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Report For NZ EQC On The Effects Of Tsunamis In NZ

Works & Development Services Corporation (NZ) Ltd

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Report For

NEW ZEALAND EARTHQUAKE AND WAR DAMAGES COMMISSION

On

THE EFFECTS OF TSUNAMIS IN NEW ZEALAND

August 1988

Works and Development Services Corporation (NZ) Ltd

REPORT ON THE EFFECTS OF TSUNAMIS IN NEW ZEALAND

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STRUCTURAL DESIGN
Technical Services : Civil Engineering
Works and Development Services Corporation (NZ) Ltd
P.O. Box 12-003, Wellington
New Zealand

Table of Contents

Executive Summary

This report summarises the published records of tsunami damage along the New Zealand coastline and comments on the risk and expected effect of future large tsunamis.

A tsunami is a seismic sea wave usually generated by a sudden change in the configuration of the sea floor which is often the result of a moderate-large earthquake. Landslides, volcanoes or atmospheric conditions can also generate tsunamis. Historically tsunamis have caused huge destruction and loss of life in countries bordering the Pacific Ocean, but New Zealand has escaped with relatively little damage. This is partly due to the protection provided by the Australian continent and outlying islands, and also due to disipation of the energy in the tsunamis on the New Zealand continental shelf.

New Zealand is susceptible to tsunamis from both distant and local sources. The east coast of New Zealand and the Chatham Islands are most vulnerable to tsunamis originating near South America, in particular from Peru or North Chile. These tend to be directed at New Zealand and there is little protection from intermediate land masses. Historically three tsunamis generated by very large earthquakes on the Chilean coast have produced wave heights of the order of three metres occurred on the New Zealand coast. Damage has not been extreme, except in the Chatham Islands. However there is a potential for tsunamis originating from this source to be up to 50% higher than has previously occurred. Coupled with this is the recent coastline property development and damage could now be substantially greater. The west coast of New Zealand is less vulnerable to tsunamis from distant earthquakes.

Tsunamis originating from local sources have generated larger wave heights in New Zealand than those originating from distant sources, but their influence has only been over a short length of coastline. These past events have not significantly affected major towns or cities, but this possibility cannot be ruled out for the future. The possibility of a major earthquake causing major warping of the sea floor with very large tsunamis causing vast damage cannot be ruled out, but there is no geological evidence for an event of this magnitude in the last several thousand years.

Brief

This report is in response to a request from the New Zealand Earthquake and War Damages Commission on 18 August 1988 (File Ref 1558). The brief is for a report addressing two specific issues with regard to tsunami hazard.

1. A history of the occurence of tsunamis about New Zealand and the damage caused.
2. An indication of what could be expected if a large tsunami should reach New Zealand.

Tsunamis in New Zealand

Description of Tsunami

Tsunami is a Japanese word for habour wave. Tsunamis are also called "seismic sea waves" or "tidal waves". The latter term is erroneous because a tidal wave actually result from the gravitational tide-producing force of the moon.

Most tsunamis are generated by a sudden change in the configuration of the sea floor, often the result of uplift or downthrust during a moderate to large shallow earthquake. Submarine landslides or slumping during or following an earthquake can also cause tsunamis, as can impulsive displacements of water resulting from volcanic eruption debris or rock slides entering the sea. The majority of tsunamis are, however, of seismic origin and in the most severe cases, tens of thousands of square kilometres of sea floor can be displaced vertically by several metres.

A tsunami is not a single wave but a series of waves which radiate outwards from the tsunami source. In the deep ocean the waves are small in height - perhaps a metre or less even for a large tsunami - and the distance between successive wave crests is very large - up to 200 kilometres. Because the wave crests are very low and the distance between them is so great, tsunamis pass unnoticed in the open ocean. The waves travel very quickly, their speed being related to the depth of water over which they are passing, the deeper the water, the faster they travel. As a tsunami approaches land and the water depth progressively decreases, the wave speed slows down, the waves become higher and steeper, For example, a 30-centimetre-high wave travelling at 700 kilometres per hour in the deep ocean may become a 20-metre-high wave travelling at 40 kilometres per hour at the shore. The effect varies, however, at different places along a coastline, depending upon the coastal configuration and variations in the depth of the water. Thus, a 20-metre-high wave may strike at one place whereas, at another place a few kilomtres away, the wave may be only 1-2 metres high. A wide continental shelf can mitigate the effects of tsunami by acting as a wave reflector and by absorbing wave energy through friction.

Massive destruction can result from the runup of water on to low lying coastal land. The water may progress as a turbulent wall of water (bore) whose passage can cause impulsive forces of tremendous magnitude, with the seawards return flow compounding the damage. The bore situation of a large, steep wave advancing shorewards is the popular image of a tsunami, but a tsunami is more often like a very high tide which takes place in the span of a few minutes. In New Zealand however, tsunamis of distant origin have produced no pronounced effects on the open coast, but the waters in some harbours have been caused to oscillate.

About 80% of all tsunami activity occurs in the Pacific Ocean and there have been a number of instances of a tsunami being observed over the whole ocean. Unlike some countries in the Pacific, New Zealand has suffered very few fatalities from tsunamis perhaps because the tsunamis' energy is dispersed by the continental shelf. However, because New Zealand lies in an active seismic area on the edge of the Pacific Ocean there is potential danger from tsunamis of local origin, as well as from those generated at a distance.

Tsunami Experience in other Pacific Countries.

Records of destructive tsunamis in Japan extend back to 684 A.D. and since then almost 70 destructive tsunamis have been experienced, including the great Meiji Sanriku tsunami of 1896 which resulted in 27,122 deaths, many thousands of injuries, and the loss of thousands of homes. The most recent Japanese tsunami occurred in 1983, causing 100 deaths and property damage amounting to US $700 million. The Hawaiian Islands have also been struck repeatedly by tsunamis. In 1946, the city of Hilo was inundated by a tsunami which originated near Alaska, and 159 people were killed. The city was hit again in 1960 by a tsunami from the coast of Chile, and 61 people were killed. This latter tsunami was the most destructive Pacific-wide tsunami of recent times and, in addition to the deaths which resulted in Hawaii, almost 1,000 people were killed in Chile, the Philippines, and Japan. The Philippines were struck by a local tsunami as recently as 1976, and more than 8,000 people were killed, and 20,000 rendered homeless.

The most famous and dramatic example of tsunami generated by volcanic eruption occurred in 1883, when Krakatoa, a volcano in Sunda Strait between Sumatra and Java, exploded in a series of detonations which blew away 8 cubic kilometres of the volcano. The subsequent tsunamis completely destroyed villages and settlements along the coasts of Java, Sumatra, Borneo, and other Islands. At one town, situated at the end of a bay which narrowed rapidly, the waves grew to over 40 metres high before striking the shore. Over 27,000 people throughout the East Indies perished as a result of the tsunamis.

In 1958, an earthquake triggered a huge rock-slide which fell into Lituya Bay, Alaska. This created a gigantic wave which stripped a mountainside opposite of trees and vegetation to a height of 500 metres. This was a very unusual occurence, but landslides and similar events can cause large tsunami waves. Such tsunamis tend to be localised and do not spread over large areas.

History of New Zealand Tsunamis

A summary of the size and effects of the most significant historic tsunamis experienced in New Zealand is given in Table 1. The size of the tsunamis has been expressed in terms of highest wave reported or maximum height of runup. Maximum runup is defined in Figure 2 on page 7 The locations where these tsunamis were observed are shown in Figure 1 on page 7. The most detailed historical data available for wave heights and effects at various locations is that collated by de Lange and Healy (2). An abridged version of their descriptions is given in "Appendix A. Summary of Reported Damage by Tsunamis in New Zealand" on page 12.

Eight of the events listed in Table 1 are from distant sources with the remainder being generated locally.

