Tsunami Motion

by

Siti Hafizah binti Othman

Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
(Civil Engineering)

DECEMBER 2006

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Tsunami Motion

by

Siti Hafizah binti Othman

A project Dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

Approved by,

(Assoc. Prof. Saied Saiedi)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
December 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SITI HAFIZAH BINTI OTHMAN

ABSTRACT

This report is prepared in response to the Final Year Project required for undergraduate students. The project is entitle "Tsunami Motion". Tsunami phenomenon and its impacts on human life have attracted considerable attention after the latest Tsunami on December 2004 hits Indonesia and neighboring ocean countries. Little knowledge is available among civil engineers while they are the ones who should deal with major consequences. The objective of this project is to develop a simple mathematical model in order to determine tsunamis speed and height. A phrase has quoted "Scientists can predict when a tsunami will arrive since the speed of the waves varies with the square root of the water depth". Tsunami waves in the deep ocean can travel at high speeds for long periods of time for distances of thousands of kilometres and lose very little energy in the process. The deeper the water, the greater the speed of tsunami waves will be. The height of a tsunami also depends upon the water depth. A tsunami that is just a meter in height in the deep ocean can grow to tens of meters at the shoreline. Other features which influence the size of a tsunami along the coast are the shoreline and bathymetric configuration, the velocity of the sea floor deformation, the slope of the basin and the efficiency which energy is transferred from the earth's crust to the water column.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my utmost gratitude to God Al-Mighty, for giving me the will and determination throughout completing my final year project.

To my supervisor, Assoc. Prof. Saied Saiedi, who has gone through a lot of trouble in order to help me through many unfamiliar concept definitions as well as programming style. His superb guidance and countless hours reviewing my work have definitely helped me a lot.

Not to forget, Mr Alessandro Annunziato from European Commission's Joint Research Centre (JRC) who delicately helped me with all my enquiries on the subject matter, for his generosity and faith, my thank you goes to him.

My sincere appreciation goes to Mr Patrick Sebastian and Mr Izzatdin Abdul Aziz, for their assistance and guidance towards programming aspects.

To all workforces in Universiti Teknologi PETRONAS who has directly helped me throughout my project, my thank you goes to them.

Last but not least, I would also like to thank all parties involved, directly or indirectly, from the very first phase of my project until the very end.

Thank you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

A PROBLEM STATEMENT

A.1 Problem Identification

Tsunamis phenomenon and its impacts on human live have attracted considerable attention after the latest Tsunami on December 2004 hits Indonesia and neighboring ocean countries. This earthquake and subsequent tsunamis reportedly killed over 200,000 people around the rim of the Indian Ocean. Little knowledge is available among civil engineers while they are the ones who should deal with major consequences. Simple mathematical model is needed to know how tsunami travels in terms of speed towards the coasts.

A.2 Significant of the Project

To understand the engineering implications of possible wave speed and height resulting from tsunami, a formulation of the speed capable of giving quantitative is required. At present, the ocean shoreline regions are the site of a high degree of development. In order to prepare suitable structural designs for these areas, one should know about the probabilities tsunamis at a certain site and the speed of wave and its height that could be expected if a tsunami did occur.

B OBJECTIVES AND SCOPE OF STUDY

B.1 The Relevancy of the Project

The main objective of this project is to develop a simplified mathematical model in determining tsunami travel in terms of its speed as it is approaching towards the coasts. Integration with the available warning system will alert the coastal communities.

B.2 Feasibility of the Project within the Scope and Time Frame

Within 28 weeks of project's time frame, a simplified mathematical model for tsunami travel is required to be developed. The model must be capable in giving quantitatively the speed of tsunami travel towards the coasts. To be able to develop the model, tsunami movement and simulation must first be understood. Data collected through internet, library and correspondence will be referred to.

METHODOLOGY

A PROCEDURE IDENTIFICATION

The total research and development process has been divided into four phases. This is to ensure that the project will be carried out smoothly and timely less constraint.

1. Selection of Project Topic

In this phase, the topic is selected cautiously and based on interest for this project will carry four credit hours per semester. The selected topic is ensured to be feasible in term of scope and time frame.

2. Project Planning

All defined scope and work is outlined along specific time frame to keep track with on-going and planned activities. It is vital to keep updates with the check list, outlined activities and its time frame to minimize behind schedule activities.

3. Literature Study

Reading for familiarity with tsunami movement and simulation is part of the nature of the project and will be carried out frequently. Data collection via internet, library and correspondence will be part of the project development.

4. Development of Mathematical Model

At the end of the project, a simple mathematical model for tsunami travel will be developed based on data collected and knowledge gained.

B TOOLS / EQUIPMENT USED

1. Relevant software and computing facilities (i.e JRC Tsunami Propagation Model, ETOPO-2, EARTH.EXE and C programming).

CHAPTER 1
LITERATURE REVIEW

With the extensive media coverage and public concern on tsunamis, it is not surprising that the topic has attracted considerable attention in recent years. In an attempt to improve the tsunami warning system, both modeling and observational components, studies have focused on anything from wave scattering, inundation, impact and design for tsunamis. While some research has focused only on the description of tsunami phenomenon, other work has sought to show it forecasting. Accordingly, Ward (2000) suggests that the ultimate goal of tsunami research is forecasting. A forecast predicts the strength of a particular tsunami, analyzing the seismograms and forecasting the expected height and time of the oncoming wave with the aid of computer models for tsunami generation.

Helene and Yamashita (2006) work used the approximation of shallow water waves to understand the behavior of a tsunami in a variable depth. The equation is deduced with the continuity equation to satisfy the discontinuity encountered by the wave in the sea depth. The inclusions of seabed topography and wave refraction were pointed out as necessary to understand some phenomena observed in tsunamis.

