6.0	1	Fish deposited above high water mark from a 'tidal wave'.
1947	Night	17-May	Tatapouri	5	3.80	3.80	1		1 - Boat	0706	17-May	38.28S 178.67E	81	Quake	5.6	1	A boat was smashed.
1947	Night	17-May	Waihau Beach	5	6.00	6.00	1		1 - Wood	0706	17-May	38.28S 178.67E	81	Quake	5.6	1	Wood washed away. Water flooded 370m inland.
1947	Night	17-May	Makarori Beach	5	*3.00*	3.00	1			0706	17-May	38.28S 178.67E	81	Quake	5.6	1	The main higway was flooded.
1947	Hight	17-May	Tolaga Bay	5	*3.00*	3.00	1			0706	17-May	38.28S 178.67E	81	Quake	5.6	1	Debris deposited 45m horizontally above high water.
1950		13-Mar	Bay of Plenty	4	*1.00*	1.00				1811	13-Mar	38.29S 178.00E	81	Quake	5.3	1	Unusual disturbances along Bay of Plenty coasts.
1952	2130	5-Nov	Matapouri	1	0.90	0.90	1		4 - Boat	1658	4-Nov	52.75N 159.50E	86	Quake	8.3	1	A bore may have been formed in the estuary.
1952	1930	5-Nov	Tutukaka	1	0.91	0.91	>1	10		1658	4-Nov	52.75N 159.50E	86	Quake	8.3	1,2	A .3m bore travelled up the river. 0.5m tide fluctuations every 30 min.
1952	2200	5-Nov	Ngunguru	1	*1.00*	1.00	1			1658	4-Nov	52.75N 159.50E	86	Quake	8.3	1	A launch was washed from its cradle.
1952		5-Nov	Auckland	2	0.10	0.10	20+			1658	4-Nov	52.75N 159.50E	86	Quake	8.3	1	Minor oscilations continued for days.
1952		6-Nov	Wellington	9	0.20	0.20	>1			1658	4-Nov	52.75N 159.50E	86	Quake	8.3	1	Max flucuation at 8 am. on the 6th.

TABLE A2.3 - Tsunami database records for 1884 - 1952

EYear	ETime	EDate	ELocation	ERegn	EH	ERunup	EWaves	EPeriod	ESpecificDamage	STime	SDate	SLocation	SRegn	SCause	SMag	Refs	Comments
1960		23-May	Ahipara	1	1.00	1.00	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Waves ran up a tidal river.
1960		23-May	Mangonui	1	1.20	1.20	1			1911	22-May	41.0S 73.5W	89	Quake	8.5	1	In 10 min a 1.2m rise and fall was observed.
1960		23-May	Waitangi	1	1.00	1.00		20		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Strong ebb and flood tides, whirlpools also formed.
1960		23-May	Russell	1	1.00	1.00	1		1 - Flashing beacon	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	A beacon was washed away by a tidal wave.
1960		23-May	Opua	1	3.00	3.00				1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Boat in 3m water was grounded. Water rose 1m in minutes.
1960	Night	23-May	Tutukaka	1	3.00	3.00	20+	15	3 - Bridge abutment	1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Max height of 3m occured at 3pm on the 24th.
1960		23-May	Ngunguru	1	1.00	1.00	1		5 - Cottage	1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Severe erosion of sand from beach.
1960		23-May	Whangarei	1	1.00	1.00	6-10			1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Series of waves 1m high.
1960		23-May	Leigh	2	2.40	2.40	1		1 - Bridge supports	1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Water dropped 2.4m and then returned as a .2 m surge.
1960		23-May	Great Barrier Is.	2	1.50	1.50	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Waves were surging across the roads at Tryphena.
1960	Night	23-May	Auckland	2	0.60	0.60	6-10	45		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Tide flucuations started late on the 23rd.
1960		23-May	Whitianga	3	2.50	2.50	6-10		5 - Airport, 3 houses	1911	22-May	41.0S 73.5W	89	Quake	8.5	1	11 boast were also swept away, but they were recovered.
1960		23-May	Great Mercury Is.	3						1911	22-May	41.0S 73.5W	89	Quake	8.5	2	The water was reported to bubble and whirl.
1960		23-May	Mercury Cove	3	3.00	3.00				1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Sandbanks, normally covered by deep water, were exposed.
1960	2100	23-May	Mercury Bay	3	2.32	2.32	>20	40		1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Oscillations every 40min for four days.
1960	2200	23-May	Mount Maunganui	4	1.40	1.40	2-5	45		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Max oscilation occured between 4:30 pm and 5:00 pm.
1960		24-May	Tauranga	4	1.20	1.20	11-20	24		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Max flucuation occured on the 25th.
1960	0230	24-May	Kaituna River	4	2.32	2.32	2-5	45		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	
1960		24-May	Maketu	4	2.32	2.32	>1	20		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	0.8 ha of land was lost during 24-27 of May.
1960		24-May	Whakatane	4	0.50	0.50	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	1	
1960	Early	24-May	Opotiki	4	1.52	1.52	1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	0500	24-May	Tokomaru Bay	5	3.05	3.05	1		1 - 27m of wooden sea wall	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	2030	23-May	Tolaga Bay	5	2.00	2.00	20+	15	5 - Camp ground	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960		23-May	Tatapouri	5	2.74	2.74	1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	2030	23-May	Gisborne	5	5.49	5.49	>1	20		1911	22-May	41.0S 73.5W	89	Quake	8.5	1,2	Reports indicazte erosion of silt banks and sand shoals.
1960	0330	24-May	Napier	6	3.05	3.05	>1	40	1 - Gas main; 3 - Footbridge, Boats	1911	22-May	41.0S 73.5W	89	Quake	8.5	1,2	17 000 cubic m of sand was scoured from the boat harbour.
1960		23-May	Te Awanga	6	3.00	3.00	>1		1 - Launch	1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Eight people were swept out of their tents.
1960	Morn	24-May	Clifton Domain	6	4.00	4.00	1		4 - Sea Wall; 5 - House	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	A sea wall 3m above mean high water was pushed over.
1960	Morn	25-May	Riversdale	9	1.50	1.50	1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	Night	24-May	Ngawi	9	1.50	1.50	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Three 20 foot whales were washed up to shore due to surges.
1960		24-May	Wellington	9	0.95	0.95	>1	20		1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Violent flucuations recorded.
1960	Night	23-May	Lyttelton	11	4.35	4.35	>1		3 - House; 5 - 2 Houses, Hotel	1911	22-May	41.0S 73.5W	89	Quake	8.5	1,2	
1960		23-May	Little Akaloa	11	3.00	3.00	1		1 - Shed; 3 - Woolshed; 4 - House	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	0230	24-May	Okains Bay	11	3.05	3.05	1		1 - Bridge; 2 - House	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	2100	23-May	Oamaru	12	3.65	3.65	>1	60		1911	22-May	41.0S 73.5W	89	Quake	8.5	1,2	Flucuations continued for 30 hours.
1960		23-May	Port Chalmers	12	1.30	1.30	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	1	Max level was 0.45m above high water.
1960	0740	23-May	Taylors Point	12	0.60	0.60				1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	0325	24-May	Dunedin	12	0.60	0.60	1			1911	22-May	41.0S 73.5W	89	Quake	8.5	1,2	
1960		23-May	Brighton	12	1.00	1.00	>1		3 - Large dingy, wooden jetty	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	
1960	Morn	23-May	Taieri River	12	1.50	1.50	2-5		1 - 35ft launch; 3 - Fishing launch	1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Two major surges.
1960	1700	24-May	Fortrose	13	1.50	1.50	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Large waves than normal.
1960		24-May	Bluff	13	0.50	0.50	>1	23		1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Tidal flucuations every half an hour. Seven from 12:15 pm to 3 pm.
1960	Early	23-May	Colac Bay	13	1.00	1.00	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Tidal surges covered the beach road with debris.
1960	Night	23-May	Stewart Is.	13	1.22	1.22	>1			1911	22-May	41.0S 73.5W	89	Quake	8.5	2	Tide would fall 1.52 m and then rise 1.22 m.