Tsunamis originating from the distant sources have generally been widely recorded around the New Zealand coastline, particularly along the eastern coast. The three most significant events, each with runup heights in excess of 3m, all originated from the Chilean coast. From the 1868 event a maximum rise in water level of 7.6m in 20 minutes was recorded in Lyttleton. Maximum water level fluctuations in Wellington and Auckland were about 1.5m. Waves and water fluctuations of 3m or more were also recorded at several other locations (see "Appendix A. Summary of Reported Damage by Tsunamis in New Zealand" on page 12). The worst damage appears to have occured in the Chatham Islands, where a Maori settlement was destroyed and a number of houses damaged (one destroyed) at the island settlement of Waitangi. Water flooded up to 6.4km inland. Damage on the mainland included at least two jetties and a bridge destroyed on Banks Peninsula and damage to several ships and a wharf at Kaiapoi.

Comparable water level fluctuations also occurred in the 1877 and 1960 events, again Lyttleton being particularly affected. Many boats were damaged as well as several bridges. Several houses were flooded and significant erosion and silting occured at some locations. The Earthquake and War Damages Commission reported 69 claims for damage as a result of this tsunami.

The damage data published by de Lange and Healy (2) undoubtably understates the true extent of damage that has been caused by distant origin tsunamis in New Zealand. It is nevertheless clear that the damage that has occurred is small by comparison both with that suffered (regularly) by a number of other areas around the Pacific, and with that caused by other natural disasters (for example, flooding and earthquake) in New Zealand.

As indicated in Table 1, locally generated tsunamis have produced waves with runups of up to between 10 and 15 metres, which is significantly higher that the worst tsunamis of distant origin. These tsunamis have generally been confined to the regions of known high seismicity in New Zealand, namely from Akaroa to the Bay of Plenty on the east coast and from Westport to New Plymouth on the west coast. The extent of damage in these tsunamis has generally been quite limited, (significant effects occuring over a 30km length of coastline), although a number of buildings and bridges were destroyed and others damaged in the Gisbourne tsunamis of 1947. Despite the larger wave heights, total damage to date from local tsunamis appears to have been even less than that from tsunamis of distant origin. (Refer to "Appendix A. Summary of Reported Damage by Tsunamis in New Zealand" on page 12 for further details of damage.)

The maximum runup in Table 1 (15m) was recorded after the Napier earthquake. However this tsunami did not cause significant damage, in part because the Napier area was uplifted by 5.5m during the causative earthquake.

TABLE 1 Main Tsunamis Experienced in New Zealand.

(Abridged from de Lange and Healy (2).)

No.	Date	Epicentre / Source	Richter Magnitude	Maximum Runup or Wave Height (m)	Reported Damage Code
1	1848 Oct 15	Lower Wairau Valley	7.1	0.3	D
2	1855 Jan 23	West Wairarapa	8.0	9.1	B, D
3	1868 Aug 13	Chile		3.1	A, B, C, D, E
4	1877 May 10	Chile		3.7	B, C, D, E
5	1883 Aug 27	Krakatoa Volcano	Eruption	1.8	C
6	1913 Feb 22	Near Westport	6.8	1.5	D
7	1922 Nov 11	Chile	8.3	0.2	
8	1922 Dec 25	Near Rangiora	6.25	0.4	D
9	1929 Jun 16	Murchison	7.75	2.5	B, D, E
10	1931 Feb 2	Napier	7.75	15.3	B, D
11	1947 Mar 25	Gisborne	6.0	10.0	B, C, D
12	1947 May 17	Gisborne	5.6	6.0	C, D
13	1952 Nov 4	NE of Japan	8.25	0.9	A, C
14	1960 May 22	Chile	8.5	3.5	B, C, D, E
15	1964 Mar 28	Alaska	8.4	0.9	
16	1976 Jan 14	Kermadec Islands	7.75	0.8	C
17	1977 Jun 22	Tonga	7.2	0.2	
18	1981 May 25	SW of Stewart Island	6.4	0.3	

Code Description

A Loss of life or personal injury.

B Damage to shore structures; wharves, jetties, bridges (some destroyed), dwellings and other buildings.

C Damage and loss of small craft and coastal shipping and other floating objects.

D Flooding of coastal regions, esturies and tidal rivers and streams.

E Geological; scouring, erosion or silting.

Figure 1. **Location of Tsunamis in New Zealand (1840-1982). (From Ref 2):** Number of reports at each location are shown in brackets.

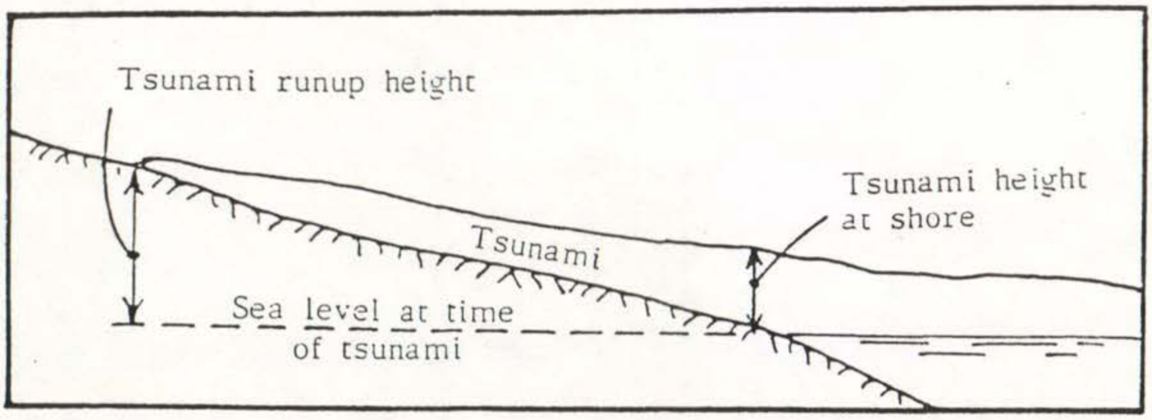

Figure 2. **Runup Height:** Tsunami runup height may be different than tsunami height at shoreline.

Effects of a Future Large Tsunami on New Zealand

In New Zealand tsunami damage of some form has been reported on at least 14 separate occasions over the last 140 years, an average of about one event every ten years. About half of these have had distant origins. Future tsunami occurance will probably follow a similar pattern to that which has occurred in the past. However because of the short length of our recorded history, larger tsunamis either from similar sources or from sources different from those that have been so far recorded, cannot be ruled out.

The main threat from distant tsunamis would appear to be those originating from the North Chilean/Peruvean coasts. Tsunamis from this source tend to be directed (beamed) towards New Zealand and maximum wave heights of up to about 50% greater than those previously recorded from this source are considered possible (8). We are, however, unable to quantify the likelihood of waves of this height. The other known distant source thought capable of causing large tsunami waves in New Zealand is Alaska. Maximum wave heights in New Zealand as a result of the 1964 Alaskan earthquake were only about one metre. However, the location of New Zealand in relation to Alaska is such that focusing of tsunami waves is considered possible (8). If this did occur much larger wave heights could be expected. Such waves could impact parts of the east coast (especially north of East Cape) more severely than any previously recorded tsunamis have.

The west coast of New Zealand is less vulnerable to tsunamis from distant earthquakes although tsunamis arising from an earthquake near New Guinea could be significant.

Because of increased coastal development since 1960, the damage resulting from distant source tsunamis could be significantly greater than in the past, even for similar sized events. Waves 50% greater than those from the past Chilean earthquakes would cause substantially greater damage.

In the future, the risk of damage may also be compounded by rising sea levels resulting from the "Green House" effect. Estimates of the likely sea level rise vary considerably, but average mid-range estimates given by Gibb (7) predict a rise of 0.4m by 2050 A.D. and 1.2m by 2100 A.D.. These magnitudes of sea level rise would make many low lying coastal communities and facilities more susceptable to tsunami damage.