Much of the earlier work by Mofjeld et al (2000) suggested that the most important factor determining the intensity of scattering and reflection is the depth of a feature compared with the depth of the surrounding region. The horizontal extent of a feature, compared with the wavelength and the angle of incidence also affect the amount of scattering and reflection. These interactions have increase the duration of tsunamis.

Choi et al (2003) work is more concerned on the energy flux conservation in calculating wave heights and travel time by using Green's law. He considered the ray tracing method to calculate the tsunami pathways on the globe and it is applied to determine the travel time of the leading wave. The calculated travel times were compared with observed values for the first wave. The agreement is quite well, mainly for points where the tsunami waves approach on the frontal direction. However, the calculations in the ray tracing method do not take into account the wave propagation in the form of the edge waves leading to increase the tsunami travel time.

Some studies, however, have taken a different approach by looking into the impact level of tsunamis. In a typical study of this type, Taro Arikawa et al (2005) studied the 8-foot-tall wave, the tallest man-made tsunami. By determining the power and behaviour of a tsunami, the scientists hope to devise better seawalls and more precise evacuation plans for coastal communities at risk of a direct hit.

Very detailed 3D models have been used worldwide to try to explain the observed behavior of tsunami events. Annunziato and Best (2005) work is dedicated to the development of a new model which can be used by the international community and in particular within the JRC Global Alert System for the prediction of the arrival time of the Tsunami along the affected coasts. The model and the accompanying calculation procedure is able to predict with a high level of accuracy the correct time of arrival of the wave.

1.0 Model Calculations

Several calculations have been performed by various research laboratories in the world in the hours and days following the 26th December Tsunami event. Other calculations will be performed in the future, as new information will be published. These calculations are important for two reasons :

1. to understand the physics of the problem
2. to check whether the models could be used for an alert system

The performance of the adopted models is very good with a small deviation between calculated and actual timings.

1.1 WL|Delft Hydraulics

Home Page	http://www.wldelft.nl
Web site	http://www.wldelft.nl/gen/news/tsunami/
Type of simulation	3D
Extent of the simulation	Local Indian ocean Whole world
Type of files	Windows Media or Quick Time
Size of files	563 kBytes, 587 kbytes, 273 kbytes

1.1.1 Model description

WL | Delft Hydraulics is an independent research institute and specialist consultancy based in the Netherlands. The Model adopted is part of a series of codes, named Delft 3d. The main modules of interest in this simulation are Flow and Wave.

Flow

The FLOW module of Delft3D is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid. In 3D simulations, the vertical grid is defined following the so-called sigma coordinate approach. This results in a high computing efficiency because of the constant number of vertical layers over the whole of the computational field.

Wave

The Delft3D-WAVE module can be used to simulate the propagation and transformation of random, short-crested, wind generated waves in coastal waters which may extend to estuaries, tidal inlets, barrier islands with tidal flats, channels etc. The module computes the evolution of waves over arbitrary depths for certain wind, flow and water level fields.

1.1.2 Model results

The preliminary simulation that produced this animation shows the propagation of the tsunami starting at 01.00 hours UTC. In the deep ocean the waves measure tens of centimetres in height. In the coastal areas however, these relatively small waves can increase up to 4 to 10 meters depending on the local topography and bathymetry.

FIGURE 1.1 Example of WL | DELFT Hydraulics modeling

Areas hit by high flood waves are shown in bright colours. Yellow and red colours indicate the worst hit areas. The calculation is started with an initial disturbance of about 650 km along the fractal coast in front of Banda Aceh. It is not evident from the model the water depression (negative height) even if it is logical to expect a negative section also in this simulation. The maximum height of the wave is above 1m.

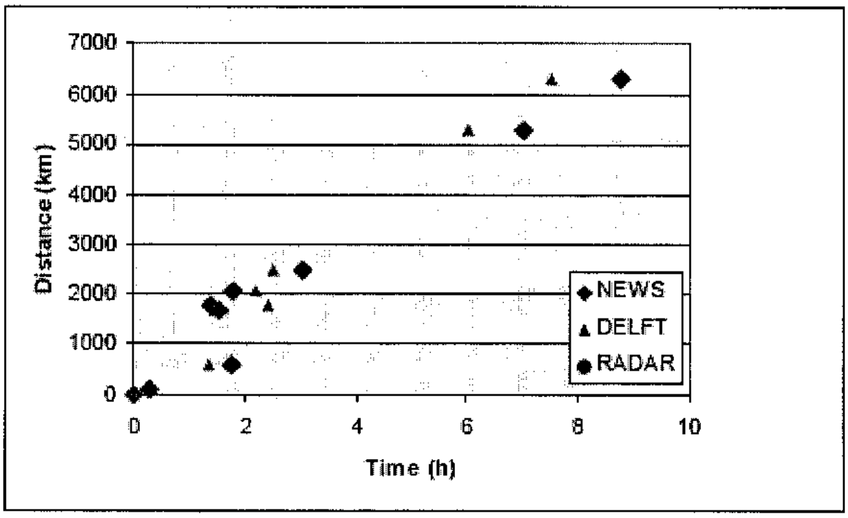


FIGURE 1.2 Comparison of the Delft Calculation with the News and the Radar data

1.1.3 General comments

The simulation is rather accurate. The timing is quite well reproduced, with a slight early wave arrival. Also the world simulation allows appreciating correct development of the wave. The CPU time of such simulation is unknown.

1.2 MOST Model NOAA

Home Page	http://www.noaa.gov
Web site	http://www.noaanews.noaa.gov/stories2005/s2365.htm
Type of simulation	3D
Extent of the simulation	Local Indian ocean Whole world
Type of files	Windows Media or Quick Time

1.2.1 Model description

The MOST Model (Method of Splitting Tsunami) developed by NOAA was used for simulating the event.