TABLE A2.4 - Tsunami database records for 1953 - 1960

EYear	ETime	EDate	ELocation	ERegn	EH	ERunup	EWaves	EPeriod	ESpecificDamage	STime	SDate	SLocation	SRegn	SCause	SMag	Refs	Comments
1964	Morn	29-Mar	Auckland	2	0.45	0.45	>1			0336	28-Mar	61.1N 147.7W	87	Quake	8.4	1	
1964	Morn	29-Mar	Tauranga	4	0.15	0.15	>1			0336	28-Mar	61.1N 147.7W	87	Quake	8.4	1	
1964	Morn	29-Mar	Wellington	9	0.35	0.35	>1			0336	28-Mar	61.1N 147.7W	87	Quake	8.4	1	
1964	Morn	29-Mar	Lyttelton	11	1.25	1.25	>1	20		0336	28-Mar	61.1N 147.7W	87	Quake	8.4	1	Max response was 1.5m peak to trough.
1964	Morn	29-Mar	Greymouth	14	0.40	0.40	>1			0336	28-Mar	61.1N 147.7W	87	Quake	8.4	1	
1970	2131	28-Sep	Waihao River	11	*1.00*	1.00	>1			1901	28-Sep	44.64S 173.62E	81	Quake	5.1	1	
1976	0700	15-Jan	Tutukaka	1	0.75	0.75	1		3 - Several yachts		14-Jan	Kermadec Islands	81	Quake	7.8	1	
1976		14-Jan	Whangarei	1	*0.20*	0.20	>1				14-Jan	Kermadec Islands	81	Quake	7.8	1	
1976		14-Jan	Tauranga	4	*0.10*	0.10	>1				14-Jan	Kermadec Islands	81	Quake	7.8	1	
1977		22-Jun	Opua	1	0.15	0.15	>1			1208	22-Jun	23.19S 175.92W	81	Quake	7.2	1	
1977		22-Jun	Whangarei	1	0.13	0.13	>1			1208	22-Jun	23.19S 175.92W	81	Quake	7.2	1	
1977		22-Jun	Auckland	2	0.10	0.10	>1			1208	22-Jun	23.19S 175.92W	81	Quake	7.2	1	
1977		22-Jun	Tauranga	4	0.15	0.15	>1			1208	22-Jun	23.19S 175.92W	81	Quake	7.2	1	
1981		25-May	Campbell Island		0.30	0.30	1			0525	25-May	48.98S 164.60E	81	Quake	6.4	1	
1982		Dec	Auckland	2	0.10	0.10				1744	19-Dec	Kermadec Islands	81	Quake	7.7	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1986		7-May	Lyttelton	11	0.40	0.40				2247	7-May	17.8S 101.6W	88	Quake	7.7	2	
1986		Oct	Auckland	2	0.10	0.10				0646	20-Oct	Kermadec Islands	81	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1987		20-May	Deep Cove	13	3.00	3.00	1		1 - Wharf		20-May	Deep Cove	81	Land		2	A 17 m lauch was lifted onto a wharf, which was distroyed.
1993		Jun	Auckland	2	0.10	0.10					Jun	Kermadec Islands	81	Quake		2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Marsden Point	1	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Auckland	2	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Tauranga	4	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Gisborne	5	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Napier	6	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Wellington	9	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Lyttelton	11	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.
1994		6-Oct	Pegasus Bay	11	0.10	0.10				1323	4-Oct	Kuril Islands	86	Quake	8.3	2	Oscilations actually less than 0.1 m but unknown so 0.1 m used.