Future **locally** generated tsunamis can generally be expected to be of the type and frequency historically observed to date. That is tsunamis with locally high waves can be expected, but the limited coastal extent of these means that the potential total damage will be smaller then that for tsunamis of distant origin, unless it directly affects a major city. The regions having the highest risk of this type of event are from the Bay of Plenty to Akaroa on the east coast and New Plymouth south on the west coast of New Zealand. In particular, the weak sediments of the seabed near Gisbourne make this region susceptable to significant tsunamis generated by even quite moderate earthquakes. This situation is not present in most other parts of New Zealand, but any earthquake large enough to cause fault displacement or other distortion of the sea floor is a potential tsunami generator. This generally requires a shallow earthquake (focal depth less than about 50km) with a Richter magnitude of at least 6.5. The Chathams Rise is another area which has been identified as a potential generator of tsunamis (as a result of sea floor slumping).

Apart from the low lying areas on the southern coast, the Wellington harbour area is not particularly vulnerable to external tsunamis. However, as occurred in 1855, a major earthquake on a nearby fault could produce large sloshing waves (seiching) in the harbour (ref. 1855 earthquake, Appendix A). Sloshing of the harbour could also result from a submarine or surface landslide into the harbour. Physical damage resulting from this type of sloshing would be small compared to the direct shake damage, but the two types of damage would be additive. Also, if large enough (and depending on the tides etc. at the time), this type of sloshing could significantly hinder early rescue operations.

One area where there are few historical records of tsunamis is the west coast of the South Island south of Westport. This coast lies close to the main Alpine Fault which has not moved in historic times, but which is considered a likely source of a major earthquake.

In addition to the types of local tsunami generator which have been observed to date, there is a possibility of a major earthquake causing major warping of the sea floor and generating a very large tsunami comparable to that which occurred in Alaska in 1964 (See "Appendix B. Description of Tsunami Damage in the Alaska Earthquake of 1964." on page 20). However DSIR geological staff have made extensive searches of the New Zealand coastline and have not found any supporting evidence for such a large tsunami in the last several thousand years (10).

Another local source which could generate very large tsunamis is major volcanic activity at one of New zealand's offshore volcanic Islands or submarine volanos. Potential for Krakatoa type eruptions exist at some of these, such as Mayor Island. Most of the low lying towns and holiday centres along the Bay of Plenty coast would be almost totally devastated by the resulting tsunami is this occurred. (Refer to reference 11 for further details.) Again there appears to be no geological record of such a large tsunami in this region in the last several thousand years (10).

While it may appear that tsunamis of "volcanic" origin are not an earthquake effect, it must be recognised that volcanos are usually accompanied by significant seismic activity, including for a period prior to the eruption. Apart from tsunamis which could be directly caused by this seismic activity, the question of whether the volcano caused the earthquakes or vice versa could be a subject of arguement, and hence of claims against the Earthquake and War Damages Commission.

Tsunami Warning System

The International Tsunami Warning System is a specially equipped seismological observatory in Honolulu, Hawaii, which is operated by the United States Government. Its role is to detect all major earthquakes that occur anywhere in the Pacific, evaluate their tsunami potential, determine whether a tsunami has been generated, and transmit information and warnings to member countries. The arrival time of the tsunami at any particular place can be predicted with a reasonable degree of accuracy so that people can evacuate danger areas. However, it is not yet possible to predict the height of the waves, the duration of the tsunami hazard, or the maximum current speeds which will be caused by water surges in harbours. In New Zealand, the Ministry of Civil Defence receives the tsunami warnings and is responsible for deciding whether any local or national tsunami warnings should be issued.

For tsunamis of distant origin, the International Tsunami Warning System works well, because there is adequate time for warnings to be issued. However, if a submarine earthquake centred near New Zealand generated a tsunami, it could arrive at the nearby coast within a matter of minutes and well before any official warning could be issued.

Conclusions

Historically tsunamis have caused comparatively little damage in New Zealand. Those arising from distant sources tend to mainly affect the east coast of New Zealand to a varying degree. Wave heights are less than those arising from local effects, such as local earthquakes, although the influence of the local tsunamis is only over a small length of coastline, and the damage caused has been less than that caused by tsunamis from distant earthquakes. All the large tsunami events recorded occurred before the boom in coastal development in the 1960s and 1970s. With the increase in population and construction in low-lying coastal areas, a large tsunami in some parts of New Zealand today would cause considerably more damage and loss of life than has occurred in the past. Larger tsunamis than those recorded to date can be expected in future. However there is no evidence in the geological record that very large tsunamis have hit the New Zealand coast in the last several thousand years.

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Appendix A. Summary of Reported Damage by Tsunamis in New Zealand

An abridged description from de Lange and Healy (2) of the reported damage caused by the main tsunamis to have affected New Zealand, and the distribution and size of wave heights is presented below.

1855 January 23
Magnitude - 8.0
Epicentre - West Wairarapa

Earthquake induced land movements involving 11,500 km2 of land with uplifts of 2.7 m in Palliser Bay and 1.5m in Wellington City, producing a tsunami and seiching in Wellington harbour. The locations affected and the wave heights follow.

WELLINGTON: Water fluctuated every 20 min ranging from 1.2m below low water spring to a maximum of 3m above high water spring. This continued for 8 hours after the main shock. The maximum level was sufficient to flood waterfront houses to a depth of 0.9m after the uplift associated with the earthquake had occurred. The Wellington Racecourse was strewn with dead fish. The tsunami and/or seiching may have contributed to the destruction of a bridge over the Hutt River.

WAIRAU RIVER: A gigantic wave swept the beach followed by an ebbing and flowing of the tide.

PALLISER BAY: A 9m high wave was seen. The wave almost swept away a sailor and his family who were camping on the beach.

AVON RIVER: A small bore is reported to have travelled up the Avon River near Christchurch during the night following the earthquake, leaving seaweed up to 0.3m above normal water level.

1868 August 13
Magnitude -
Epicentre - Chile

This tsunami from northern Chile is the most extensive tsunami reported in New Zealand. It is also the only tsunami to have caused a death in New Zealand. A number of detailed reports of the tidal fluctuations were presented by the harbourmasters at various ports around New Zealand. These are summarised below along with other reports from around New Zealand.

MANGONUI: Maximum rise of 1.2-1.5m on the 15th.

GREAT BARRIER Island: At Rosalie Bay the water rose 2 m above normal high water, while at Tryphena Harbour a boat was deposited 1.5m above high water level by a wave.

TAMAKI ESTUARY: A bore occurred in the upper reaches of the estuary followed by 1.2-1.5 m water level fluctuations.

OPOTIKI: A 1.8 m high bore raced up the river on 15 August

CAPE RUNAWAY: A 3 m wave was observed between 4 and 5 a.m. on 15 August.

NAPIER: A 1.8 m variation in tide level.

WELLINGTON: About a 1.5m variation.

NELSON: Disturbances continued until 17 August with a maximum variation of 1.5 m.

WHITE'S BAY: The water receded 27 m horizontally at 10 a.m. on 15 August. Returned at 10:20 a.m. with high surf. At 11:30 a.m. the water had reached the door of the telegraph office.

KAIAPOI: Seven bores reported in the Waimakariri River. The first, and largest, occured at 3 a.m. on 15 August and was 1.2 m high. Several ships were damaged at the wharf. Small waves were recorded during the day.

LYTTELTON: Detailed observations were made by the harbourmaster. These can be summarised as follows for the morning of 15 August:

3:30 a.m. - water receded suddenly at half ebb tide.

4:30 a.m. - water level 4.6 m below normal low water. A 2.5 m high wave recorded.

4:50 a.m. - water level 0.9 m above highest spring tide. Equalled a 7.6 m rise in 20 min.

7:15 a.m. - water rose 4.9 m before receding.

9:30 a.m. - part of harbour was dry when water rushed back with greatest velocity seen. Water reached high water spring.

10:15a.m. - water receded for half an hour before rising 5.5 m by 11 a.m. The rush of water was sufficient to move Skelton Buoy with a 200 kg anchor over 800 m. The tidal disturbances continued for three more days with tidal fluctuations of 0.3-0.4 m greater than normal.