1.2.2 Model results

The model shows a pink section in front of the main wave. The "pink" color indicates very low (below 3cm) positive amplitudes. It is not a numerical problem. The sea floor deformation from earthquake, which is the initial condition for the tsunami propagation model, is computed using elastic deformation model. The resultant displacement of the ocean floor is spread for thousands of kilometers, even though the main deformation occurs in the vicinity of the fault (you could see the spread of this initial displacement at the first frames of the animation for the global propagation model). The tsunami wave is the result of the main portion of the displacement, but the model "sees" the entire displacement field and, as a result, small disturbance is propagating before the main tsunami wave.

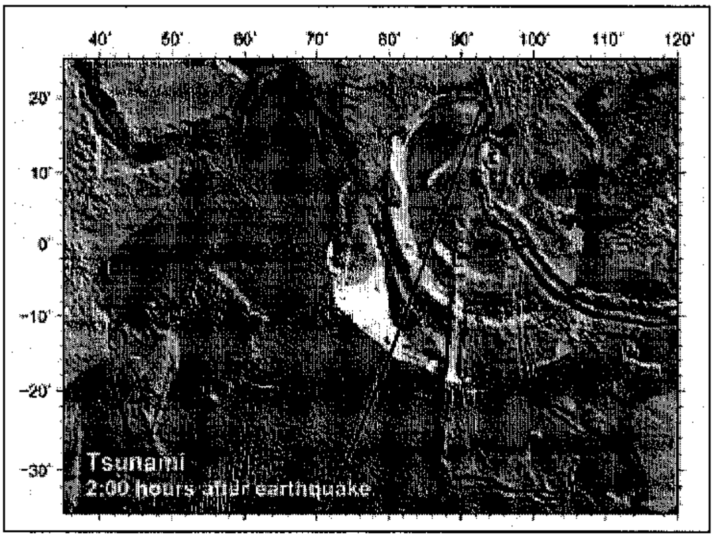


FIGURE 1.3 MOST Model results

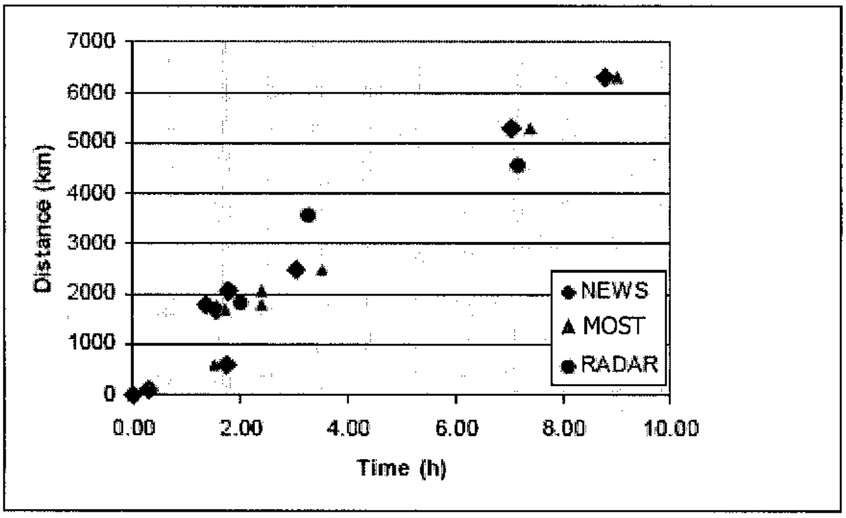


FIGURE 1.4 Comparison of the MOST calculation with the News and Radar measurements

1.2.3 General comments

The MOST simulation is quite accurate also at distances very far from the epicenter. Particularly good is the time of arrival in Tanzania, predicted with 15 minutes delay, after 9 h travel time. Particularly interesting is the simulation of

1.3 INGV – Istituto Nazionale Geofisica e Vulcanologia

Home Page	http://www.ingv.it
Web site	http://www.ingv.it/%7eroma/reti/rms/terremoti/estero/indonesia/indonesia.htm
Type of simulation	3D
Extent of the simulation	Local Indian ocean Whole world
Type of files	Windows Media or Quick Time
Size of files	563 kBytes, 587 kbytes, 273 kbytes

1.3.1 Model description

The code used for this simulation is based on a finite difference numerical scheme that solves the hydrodynamic equations in the shallow-water approximation. The cell size is 2x2 minute and for 7 hours of propagation it takes about 6 hours of CPU time (on a laptop with a 1.7 GHz processor). The initial water elevation field is computed by means of the Okada's equations.

1.3.2 Model results

The preliminary simulation produced by this animation shows the propagation of the tsunami starting phase. Areas hit by high flood waves are shown in red for positive heights and green for negative heights. It is possible to see that already at initialization the disturbance towards Thailand is negative (water removal). This disturbance continues for the whole simulation. The fault length and width is 700 and 100 km respectively, the slip amplitude is 20 m and the dip angle is 15 degrees. It is not clear which is the maximum height of the wave when it travels in the Ocean.