TABLE A2.5 - Tsunami database records for 1961 - 1997

Appendix 3

Return Periods

APPENDIX 3 - RETURN PERIODS

WHANGAREI HARBOUR CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
1.00	1	0.0056
0.20	2	0.0113
0.13	3	0.0169

TABLE A3.1 - Maximum runup heights and exceedance frequencies for Whangarei Harbour.

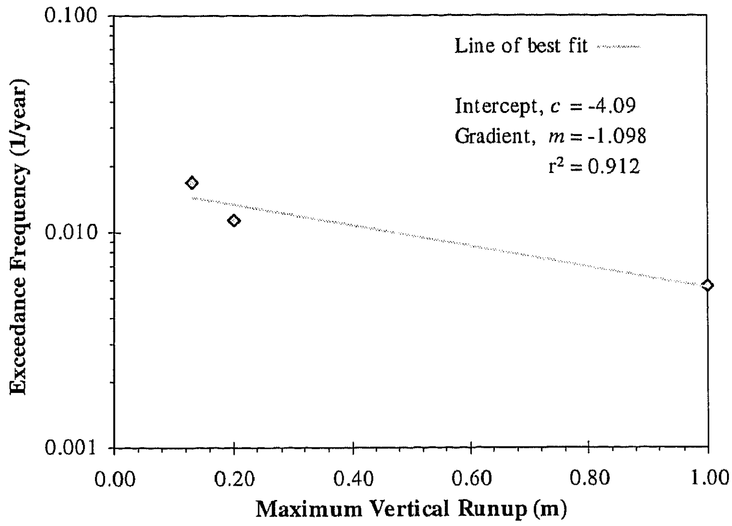

FIGURE A3.1 - Exceedance frequencies of waves at Whangarei Harbour.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-1.098H-4.09}$$

H (m)	R. Period (y)
10.0	3 501 917
6.0	43 399
3.0	1 612
1.5	311

TABLE A3.2 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Whangarei Harbour.

Period (y)	Exp. *H* (m)
100	0.47
50	
20	
10	

TABLE A3.3 - Expected tsunami size (m) to strike Whangarei Harbour in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

AUCKLAND PORT CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
1.80	1	0.0065
0.45	2	0.0113
0.10	9	0.0508

TABLE A3.4 - Maximum runup heights and exceedance frequencies for Auckland Port.

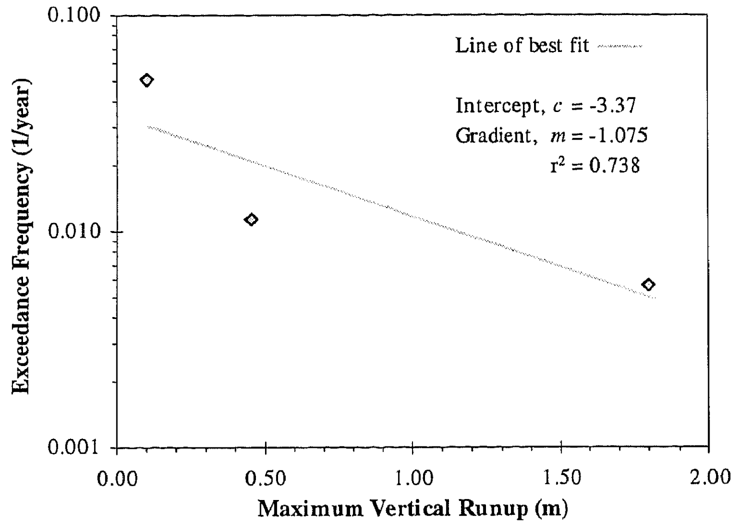

FIGURE A3.2 - Exceedance frequencies of waves at Auckland Port.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-1.075H - 3.37}$$

H (m)	R. Period (y)
10.0	1 356 326
6.0	18 406
3.0	732
1.5	146

TABLE A3.5 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Auckland Port.

Period (y)	Exp. *H* (m)
100	1.15
50	0.50
20	
10	

TABLE A3.6 - Expected tsunami size (m) to strike Auckland Port in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

TAURANGA DISTRICT CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
1.80	1	0.0056
0.20	2	0.0113
0.15	4	0.0226
0.10	6	0.0339

TABLE A3.7 - Maximum runup heights and exceedance frequencies for Tauranga District.

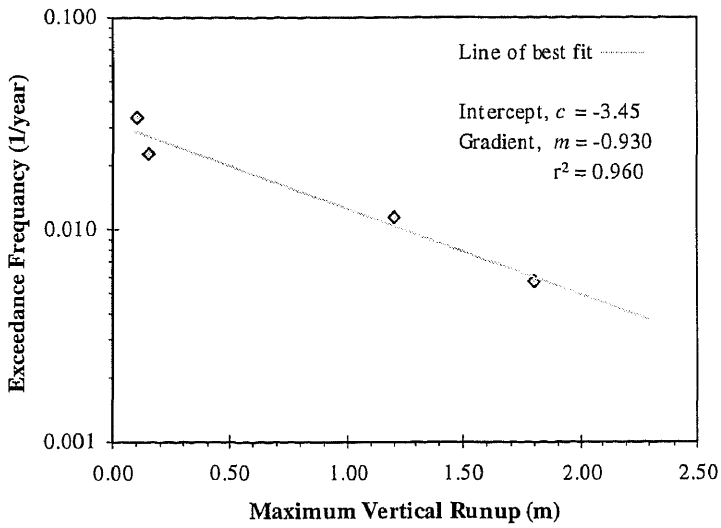

FIGURE A3.3 - Exceedance frequencies of waves around Tauranga.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.930H - 3.45}$$

H (m)	R. Period (y)
10.0	344 895
6.0	8 364
3.0	514
1.5	127

TABLE A3.8 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Tauranga District.