PIGEON BAY: Detailed records were also made here as follows for 15 August:

7:00 a.m. - water level below normal low water. Rose suddenly to 0.3 m above normal high water in 10 min. Rose and fell 1.5 m.

10:10 a.m. - water level 1.2 m above normal high water level.

10:35 a.m. - water receded to lowest ebb.

11:15 a.m. - water rushed in removing jetty and a wooden fence 1.2 m above normal high water.

12:00 noon - large wave removed boat house, more fences, and 40,000 board feet of timber stacked 1.5 m above high water level.

12:40 p.m. - water level rose 2.1 m above high water and washed away another jetty and a 30 ton ketch

OKAINS BAY: A bridge 3.2 km from the sea was washed away. The water level rose 3 m above normal high water and covered the main road to a depth of 1.5 m . Water marks on the remaining bridges were 1.8 m above high water level.

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OAMARU: The tide rose and fell 4.6m dropping to 2.4 m below normal low water mark. The largest wave reported was 1.5 m high following a sudden 3.6 m drop in water level in one 5 min period.

TIMARU: The sea suddenly rose 1.8 m at about 5 a.m. on 15 August before dropping lower than ever seen before. Strong whirlpools formed in the harbour, endangering several ships. No major damage reported.

WESTPORT: A bore 1.2-1.5 m high was reported.

CHATHAM ISLANDS: This area was probably the worst affected. The Maori settlement of Tupunga on the northern side of Chatham Island was totally destroyed. Three waves were reported . The force of the water smashed drays and moved large stones of up to 500 kg in weight. No trace of the settlement remained, and from indirect evidence it appears to have been abandoned as a consequence. The water flooded up to 6.4 km inland. At Waitangi a number of houses were moved off their foundations and a large amount of Government Stores were lost. At least one house and its contents, including its occupant, were swept away.

The tsunami occurred from 15 to 17 August, with the main effects occurring during low tide on 15 August. On 17 August the reports are interspersed with reports of an earthquake which was felt over most of central New Zealand on the morning of that day.

1877 May 10
Magnitude -
Epicentre - Chile

This tsunami was extensively recorded around New Zealand, although the effects were less pronounced than those of the previous tsunami from near Chile in August 1868.

MANOWAORA BAY: The maximum water level was 1.8 m above mean high water spring.

WAITANGI: The wave height was 3 m. The ship's boat from the Iona was swept above the high tide mark.

RUSSELL: The tide ebbed and flowed seven times during the day of 11 May with a maximum fluctuation of 1.8 m.

PAIHIA: At noon on 11 May the water dropped 1.2 m in 10 min, then rose 1.9 m by 12:25 p.m.

WAIROA BAY: At 4 p.m. a wave rushed in and flooded at least 9 m horizontally above the high water mark. Two boats were washed ashore and left high and dry in a paddock.

BAY OF ISLANDS: In addition to the above locations, a number of islands within the bay reported a sudden 2.5 m rise in the space of a few minutes around 5 p.m. on the 11th, followed by ebbing and flowing every 20 min.

WARKWORTH: At 7 a.m. on 11 May the water level rose 1.8 m in a few minutes before receding. There were three more waves. Two 1.5 m high waves, occurred at 9 a.m. and 10 a.m., with a 1.2 m wave at 12:45 p.m. Between the peaks the water receded sufficiently to ground the steamer Kina as it was navigating the Mahunrangi Estuary just below the Warkworth Wharf.

PORT CHARLES: The wave of 11 May washed 200-300 logs away from the sawmill. The tide rushed in and out every 20 min all day long with an average range of 2.5 m and a maximum of 3.0-3.6 m. A punt anchored in Reef Bay broke its moorings and was swept ashore, and the wharf was damaged.

TAURANGA: At 8 a.m. on 11 May the water at the beach suddenly rose 1.5-1.8 m up the beach reaching 0.6-0.9 m higher than normal. The water receded rapidly.

GISBORNE: The water rose 2.2-2.4 m in a few minutes. When it receded it eroded about 45 m from the end of a sandy spit within the harbour. The largest wave swept 2.5 m over the bulwarks of the vessel Go-Ahead which was aground in the harbour at the time. The river rose 0.9-1.2 m flooding low-lying regions.

WELLINGTON: Ebbing and flowing every 15 min with a variation of 1.5 m.

CHRISTCHURCH: A 0.9 m rise in the Avon River was reported.

LYTTELTON: The first wave was reported at 7 a.m. The water level reached above high water mark at half flood tide then fell exceedingly low. No damage was reported

AKAROA: The first wave was reported at 7 a.m. on 11 May at almost dead low water and it was described as heavy. The water rose rapidly about 2.5 m and then receded immediately. The waves returned every 20 min and were still noticeable at noon. No damage was reported.

1883 August 27
Magnitude - A volcanic eruption.
Epicentre - Krakatoa

This tsunami does not appear to represent a direct wave from Krakatoa. Instead it was probably generated by atmospheric coupling within the South Pacific Ocean basin close to New Zealand.

WARKWORTH: A bore was reported in the Mahunrangi estuary. It was still 1.2m high at Craigieburn.

AUCKLAND: At 8 a.m. on the 29th, during ebb tide, the water level rose 1.8 m in 30 min and then receded to normal within another 30 min. This was observed by a large number of people who all gave the fluctuation as 1.80 m in the anchorage and 0.9-1.2m at the Auckland docks.

COROMANDEL: A 0.9 m wave was noticed at low tide, followed by unusual tidal fluctuations for a period. The tide was back to normal by the afternoon of the 29th.

WHITIANGA: The tsunami was first noted at 4 a.m. on the 29th. The water rose suddenly by 1.8 m at ebb tide then receeded leaving the vessels in Whitianga Harbour high and dry. During the next wave, moorings broks and a vessel came close to capsizing as it got caught under the wharf.

TAIRUA: A 1.8 m rise and fall observed.

MAKETU: 0.9 m bore travelled 4.8 km up the Kaituna River.

GISBORNE: A sudden 0.9 m rise was recorded at 2 a.m. on the 29th and again at 2 p.m.

LYTTELTON: Usually high tides occurred on the night of the 28th and the morning of the 29th. Between 7 a.m. and 9 a.m. the water receded 0.9-1.2 m dropping to 0.9 m below low water. At 10.30 a.m. the water dropped suddenly by 0.8 m at the docks during a flood tide. At 7.30 a.m. on the 29th the water level dropped to 1.8 m below normal low water, leaving the wharf at Purau high and dry.

1913 February 22
Magnitude - 6.8
Epicentre - Near Westport

At Westport the tide was extraordinary high. Strong seiches were reported in the river at Westport. At Ngakawau, the tide was 0.9-1.5 m above normal high spring tide. A number of coastal landslides were reported as a result of the earthquake and these may have induced the tsunami, which was restricted to an 85 km stretch of coast.

1929 June 16
Magnitude - 7.75
Epicentre - Murchison

This earthquake was accompanied by a large rotational slump at Whitecliffs about 20 km south of Karamea. An area of sea floor was uplifted as a result involving a region of 1[illegible]6,000 m2 and a vertical motion of about 16 m. Prior to the earthquake this area was an average of 3 m below sea level (Henderson 1937). It is possible that this event is responsible for the 2.5 m tsunami reported at Karamea.

1931 February 2
Magnitude - 7.75
Epicentre - Napier

The Napier earthquake involved extensive regional uplift. There was a sudden expulsion of water from Port Ahuriri and the Napier foreshore, but no real evidence exists for a large-scale surge or tsunami sweeping in over the beach. The reason for this is probably the large uplifts undergone by the foreshore as the water receded. The harbour was uplifted by 5.5 m causing the sudden withdrawal of the water. Although it appears the water did surge back, the height of the surge was insignificant relative to the change in elevation of the terrain.

WAIROA: A 3 m or wave is reported from the Wairoa river following the earthquake.