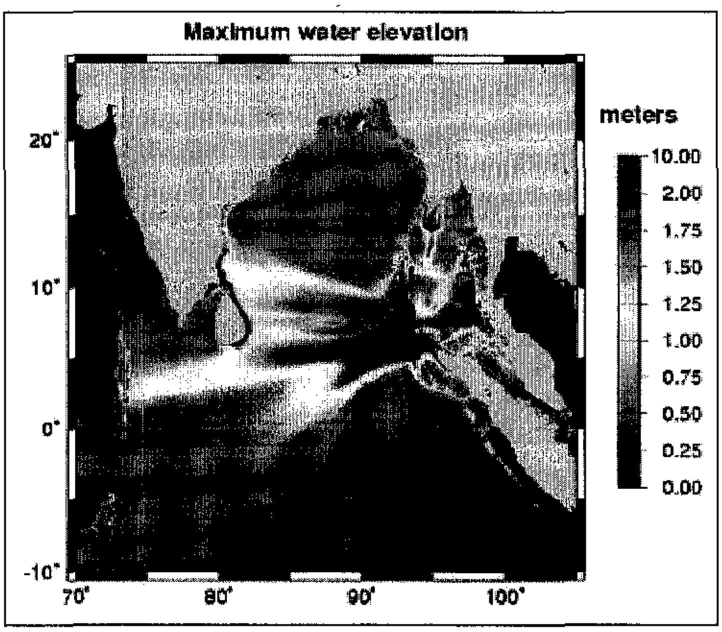


FIGURE 1.5 Tsunami calculations by INGV

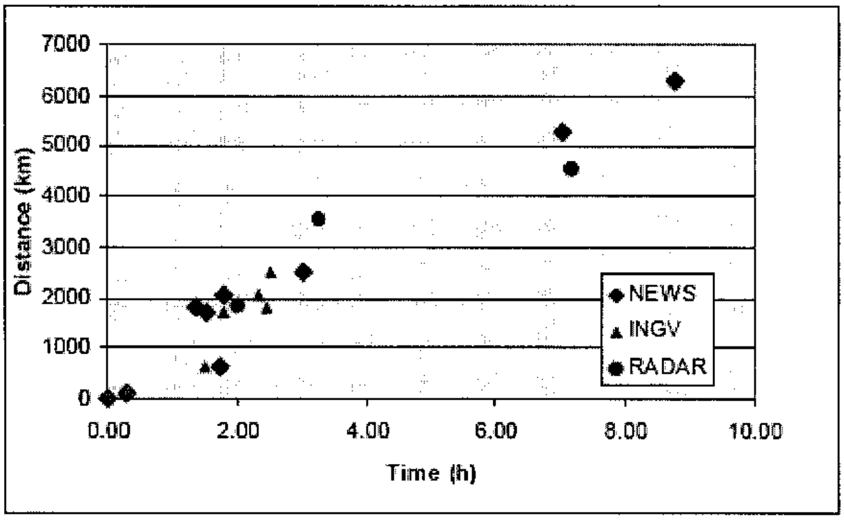


FIGURE 1.6 Comparison of the INGV calculation with the News and Radar measurements

1.3.3 General comments

The simulation is rather accurate. The timing is quite well reproduced, with a slight delay of arrival in Maldives.

1.4 JRC Tsunami Propagation Model

Home Page	http://tsunami.jrc.it
Web site	http://tsunami.jrc.it/model/model.asp
Type of simulation	On-line procedure

1.4.1 Model description

The simulation is simply based on the shallow water approximation for velocity of gravity driven waves. It uses a coarse 5 minute Ocean Bathymetry (generally known as ETOPO5 data) to calculate the local velocity at each point on the wave front. No wave diffraction or hydrodynamic effects are currently included. It's purpose is just to rapidly predict arrival times for line of sight coasts, for inclusion in immediate Earthquake alerts in Oceanic areas. The JRC Tsunami Model runs in about 15 s on a 1.7 GHz Intel Processor; the use of a faster CPU can reduce the CPU time even further.

1.4.2 Model results

The timings are not very correct because, as an example, the wave arrives in Sri-Lanka at 2:48, while in reality was at 1:32. The reason of this difference is the shallow depth at the point of the epicenter, about 618 m, which gives an initial velocity of about 280 km/h.

FIGURE 1.7 Resulting page from the calculation on-line for the 26th December

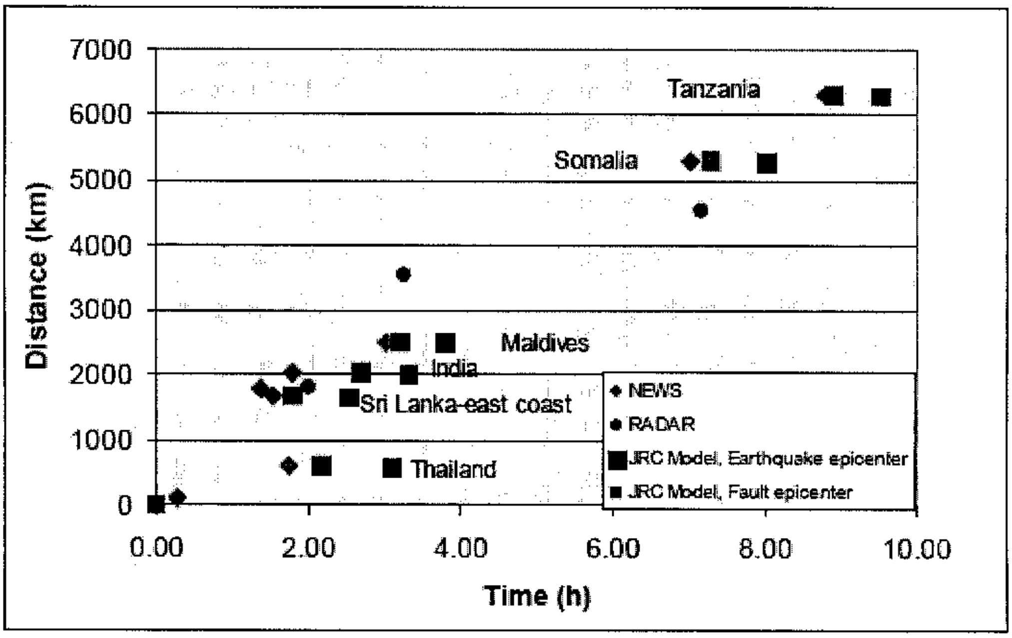


FIGURE 1.8 Comparison of the JRC Model with the news and radar measurements

1.4.3 General comments

One problem of this model is the presence of isles. The model does not take diffraction into account (i.e. it doesn't curve the wave front round obstacles). Hence when it hits land it appears to shadow casts behind.