Period (y)	Exp. *H* (m)
100	1.24
50	0.49
20	
10	

TABLE A3.9 - Expected tsunami size (m) to strike Tauranga District in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

GISBORNE HARBOUR CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
5.49	1	0.0065
4.00	2	0.0113
2.40	3	0.0169
0.90	4	0.0226
0.10	5	0.0282

TABLE A3.10 - Maximum runup heights and exceedance frequencies for Gisborne Harbour.

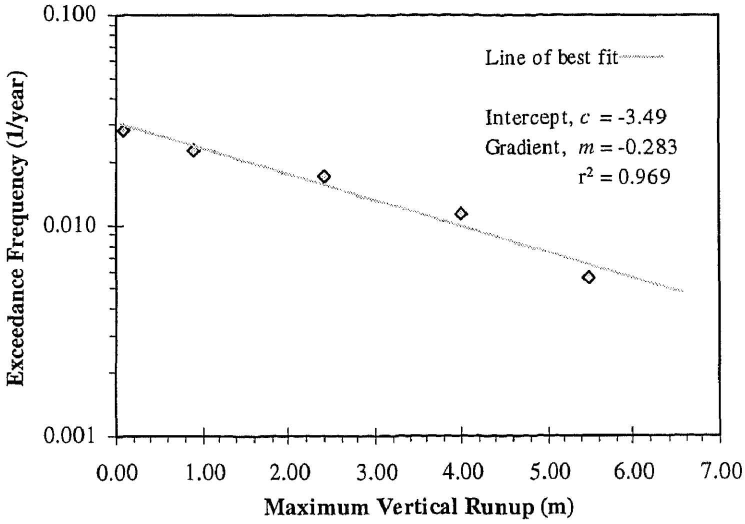

FIGURE A3.4 - Exceedance frequencies of waves at Gisborne Harbour.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.283H-3.49}$$

H (m)	R. Period (y)
10.0	557
6.0	179
3.0	77
1.5	50

TABLE A3.11 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Gisborne Harbour.

Period (y)	Exp. *H* (m)
100	3.94
50	1.50
20	
10	

TABLE A3.12 - Expected tsunami size (m) to strike Gisborne Harbour in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

NAPIER DISTRICT CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
3.05	1	0.0056
3.00	2	0.0113
1.80	3	0.0169
0.10	4	0.0226

TABLE A3.13 - Maximum runup heights and exceedance frequencies for Napier District.

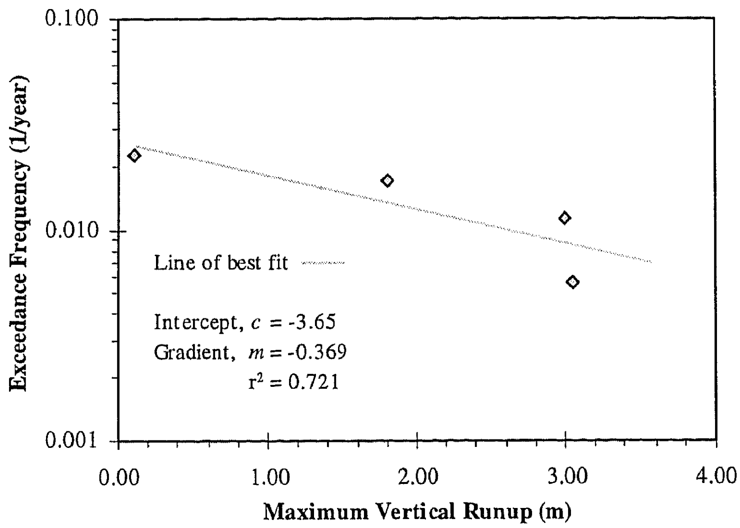

FIGURE A3.5 - Exceedance frequencies of waves around Napier District.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.369H-3.65}$$

H (m)	R. Period (y)
10.0	1 535
6.0	351
3.0	116
1.5	67

TABLE A3.14 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Napier District.

Period (y)	Exp. *H* (m)
100	2.59
50	0.71
20	
10	

TABLE A3.15 - Expected tsunami size (m) to strike Napier District in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

WANGANUI CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
3.00	1	0.0056
1.00	2	0.0113
1.50	3	0.0169

TABLE A3.16 - Maximum runup heights and exceedance frequencies for Wanganui.