WAIKARE RIVER: A large wave destroyed a woolshed and left fish strewn 15.2 m vertically above high tide level. This suggests that the wave was at least 15 m high. It seems that this was a locally generated wave produced by a large rotational slump on the opposite side of the Waikare Estuary.

1947 March 25
Magnitude - 6.0
Epicentre - Gisborne

This is the most extensively reported local tsunami. It is unusual in a number of respects, the most notable bring the large response produced by what was a relatively small earthquake.

TATAPOURI HOTEL: Two waves greater than 10 m were seen approaching. They were still 3 m high when they reached the hotel. After the second wave, the water remained at window sill height for about 10 min. The building was structurally damaged and a number of the fittings were also affected. A nearby cottage was destroyed.

TURIHAUA POINT: Two waves greater than 10 m were observed. The water depth was greater than 1 m on the main road, and the receding water swept furniture out of a house.

POUAWA BEACH: A house was swept out to sea and six people were endangered. The local bridge was swept off its piles by a bore and carried 1 km upstream. Two bridges 3 m above high tide level were totally destroyed on the coast road.

MURPHYS BEACH: Land was inundated to 4 m above high water.

MANUNGA BEACH: The main wave was 6-7 m high, and a house was swept off its foundations.

UAWA RIVER: Several high bores travelled up to 3 km upstream.

WAINUI BEACH: The wave almost crested a large embankment between the beach and houses. The surf club was demolished and a caravan deposited on top of a fence. One house was flooded.

GISBORNE: In the harbour, 4 m high waves were reported and a bore formed in the Turanganui River. A dredge was swept away but it was recovered. Houses around the harbour were flooded.

1947 May 17
Mangnitude - 5.6
Epicentre - Gisborne

This tsunami occured at night and at low tide. Its effects were therefore not as well reported as the tsunami two months earlier. This tsunami appears to have been concentrated further north and on a smaller section of coastline than the previous one.

TATAPOURI HOTEL: A wave was estimated to be about 3.8 m high.

WAIHAU BEACH: Wood stacked to repair bridges damaged in the previous tsunami was swept away. It had been stacked 40 m horizontally above high tide level. The water flooded inland for 370 m and about 1.8 m higher than the previous tsunami. This appears to represent a wave 5-6 m high.

TOLAGA BAY: The wave deposited debris 45 m horizontally above high water, which was further than during the previous tsunami.

This tsunami is also thought to be associated with mud volcanism

1960 May 22
Magnitude - 8.5
Epicentre - Chile

This is the most extensive recorded tsunami in New Zealand so far this century. Its distribution is similar to the tsunamis of 1868 and 1877, but the wave heights were generally smaller.

MANGONUI: A 1.2 m rise and fall was recorded within 10 min.

WAITANGI: Strong flood and ebb flows were reported at 20-40 min intervals starting late on the 23rd. Whirpools were observed and one boat was damaged following a collision with the Waitangi Bridge.

OPUA: The water level changed by 1 m in a matter of minutes. Boats moored in 3 m of water were grounded.

TUTUKAKA: On the night of the 23rd the water receded and then returned, rising 2.8 m within minutes. Surges continued at 15-30 min intervals. The water level reached a maximum of 3 m at high tide. The coast road was flooded and a bridge abutment damaged.

LEIGH: The water level dropped 2.4 m in a few minutes and then returned as a 1.2 m surge washing away bridge supports.

AUCKLAND: The tide was irregular starting late on the evening of the 23rd. Fluctuations exceeding 0.6 m were recorded in the Waitemata Harbour during the 24th and 25th. Waves with an amplitude of 0.3 m and a 45 min period were recorded in the Manakau Harbour on the 24th.

WHITIANGA: Oscillations of 1 8-2.5 m were recorded. At surge damaged rock formations opposite Whitianga and swept 11 boats from their moorings. At the peak, the waterfront road was under water and the airport and two or three houses were flooded.

WHAKATANE: Fluctuations of 0.5 m were recorded at Whakatane Heads

GISBORNE: At 8:30 p.m. on the 23rd, a 1.2 m bore was reported in the Waimata and Taruheru Rivers. Earlier at 8 p.m., a 1.0m bore was reported in the harbour channel. Strong surges with a period of about 20 min and a 4 m maximum amplitude were recorded. These are reported to have extensively eroded silt banks and sand shoals within the harbour and rivers.

NAPIER: The maximum tidal disturbance ranged 3 m above chart datum and 1 m below (compared with the normal maximum range of 1.6 m) Many boats were damaged and several were swept out to sea. The maximum runup reported was 5 m above high tide level but this appears to be an exaggeration. A 3.0 m wave swept into beach homes at Scapa Flow. About 17,000m3 of sand were scoured from the boat harbour and a 0.7 m depth of silt was deposited on the Westshore Slipway.

WELLINGTON: The maximum rise was 0.95 m for a period of 20 min.

LYTTELTON: The highest level above normal high tide was estimated at 3.3-3.5 m.

OAMARU: The oscillations began at about 9 p.m. on the 23rd At 10:05 p.m. the water rose 0.6 m before dropping 1.5 m in 10 mins. Fluctuations of 0.9-2.8 m occurred during the following 30 hours.

The Earthquake and War Damage Commission (1961) reported 69 claims for damage as a result of this tsunami. Most were reported from Banks Peninsula and Napier although damage claims extended from the mouth of Catlins river in the South Island to Whangarei in the North Island. The value of these claims is not known.

1964 March 28
Magnitude - 8.4
Epicentre - Alaska

The source of this tsunami was the Alaskan earthquake of 1964 and the tsunami was very devasting around the North Pacific. At most locations around New Zealand it was barely noticeable.

AUCKLAND: A maximum fluctuation of 0.45 m was observed.

WELLINGTON: Maximum oscillation of 0.35 m occurred.

LYTTELTON: Fluctuations of about 0.9 m occured every 20 min, with a maximum rise of 1.25 m for 40 min. Later reports state that the maximum response was 0.5 m and the peak to trough range was 1.5 m

GREYMOUTH: A maximum rise of 0.4 m for 20 min.

Appendix B. Description of Tsunami Damage in the Alaska Earthquake of 1964.

Extracted from Steinbrugge, Reference 9.

Alaska

It is evident from the historic record that Alaska has a significant tsunami hazard along its southern shorelines. Based on this record, and limited to damaging tsunamis which, of course, are fewer than the total number recorded, it has been roughly estimated by some authorities that the recurrence interval for various parts of Alaska may be in the order of:

Western Aleutian Islands	5 years
Eastern Aleutian Islands	10–20 years
South central Alaska	20–90 years
Southeastern Alaska	Less than 30 years

Table 11-2
Selected Recorded Northern California Tsunami Wave Heights*

Tide Station	Tsunami Origin and Year		Alaska 1964
	Alaska 1946	Chile 1960	
Pacific Grove	—	6	6
Monterey Harbor	—	5	9
Moss Landing	—	5	9
Santa Cruz	10	6	10[b]
Pacifica	—	8	9
San Francisco (Presidio)	1.7	2.9	7.4
Bodega Bay	—	2	5
Arena Cove	16	—	12
Crescent City	—	10	28[b]

* Adapted from studies by C. T. Magoon and others. Elevations in feet. Heights are maximum.
[b] Estimated.

South central Alaska includes the region of the 1964 earthquake, that is, from Kodiak to Prince William Sound. Southeastern Alaska is the panhandle which includes Juneau and Sitka. While above recurrence intervals are rough, they are satisfactory for insurance purposes. About 20–25 historic tsunamis are known for Alaska, but only about one-fourth of these have had wave runups over 3 feet. Comparatively speaking, Japan has many more tsunamis and greater damage potential.

In the 1964 earthquake, waves destroyed portions of numerous Alaskan coastal cities simultaneously with the shock or a few minutes thereafter. In many cases, this damage was mostly due to submarine landslides such as those which occurred at Seward, Whittier, and Valdez.