CHAPTER 2

INTRODUCTION TO WORLD OCEANS

2.0 PROFILE OF AN OCEAN

The world oceans are introduced in this chapter to better understand the phenomenon of tsunamis. [1]71 percent of the Earth's surface is covered by oceans while the remaining 29 percent is of land. The world ocean has been categorized into five oceans namely Pacific Ocean, Atlantic Ocean, Indian Ocean, Arctic Ocean and Antarctic Ocean. However, it remains common practice to divide the world ocean into the four independent oceans, excluding Antarctic Ocean. Figure 2.1 below shows the fraction of each ocean.

If the physical features of Earth's surface are dramatic on land, they are even more so under the ocean. The oceans are much deeper than the land is high; [2]the average depth of the oceans is about 12,470 feet (3,800 m), whereas the average height of the land above sea level is 2,760 feet (840 m). The tallest mountain emerging from the sea is Mauna Kea in Hawaii at about 33,450 feet (10,200 m) above the ocean floor; on land, Mount Everest reaches 29,020 feet (8,848 m) above sea level. The Grand Canyon in the United States, one of the deepest canyons on land at 5,300 feet (1,615 m) deep almost pales into insignificance against the Mariana Trench, which is 36,163 feet (11,022 m) below sea level and about 16,400 feet (5,000 m) below the level of its flanking seafloor.

The physical features of the ocean floor are dominated by the workings of plate tectonics and seafloor spreading; broadly speaking there are similarities in the physical features of the ocean floor across the world. The seafloor is divided intro three regions; the continental margins, the ocean-basin floor, and the mid-oceanic ridge.

[1]Ross D.A., 1995

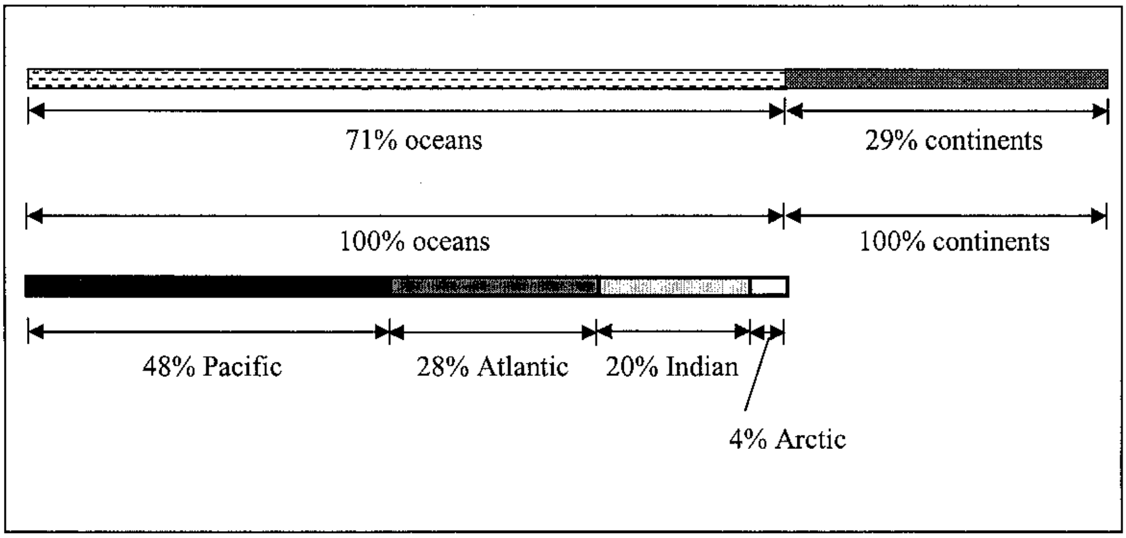


FIGURE 2.1 Distribution of land and water

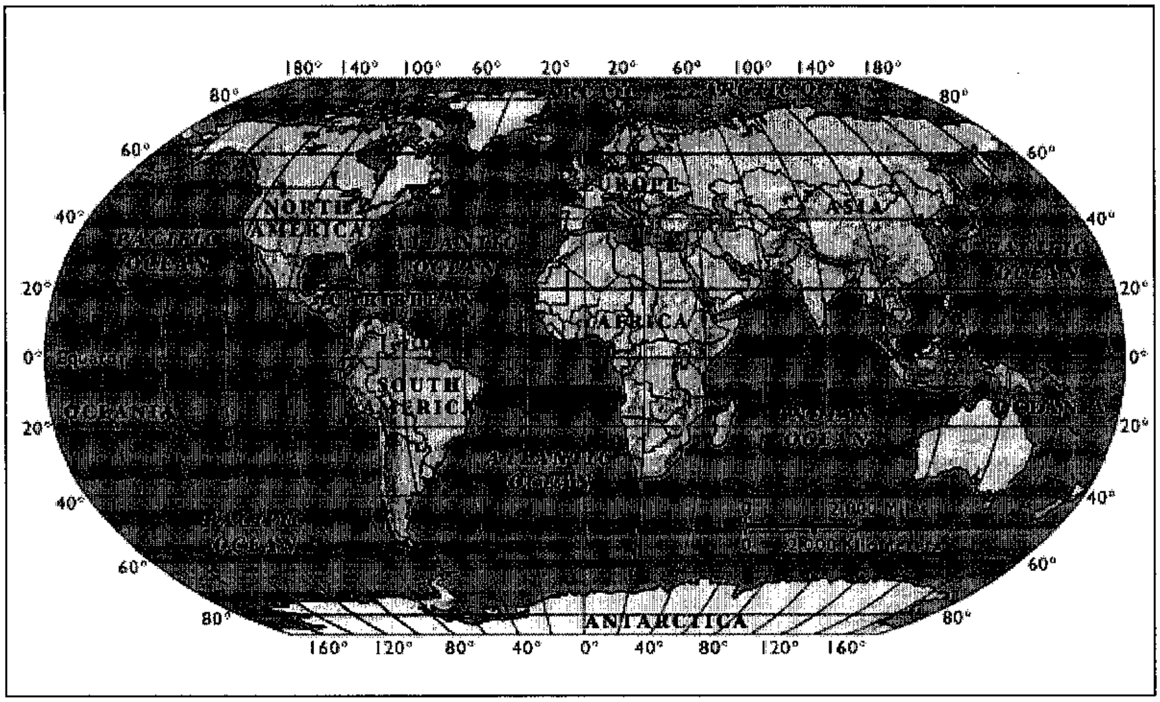


FIGURE 2.2 World oceans atlas

(*Source* : http:// www.welt-atlas.de)