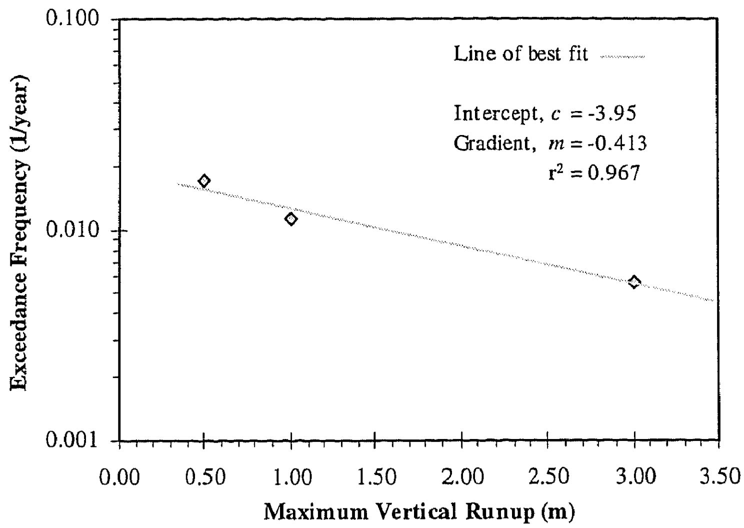

FIGURE A3.6 - Exceedance frequencies of waves around Wanganui.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.413H-3.96}$$

H (m)	R. Period (y)
10.0	3 257
6.0	625
3.0	181
1.5	97

TABLE A3.17 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Wanganui.

Period (y)	Exp. *H* (m)
100	1.56
50	
20	
10	

TABLE A3.18 - Expected tsunami size (m) to strike Wanganui in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

WELLINGTON PORT CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
3.10	1	0.00.56
1.50	3	0.0169
1.00	4	0.0226
0.95	5	0.0282
0.36	6	0.0339
0.35	7	0.0395
0.20	8	0.0452
0.10	10	0.0565

TABLE A3.19 - Maximum runup heights and exceedance frequencies for Wellington Port.

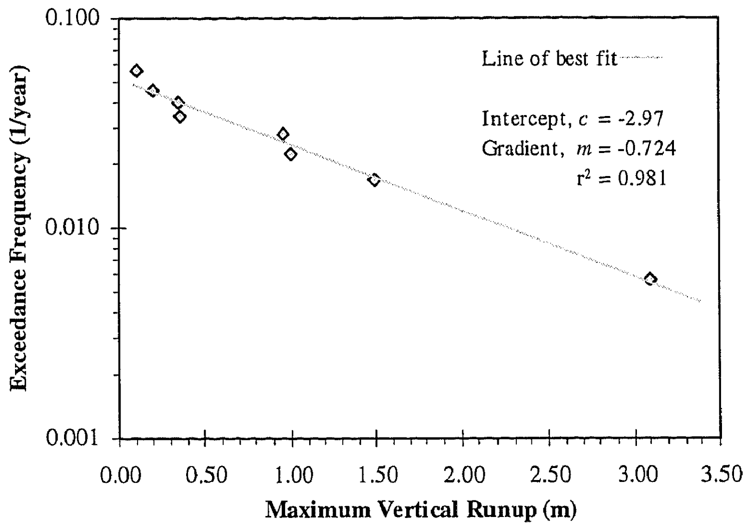

FIGURE A3.7 - Exceedance frequencies of waves at Wellington Port.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.724H-2.97}$$

H (m)	R. Period (y)
10.0	26 919
6.0	1 490
3.0	170
1.5	57

TABLE A3.20 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Wellington Port.

Period (y)	Exp. H (m)
100	2.27
50	1.31
20	0.04
10	

TABLE A3.21 - Expected tsunami size (m) to strike Wellington Port in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

LYTTELTON PORT CALCULATIONS FOR RETURN PERIODS

Max Runup	N	f (N/177)
7.60	1	0.0056
4.35	2	0.0113
1.80	3	0.0169
1.25	4	0.0226
0.90	5	0.0282
0.50	6	0.0339
0.40	7	0.0395
0.10	8	0.0452

TABLE A3.22 - Maximum runup heights and exceedance frequencies for Lyttelton Port.

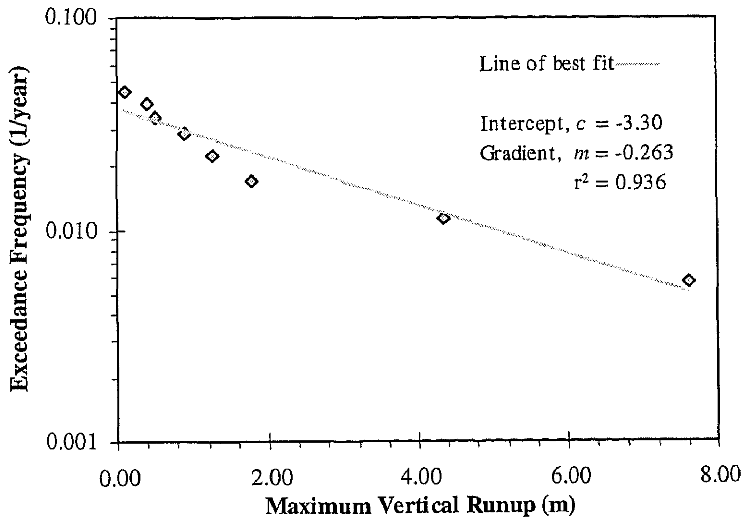

FIGURE A3.8 - Exceedance frequencies of waves at Lyttelton Port.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.263H - 3.30}$$

H (m)	R. Period (y)
10.0	373
6.0	131
3.0	59
1.5	40

TABLE A3.23 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Lyttelton Port.

Period (y)	Exp. H (m)
100	4.99
50	2.35
20	
10	

TABLE A3.24 - Expected tsunami size (m) to strike Lyttelton Port in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

TIMARU CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
3.10	1	0.0056
1.00	3	0.0169
0.20	4	0.0226

TABLE A3.25 - Maximum runup heights and exceedance frequencies for Timaru.