In Seward during the 3–4 minutes of strong ground shaking, strips of the shoreline containing docks and other port facilities disappeared under the water due to a submarine landslide. This landslide developed large waves. About 20 or more minutes later the first wave from the main tsunami arrived. Highest wave runup of all waves was 30 feet.

The tsunami events during and following the earthquake in many coastal cities were spectacular as well as devastating, and Seward is one such example. The following is an extract from "Effects on Communities, Seward," Richard W. Lemke, U.S. Geological Survey Professional Paper 542-E (1967); Lemke interviewed more than 100 individuals after the event as the basis for his account:

Strong ground motion at Seward ... 3 to 4 minutes. Nearly all accounts indicate that the shaking started gently but increased markedly in a few seconds and continued to grow in violence until people could hardly stand without support ... Two gantry cranes at the Alaska Railroad dock bounced off their tracts and into Resurrection Bay ... [Figures 7-46 and 7-47].

The more extensive and spectacular effects of the earthquake, however, were along the Seward waterfront. Between 30 to 45 seconds after violent shaking began ... an area extending from the Standard Oil Co. dock to beyond the San Juan dock, began sliding seaward as a result of large-scale offshore landsliding. Slice after slice of ground along the shore slid progressively as shaking continued, until a strip of harbor area 50 to 500 feet wide had disappeared into the

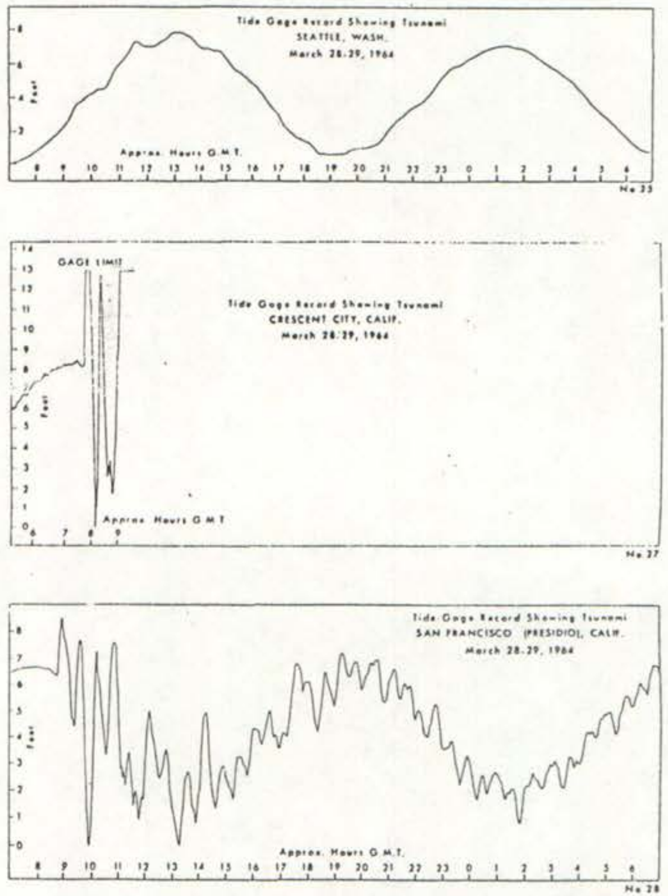

Figure 11-6. Tide gage records of the 1964 Alaskan tsunami at Seattle (Washington), Crescent City (California), and San Francisco (California).

bay. Large fractures broke the ground surface behind the slide area and extended several hundred feet inland as shaking continued. Some fractures near the Texaco tanks reportedly opened and closed repeatedly during the shaking; some were at least 20 feet deep. They filled quickly with water and, as the shaking continued, spewed muddy water at intervals . . . [Figure 11-7].

Pipes and valves of the tanks at the Standard Oil Co. dock began rupturing 30 to 45 seconds after shaking started, and fuel poured from the tanks. As the tanks began to overturn and slide into the bay, they exploded with a roar, and flames leaped 200 feet into the air. Water, displaced by landsliding, receded rapidly from the shore carrying burning fuel on its surface. A tanker unloading at the Standard Oil Co. dock reportedly hit bottom when the water level suddenly dropped 15 to 20 feet. . . .

As the water was displaced suddenly from the shore, a large mound of water formed several hundred yards out in the bay and in line between the Standard Oil Co. tanks and the Fourth of July Point. . . .

The wave moving toward Lowell point overran the northeast corner of the fan approximately 1 minute and 15 seconds after shaking started, or about half a minute after the landsliding started in the Standard Oil Co. dock area. It was estimated to be 30 feet high. . . .

The water surged . . . toward the southwest part of the Seward waterfront also. A large swell broke over The Alaska Railroad dock area, lifting flat cars off the tracks . . . As the wave hit the shoreline at the Standard Oil Co. tanks, burning oil was carried back onto shore. An 80-car freight train on the tracks between the Standard and Texaco tanks was just ready to start moving north. Its last 40 cars were filled oil tankers and as the fire swept onto shore, the tankers caught fire in a chain reaction of exploding cars down the track toward the Texaco yard. . . .

After strong ground motion had ceased and before the first seismic sea wave arrived, at least two additional waves swept the Seward waterfront. Water continued to slosh back and forth in the bay for at least 15 minutes following the quake. . . .

Fires ignited during the shaking continued to burn intensely after shaking had ceased, and new ones were started as explosions periodically ripped the waterfront. Burning oil and combustible debris covered most of the water surface from beyond the south end of Seward to the head of the bay. Without water (because of broken mains), the efforts of firemen and volunteers were largely futile. . . .

The arrival time of the first seismic sea wave from outside the Seward area is conjectural. . . . By estimating the time that it would take these observers to perform a series of activities after shaking stopped and before the wave hit, it is concluded that the wave arrived between 20 to 30 minutes after shaking stopped. . . .

The first seismic sea wave is reported to have spanned the width of the bay as it entered the Seward area and to have been 30 to 40 feet high as it neared the head of the bay. Burning oil covered much of its surface. Carrying boats, houses, and railroad cars collected from the Seward waterfront area, the wave crashed over the railroad embankment into the lagoon area and moved inland at the head of the bay. Debris was piled so high on the road across the lagoon that it blocked all motorized exit from the town. At the airport, a wall of water rushed part way up the airstrip at an estimated speed of 50 to 60 miles per hour. . . .

Several other large waves followed the first seismic sea wave . . . The third seismic sea wave was probably the largest, but most of the destruction had already been done by the earlier waves. Fires burning on the surface of the bay were extinguished several times by incoming waves, only to start anew as burning oil poured out along the waterfront. . . .

Figure 11-8 is a before-and-after navigational chart of Seward showing the outline of the old and new shorelines as well as outline of the head of the submarine landslide. Twelve people lost their lives, all but

Figure 11-7. Texaco oil tanks after the 1964 tsunami and fire at Seward, Alaska.