[2]Garrison T., 2002

2.1 THE PACIFIC OCEAN

[3]The Pacific Ocean covers more than a third of the surface of the globe and is by far the world's largest ocean. It is also the deepest ocean, and the Mariana Trench of the Northwest Pacific is the deepest place on Earth, at about 7 miles (11 km) below sea level. Distances across the Pacific are equally daunting; from the equatorial west coast of South America to the easternmost islands of Indonesia is about 10,000 miles (16,000 km).

PACIFIC OCEAN : DATA FILE	
Area	64×10^6 mi^2 (166×10^6 km^2)
Average depth	13,741 feet (4,188 m)
Maximum depth	36,161 feet (11,022 m) – Mariana Trench
Volume of water	167×10^6 mi^3 (696×10^6 km^3)

Geology

Geologically, the Pacific Ocean basin is very active. It comprises one of Earth's largest crustal plates, and its mid-ocean ridges are constantly producing new ocean crust; indeed, the East Pacific Ridge is one of the world's fastest spreading plate boundaries. The oceanic crust on either side of the ridge is moving apart at the rate of around 15 cm (6.5 in) per year.

The edges of the plate submerge below surrounding plates so that the whole of the Pacific basin is encircled by destructive plate margins. This result in a ring of volcanoes, both active and dormant, that are a testament to the geological stresses generated by these boundaries called the Ring of Fire.

[3]All information on the five oceans are obtained from Day T., 1999

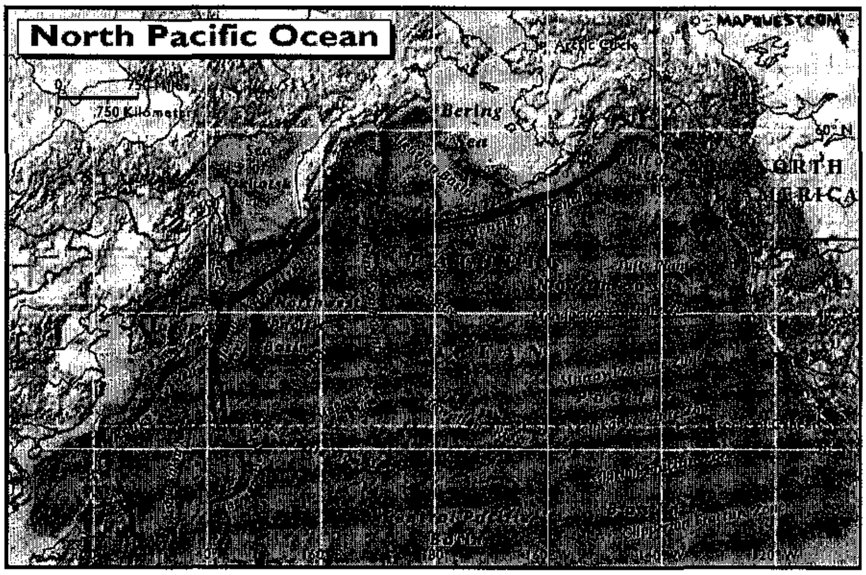


FIGURE 2.3 Bathymetry of North Pacific Ocean

(*Source* : http://www.mapquest.com)

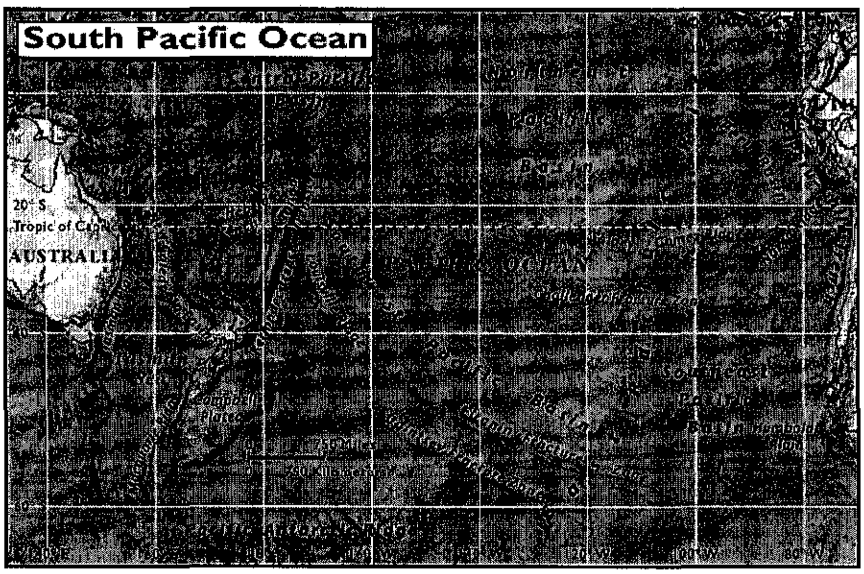


FIGURE 2.4 Bathymetry of South Pacific Ocean

Human Population

Bordering the Pacific Ocean are some of the world's most populous countries, including China, Japan and Russia to the west and the United States and Brazil to the east. These five alone make up more than one-third of the world's population. Based on the United Nations Human Development Index, most of the countries bordering the Pacific Ocean are among the most highly developed, with some exceptions such as Guatemala to the east and Vietnam, Cambodia and Papua New Guinea to the west. The islands of the South Pacific are not the idyll so commonly depicted, and levels of development are often low in these areas.