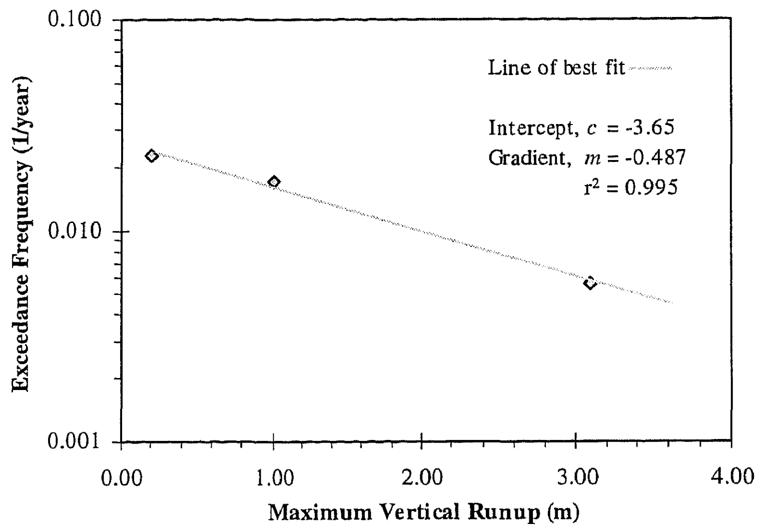

FIGURE A3.9 - Exceedance frequencies of waves at Timaru.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.487H-3.65}$$

H (m)	R. Period (y)
10.0	5 021
6.0	715
3.0	166
1.5	80

TABLE A3.26 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Timaru.

Period (y)	Exp. *H* (m)
100	1.96
50	0.54
20	
10	

TABLE A3.27 - Expected tsunami size (m) to strike Timaru in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

PORT CHALMERS CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
1.30	1	0.0056
0.60	2	0.0113
0.50	3	0.0169
0.30	4	0.0226
0.20	5	0.0282

TABLE A3.28 - Maximum runup heights and exceedance frequencies for Port Chalmers.

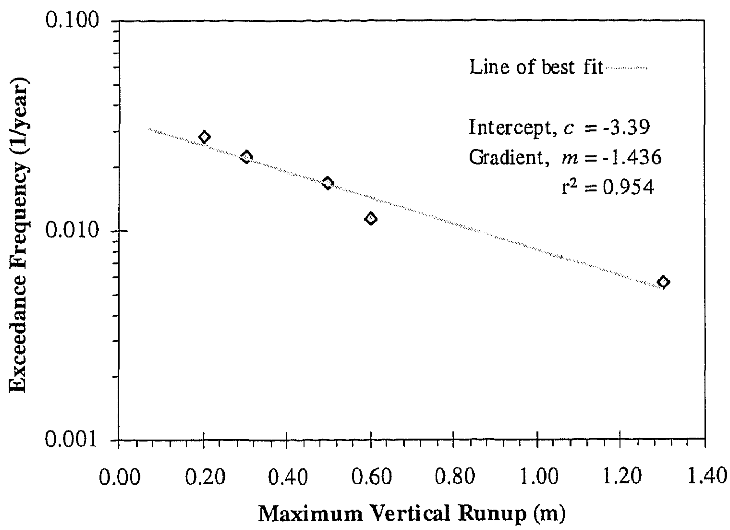

FIGURE A3.10 - Exceedance frequencies of waves at Port Chalmers.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-1.436H-3.39}$$

H (m)	R. Period (y)
10.0	50 694 307
6.0	162 627
3.0	2 192
1.5	255

TABLE A3.29 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for Port Chalmers.

Period (y)	Exp. *H* (m)
100	0.85
50	0.37
20	
10	

TABLE A3.30 - Expected tsunami size (m) to strike Port Chalmers in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

NEW ZEALAND CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
15.85	1	0.0056
10.00	4	0.0226
9.10	5	0.0282
6.35	6	0.0339
6.00	7	0.0395
5.49	8	0.0452
3.60	9	0.0508
3.00	15	0.0847
2.50	16	0.0904
1.80	17	0.0960
1.50	18	0.1017
1.25	19	0.1073
1.00	24	0.1356
0.75	25	0.1414
0.50	26	0.1469
0.40	27	0.1525
0.36	28	0.1582
0.30	29	0.1638
0.20	30	0.1695
0.15	31	0.1751
0.10	36	0.2034

TABLE A3.31 - Maximum runup heights and exceedance frequencies for New Zealand.

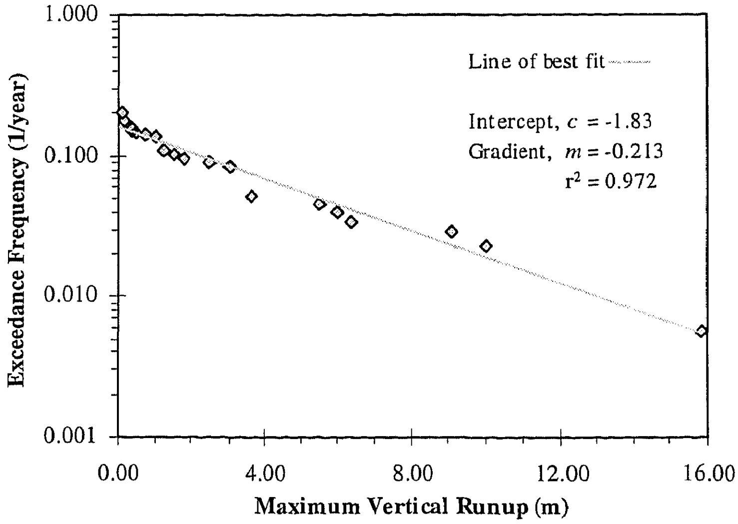

FIGURE A3.11 - Exceedance frequencies of waves at New Zealand.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.213H-1.83}$$

H (m)	R. Period (y)
10.0	53
6.0	22
3.0	11
1.5	8

TABLE A3.32 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m for New Zealand.