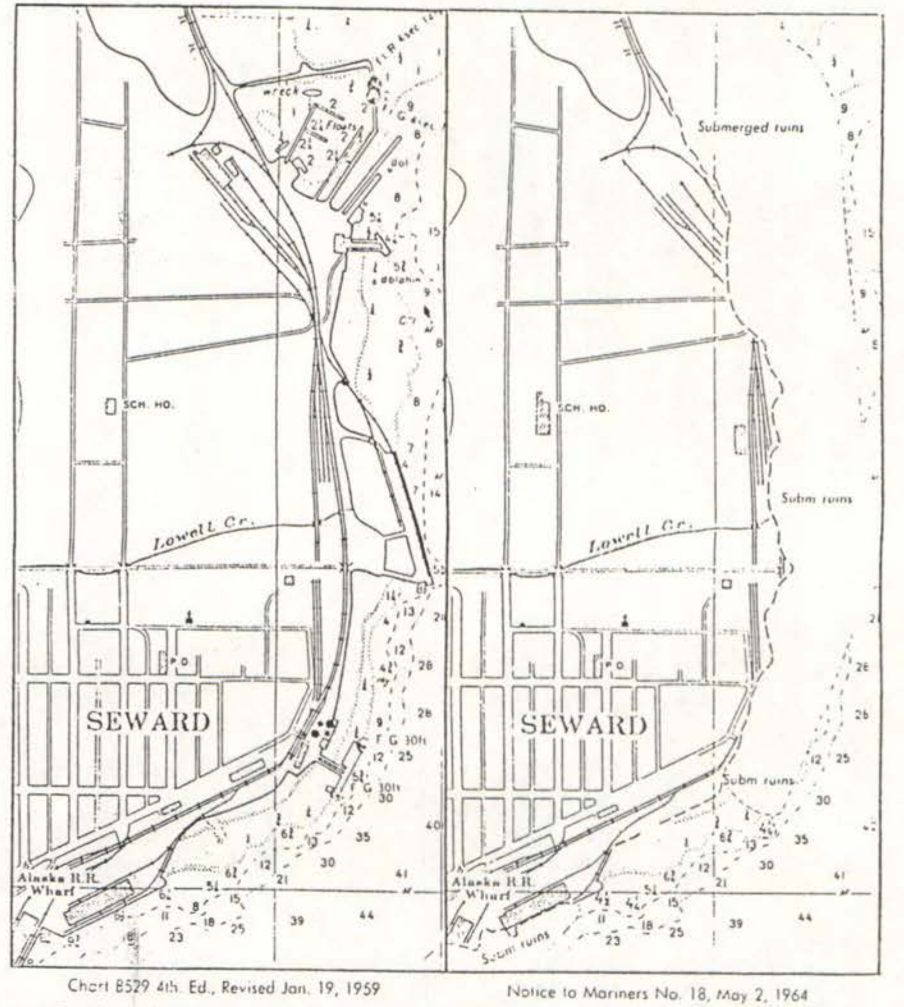

Figure 11-8. Before-and-after U.S. Coast and Geodetic charts of the shoreline of Seward, Alaska. Note changes in shoreline with respect to the railroad tracks. (A small amount of other culture shown on the 1959 chart had changed before the earthquake.)

Figure 11-9. Head of submarine landsliding where tracks enter the water. Ensuing tsunami knocked boxcars and tank cars off the rails, sometimes carrying the rails along with the cars. Seward, Alaska, after the 1964 tsunami.

one by the tsunami. Figures 11-7 through 11-11 show the tsunami damage and the head of submarine landsliding. However, based on the author's personal inspections, building damage in the city due only to ground vibration was minimal to moderate, and these inspections included non-earthquake-resistive masonry buildings.

Whittier also experienced submarine landslides and tsunamis which destroyed docks, oil facilities, and rail facilities (Figures 11-12 and 11-13). Wave runup was highest on the north shore of Passage Canal where it reached a height of 104 feet. Twelve lives were lost. The nearby 14-story building was not subject to tsunami forces; the ground vibration caused only minimal to moderate structural damage (Figure 11-14).

Valdez also had tsunami damage due to submarine landsliding. The ship *Chena* was moored at a dock which collapsed. Lives were lost on the dock and the ship. Contemporary accounts provide fascinating reading. The highest wave rose to 23 feet. Figure 11-15 is of tsunami damage. Valdez has since been rebuilt on a different site with the view of minimizing the hazard from future submarine landslides and tsunamis.

Damage at Kodiak is among the best of those documented after the tsunami, with Figure 11-16 being a typical view of boats driven ashore. The following is quoted from the abstract to "Effects of the Earthquake of March 27, 1964, on the Communities of Kodiak and Nearby Islands" by Reuben Kachadoorian and George Plafker (U.S.G.S. Prof. Paper 542-F):

> ... It is the most severe earthquake to strike this part of Alaska in modern time, and took the lives of 18 persons in the area by drowning; this includes two in Kodiak and three at Kaguyak. Property damage and loss of income to the communities is estimated at more than $45 million.
>
> ... The largest community, Kodiak, had the greatest loss from the earthquake. Damage was caused chiefly by 5.6 feet of tectonic subsidence and a train of 10 seismic sea waves that inundated the low-lying areas of the town. The seismic sea waves destroyed all but one of the docking facilities and

Figure 11-10. Tsunami at Seward pushed railroad cars off of tracks into a jumbled belt as shown in Figure 11-11. After the 1964 Alaskan tsunami.

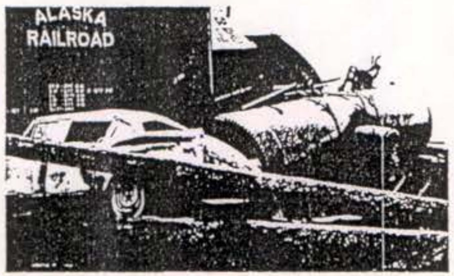

Figure 11-11. Detail of tsunami damage shown in Figure 11-10.

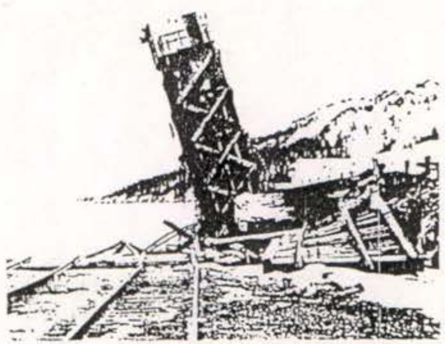

Figure 11-12. Submarine landsliding and tsunami damage at Whittier, Alaska, after the 1964 earthquake.

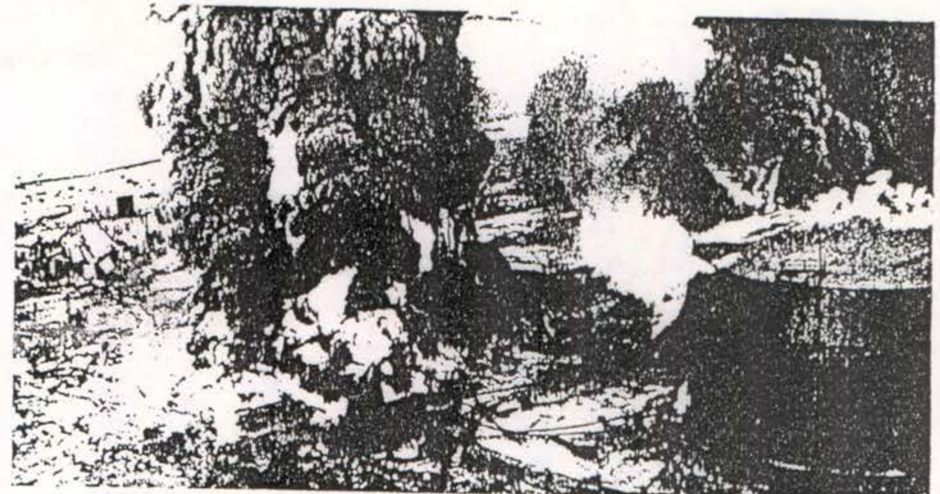

Figure 11-13. Union Oil tanks on fire at Whittier, Alaska, after the 1964 earthquake and tsunami.

Figure 11-14. Hodge Building at Whittier, Alaska, after the 1964 earthquake. Building suffered between minimal and moderate structural damage.

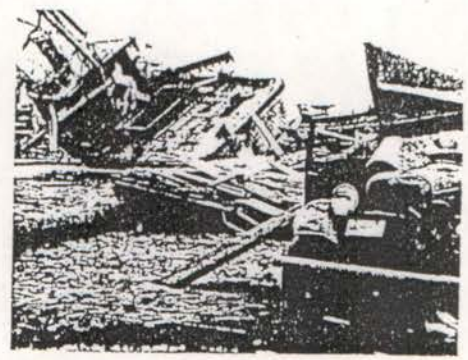

Figure 11-15. Valdez, Alaska, after the 1964 earthquake and tsunami.