2.2 THE ATLANTIC OCEAN

The Atlantic, the second largest ocean, contains about one-quarter of the world's oceanic water and is about one-half the volume of the Pacific Ocean. Its most prominent underwater feature is the Mid-Atlantic Ridge that curves through the basin roughly halfway between North and South America to the west and the coast of Europe and Africa to the east. The Puerto Rico Trench, close to the West Indies, is the deepest part of the Atlantic, at more than 5.6 mi (9 km) below sea level.

ATLANTIC OCEAN : DATA FILE	
Area	32 x 10^6 mi^2 (84 x 10^6 km^2)
Average depth	12,612 feet (3,844 m)
Maximum depth	30,248 feet (9,219 m) – Puerto Rico Trench
Volume of water	77 x 10^6 mi^3 (323 x 10^6 km^3)

Geology

Geologically, the Atlantic Ocean basin is less obviously active than the Pacific. Along the zigzag middle line of the Atlantic basin, the Mid-Atlantic Ridge produces seafloor spreading at the rate of 0.4 – 0.8 in (1 – 2 cm) per year. There are only minor destructive plate boundaries, and these are found where continents are moving past one another, as in Atlantic-connected seas of the Caribbean and the Mediterranean. Thus the Atlantic Ocean is gradually expanding.

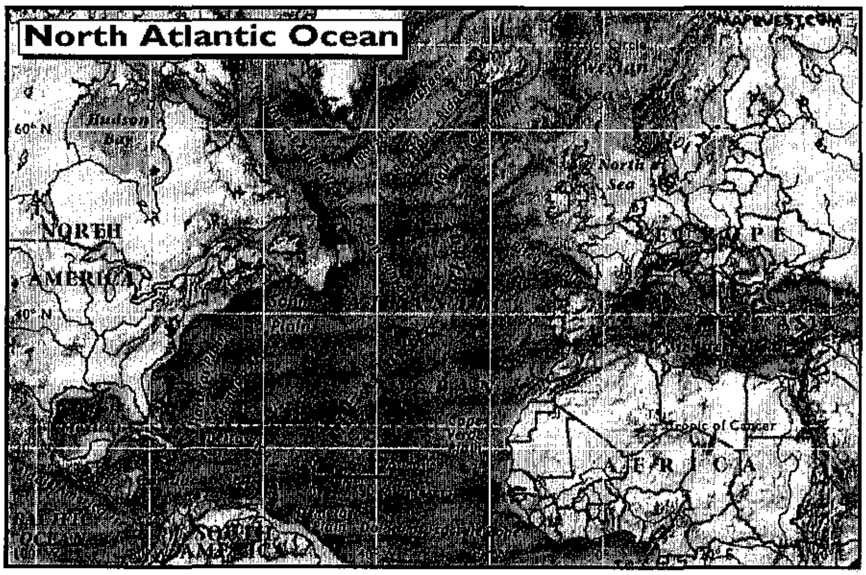


FIGURE 2.5 Bathymetry of North Atlantic Ocean

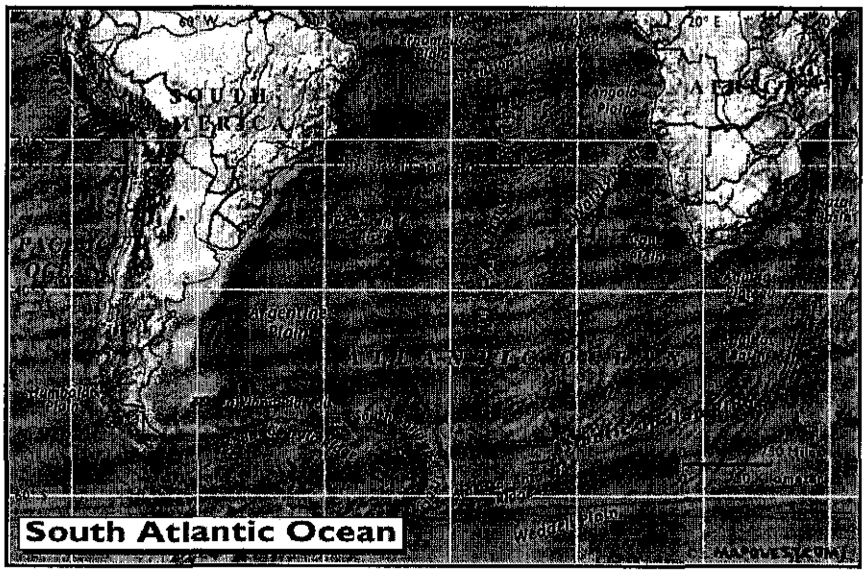


FIGURE 2.6 Bathymetry of South Atlantic Ocean

Human Population

Bordering the Atlantic Ocean is many of the world's most economically developed countries, particularly those of the North America and North-west Europe. Three of the world's largest cities, Buenos Aires, Rio de Janeiro, and Sao Paulo, are located along the east coast of South America and border the South Atlantic.

2.3 THE INDIAN OCEAN

The Indian Ocean, the third largest ocean, occupies about one-fifth of the world's surface area of oceanic water. The surface condition of the northern Indian Ocean; the Arabic Sea and the Bay of Bengal, are dominated by monsoon winds that reverse direction seasonally. Far south of the equator, the Indian Ocean basin opens out into the Antarctic Ocean and South Atlantic. The Indus and the Ganges-Brahmaputra, two of the world's largest river systems, empty into the Indian Ocean. They have created enormous fans of sediments brought down from erosion of the Himalayas, which in turn has created large areas of shallow water off the Indian coast.