Period (y)	Exp. *H* (m)
100	12.99
50	9.74
20	5.45
10	2.20

TABLE A3.33 - Expected tsunami size (m) to strike New Zealand in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

LOCAL SOURCE CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177
15.85	1	0.0056
10.00	2	0.0113
9.10	3	0.0169
6.00	4	0.0226
3.00	9	0.0508
2.50	10	0.0565
1.50	11	0.0621
1.00	15	0.0847
0.50	16	0.0904
0.36	17	0.0960

TABLE A3.34 - Maximum runup heights and exceedance frequencies for local tsunami sources.

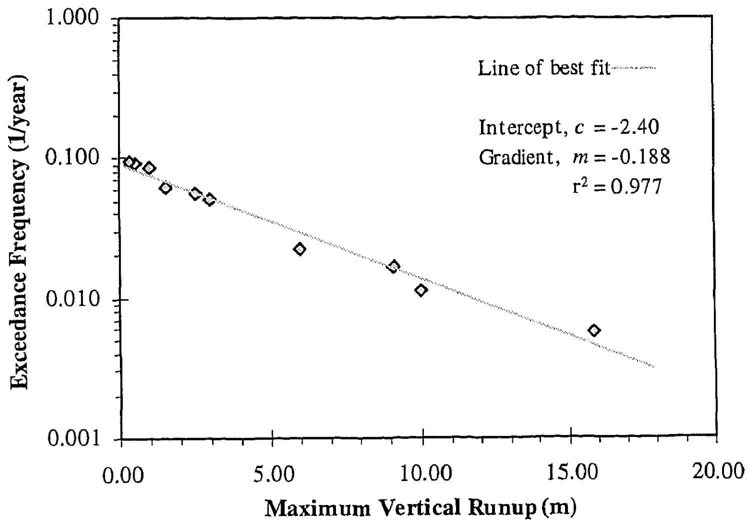

FIGURE A3.12 - Exceedance frequencies of waves at local tsunami sources.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.188H-2.40}$$

H (m)	R. Period (y)
10.0	72
6.0	34
3.0	19
1.5	15

TABLE A3.35 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m from local tsunami sources.

Period (y)	Exp. *H* (m)
100	11.72
50	8.04
20	3.17
10	

TABLE A3.36 - Expected tsunami size (m) from local sources in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

FAR-FIELD SOURCE CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
10.00	1	0.0056
5.49	2	0.0113
3.60	3	0.0169
1.80	4	0.0226
1.25	5	0.0282
1.00	6	0.0339
0.75	7	0.0395
0.40	8	0.0452
0.30	9	0.0508
0.2	10	0.0565
0.15	11	0.0621
0.10	16	0.0904

TABLE A3.37 - Maximum runup heights and exceedance frequencies for far-field tsunami sources.

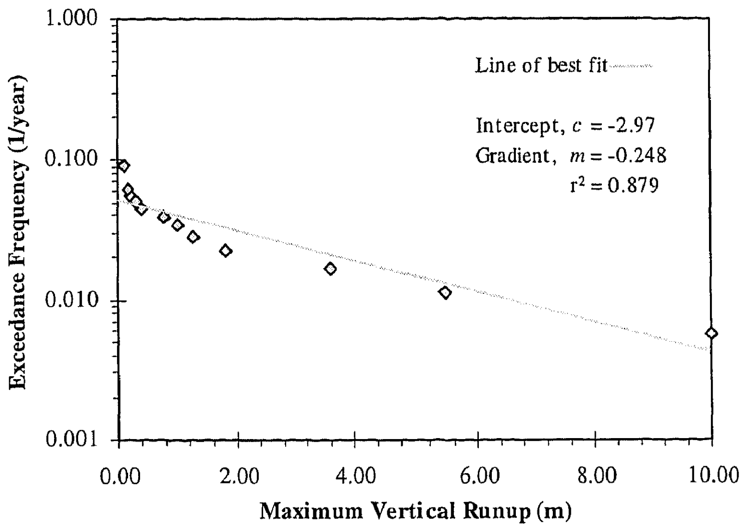

FIGURE A3.13 - Exceedance frequencies of waves from far-field tsunami sources.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.248H-2.97}$$

H (m)	R. Period (y)
10.0	233
6.0	86
3.0	41
1.5	28

TABLE A3.38 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m from far-field tsunami sources.

Period (y)	Exp. H (m)
100	6.60
50	3.80
20	0.11
10	

TABLE A3.39 - Expected tsunami size (m) from far-field sources in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

SOUTH PACIFIC ISLANDS SOURCE (REGION 81) CALCULATIONS FOR RETURN PERIODS

Max Runup	N	f (N/177)
0.75	1	0.0056
0.30	2	0.0113
0.15	3	0.0169
0.10	6	0.0339

TABLE A3.40 - Maximum runup heights and exceedance frequencies for South Pacific Islands source region.