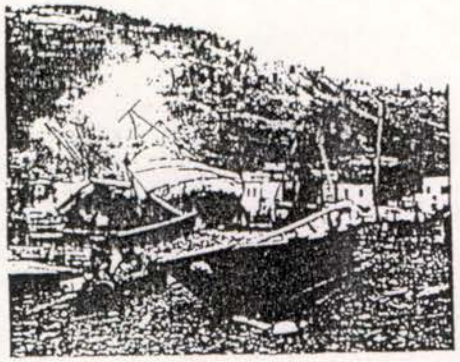

Figure 11-16. City of Kodiak Alaska after the 1964 earthquake and tsunami.

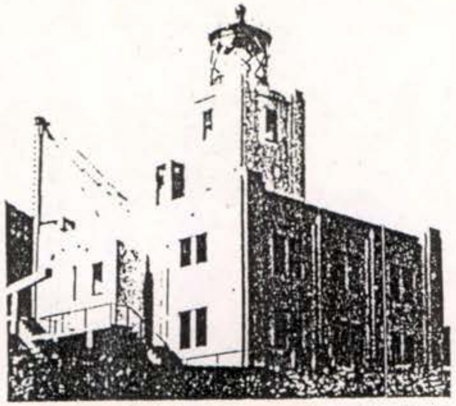

Figure 11-17. Scotch Cap Lighthouse on Unimak Island in the Aleutian Islands before the April 1, 1946, tsunami.

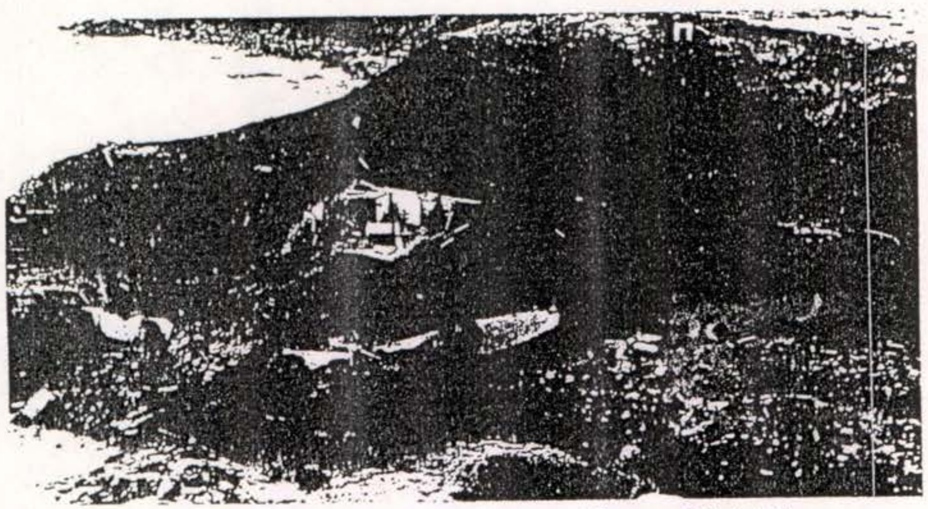

Figure 11-18. Site of Scotch Cap Lighthouse after the 1946 tsunami. Five persons died in the lighthouse.

more than 215 structures; many other structures were severely damaged . . . [The waves] reached their maximum height of 29-30 feet above mean lower low water at Shahafka Cove. . . .

Seismic shaking lasted 4½ to 5½ minutes at Kodiak and had a rolling motion . . . [and] . . . very little if any damage occurred from the ground motion or seismic shaking. . . .

Other tsunamis have been damaging in Alaska but all at a much lesser scale. Figures 11-17 and 11-18 are before-and-after photographs of the Scotch Cape Lighthouse on Unimak Island of the April 1, 1946, tsunami. There is evidence to indicate that the wave reached a height of 90-100 feet. Five lives were lost at the lighthouse as a result of the wave which followed only a few minutes after the earthquake.

Table 11-3 is a summary of significant tsunamis recorded in Alaska.

The 1964 Alaskan earthquake and tsunami has been thoroughly studied and the results widely published. The reader may wish to refer to the volume "Oceanography and Coastal Engineering" in the series entitled *The Great Alaska Earthquake of 1964* by the National Academy of Sciences. This 556-page book, with its numerous photographs and diagrams, is probably the best single source of information although some of the text may be beyond the technical background of readers.

Hawaiian Islands

Due to their location in the central portion of the Pacific and their orientation to the oceanic trenches, the Hawaiian Islands have experienced numerous tsunamis from distant origins including Alaska, Chile, Japan, and Kamchatka. Tsunamis generated in Indonesia and elsewhere in the South Pacific have been recorded, but they have not been damaging. Additionally, there have been locally generated tsunamis.

The 1819 tsunami at Hawaii is the earliest on record. Its origin was a Chilean earthquake. Over 100 tsunamis have been recorded in the Hawaiian Islands, with perhaps 16 or 17 of them producing significant damage. A number of the principal ones have been included in

Table 11-3
Tsunamis Generated on Alaskan Coasts, 1788-1965 (Doubtful Events Are Excluded)*

Date	Area of Generation	Maximum Runup in Meters[b]	Place	Effects
1788 July 27	Alaska Peninsula	?	Shumagin Island	Effects uncertain
		?	Unga Island	Many natives drowned
		?	Sanak Island	Hogs drowned
		?	Kodiak Island	Ship cast ashore, cabins washed away
1845	Yakutat Bay	?	Yakutat Bay	Local tsunami from ice fall; 100 drown
1853-1854	Lituya Bay	120	Lituya Bay	Local tsunami
1874	Lituya Bay	24	Lituya Bay	Local tsunami
1878 Aug. 29	Fox Islands	?	Unalaska	Village of Makushin destroyed
1883 Oct. 6	Mt. Augustine eruption	7½-9	Port Graham	
1899 Sept. 10	Yakutat Bay	10	Yakutat Bay	Local tsunami
		1	Controller Bay	Perhaps an independent tsunami
		2	Valdez	Probably an independent tsunami
		60	Lituya Bay	Independent local landslide—origin tsunami
1905 July 4	Yakutat Bay	35	Yakutat Bay	Local tsunami from ice fall
1925 Feb. 23	Port Valdez	?	Valdez	Local tsunami in Valdez
1929 Mar. 6	Fox Islands	?		
1936 Oct. 27	Lituya Bay	150	Lituya Bay	Local landslide-origin tsunami; no quake
1938 Nov. 10	Shumagin Island. Alaska Peninsula	0.2	Sitka	
1946 April 1	Fox Islands	30	Unimak Island	
1949 Aug. 22	South Alaska	0.1	Ketchikan	
1957 Mar. 9	Andreanof Islands	12	Unimak Island	Doubtful record
		4	Sweeper Cove, Adak	
1958 July 9	Lituya Bay	525	Lituya Bay	Local tsunami; see Chapter 4
	Off Lituya Bay	0.2	Yakutat	General tsunami
1964 Mar. 28[c]	Valdez Inlet	30	Valdez	Local tsunami; great damage
	Passage Canal	9.2	Whittier	Local tsunami; great damage
	Prince William Sound	16.6	Chenega	Local tsunami; village destroyed
	Resurrection Bay	7.0	Seward	Local tsunami; great damage
	Gulf of Alaska	20	S.E. Kodiak Island	
	Gulf of Alaska	9	Kaguyak	
	Gulf of Alaska	9.2	Old Harbor	
	Gulf of Alaska	6.1	Kodiak	
	Gulf of Alaska	6.1	Women's Bay	
	Gulf of Alaska	4.2	Cordova	
1965 Feb. 4	Rat Islands	10	Shemya Island	
1965 Mar. 29	Rat Islands	3.2	Massacre Bay, Attu	
1965 July 2	Fox Islands	0.1	Dutch Harbor	

* Condensed from "Technical Evaluation of the Seismic Sea Wave Warning System," Doak C. Cox and Harris R. Stewart, Jr., in *Oceanography and Coastal Engineering* of the National Academy of Sciences.
[b] Runup is measured above contemporaneous sea level.
[c] Heights shown for the 1964 tsunami are selected examples from a much longer list.