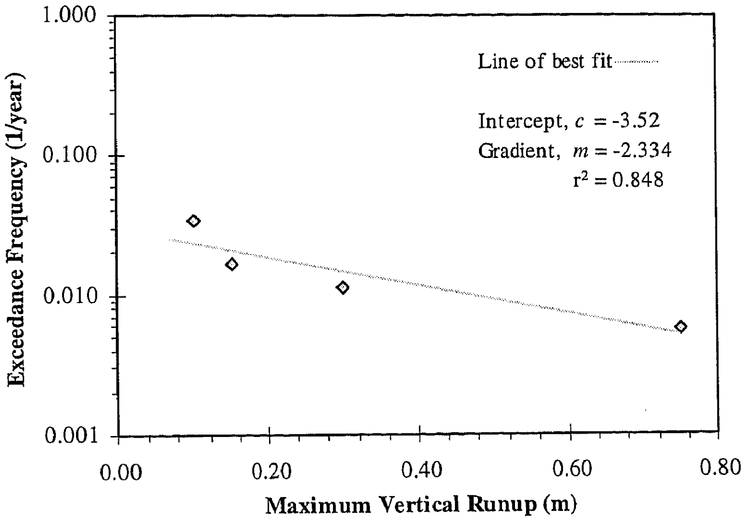

FIGURE A3.14 - Exceedance frequencies of waves from South Pacific Islands source region.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-2.334H-3.52}$$

H (m)	R. Period (y)
10.0	462 540 M
6.0	40.9 M
3.0	37 209
1.5	1 122

TABLE A3.41 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m from South Pacific Islands region.

Period (y)	Exp. H (m)
100	0.46
50	0.17
20	
10	

TABLE A3.42 - Expected tsunami size (m) from South Pacific Islands region in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

KURIL ISLANDS AND KAMCHATKA SOURCE (REGION 86) CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
1.00	1	0.0056
0.10	2	0.0113

TABLE A3.43 - Maximum runup heights and exceedance frequencies for Kuril Islands and Kamchatka source region.

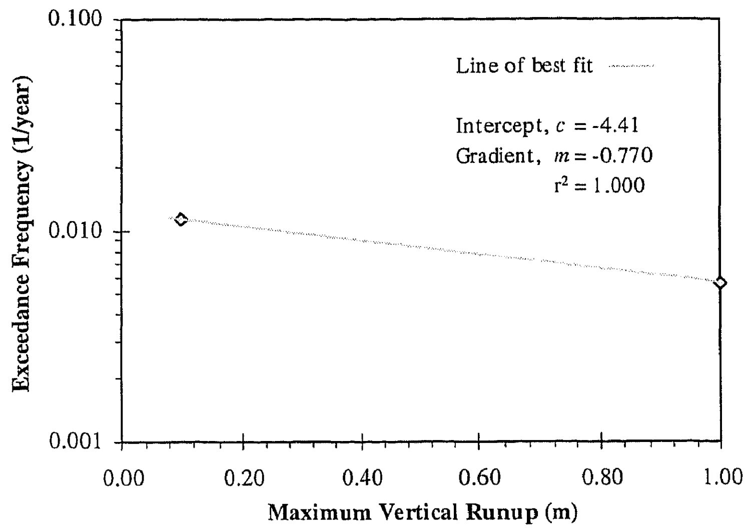

FIGURE A3.15 - Exceedance frequencies of waves from Kuril Islands and Kamchatka source region.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.770H-4.41}$$

H (m)	R. Period (y)
10.0	181 248
6.0	8 325
3.0	826
1.5	260

TABLE A3.44 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m from Kuril Islands and Kamchatka region.

Period (y)	Exp. H (m)
100	0.26
50	
20	
10	

TABLE A3.45 - Expected tsunami size (m) from Kuril Islands and Kamchatka region in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

WEST COAST OF SOUTH AMERICA SOURCE (REGION 89) CALCULATIONS FOR RETURN PERIODS

Max Runup	*N*	f (*N*/177)
10.00	1	0.0056
5.49	2	0.0113
3.60	3	0.0169
0.20	4	0.0226

TABLE A3.46 - Maximum runup heights and exceedance frequencies for West Coast of South America source region.

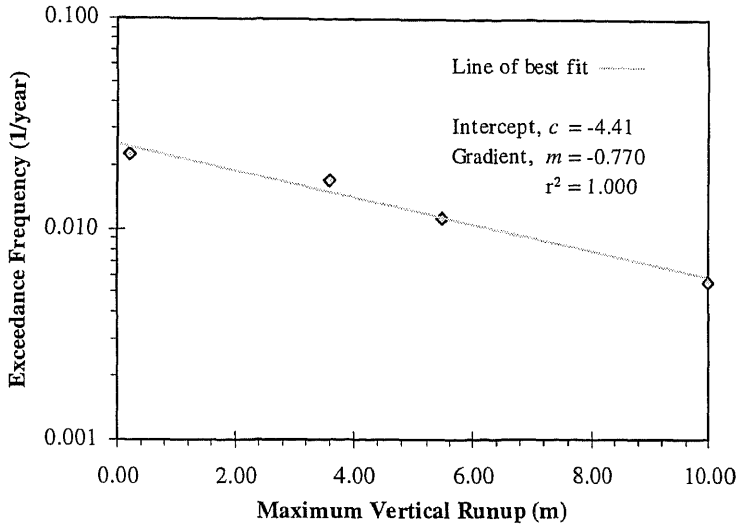

FIGURE A3.16 - Exceedance frequencies of waves from West Coast of South America region.

Equation used to calculate return periods and expected wave heights:

$$f = e^{-0.145H-3.68}$$

H (m)	R. Period (y)
10.0	170
6.0	95
3.0	61
1.5	49

TABLE A3.47 - Return periods (years) of tsunami waves of heights 10 m, 6 m, 3 m and 1.5 m from West Coast of South America region.

Period (y)	Exp. H (m)
100	6.36
50	1.59
20	
10	

TABLE A3.48 - Expected tsunami size (m) from West Coast of South America region in 100, 50, 20 and 10 years. Blanks indicate that the waves are too small to be detected.

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