INDIAN OCEAN : DATA FILE	
Area	28×10^6 mi^2 (73×10^6 km^2)
Average depth	12,704 feet (3,872 m)
Maximum depth	24,460 feet (7,455 m) – Sunda Trench
Volume of water	68×10^6 mi^3 (284×10^6 km^3)

Human Population

Countries bordering the north coast of the ocean; Pakistan, India, and Bangladesh, are among the poorest in the world. This is the most congested part and the highest population densities are often found in low-lying areas. When natural disasters strike the loss of life may be enormous. The countries of the North Indian Ocean contrast with

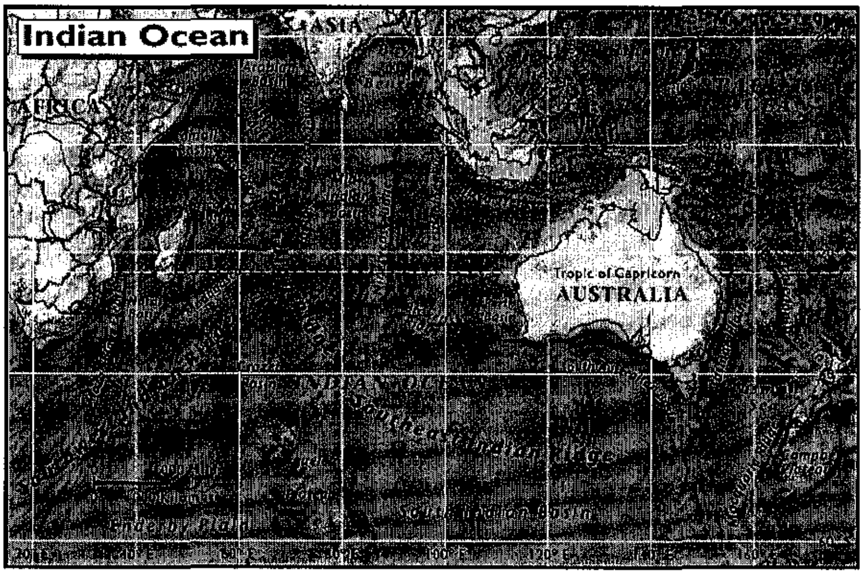


FIGURE 2.7 Bathymetry of Indian Ocean

the relatively affluent countries within Indonesia and Australasia to the east. Some oil-rich states, such as Oman and Iran, lie to the northwest. Five of the world's largest cities; Bangkok, Bombay, Calcutta, Karachi and Jakarta, lie on or near Indian coasts. Along the West Africa coast, most countries, except South Africa, are still relatively underdeveloped, and much of the activity in this region is at a subsistence level.

2.4 THE ARCTIC OCEAN

The Arctic Ocean around the North Pole is the world's smallest and shallowest ocean. Unlike other oceans, it is virtually surrounded by land. It is almost enclosed by Russia, Eurasia, Greenland, and North America and is contained by four major basins separated by three oceanic ridges; Alpha Ridge, Lomonosov Ridge and Nansen Cordillera. As an ocean, the Arctic is particularly unusual in having vast areas of continental shelf – up to 1600km wide off the Eurasian land-mass – forming extensive shallow areas. It is covered by a skin of floating ice to a depth of 10 feet (3 m) or so. During the winter, the sea ice extends over most of the Arctic Ocean; in summer, when temperatures rise well above freezing, the sea ice shrinks to about half that of the winter coverage.

ARCTIC OCEAN : DATA FILE	
Area	4.7×10^6 mi^2 (12.2×10^6 km^2)
Average depth	3,665 feet (1,117 m)
Maximum depth	17,878 feet (5,449 m) – Eurasian Basin
Volume of water	3.3×10^6 mi^3 (13.7×10^6 km^3)

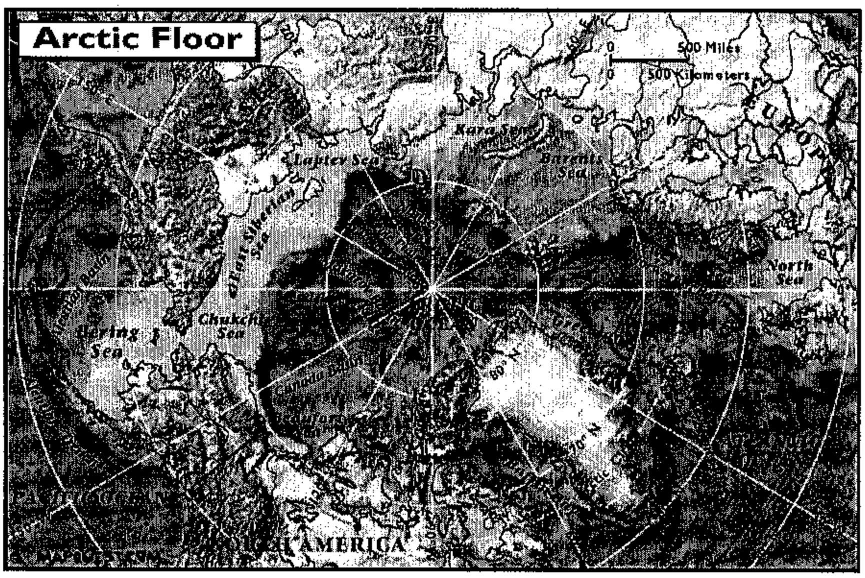


FIGURE 2.8 Bathymetry of Arctic Ocean

2.5 THE ANTARCTIC OCEAN

The Antarctic Ocean is, like the Arctic, extremely cold and substantially frozen. It is an open ocean that surrounds a continent, rather than an ocean enclosed by continents. Antarctica itself comprises an ice-covered landmass about twice the size of Western Europe and straddling the South Pole. The region contains about 90 percent of the planet's permanent ice; the South Polar icecap averages more than 1,600 m deep, compared to the few dozen meter at the North Pole.

ANTARCTIC OCEAN : DATA FILE	
Total area	13.5×10^6 mi^2 (35×10^6 km^2)
Area of permanent sea ice	1.2×10^6 mi^2 (3×10^6 km^2)
Total area of sea ice in winter	3.9×10^6 mi^2 (10×10^6 km^2)
Maximum depth	17,878 feet (5,449 m)

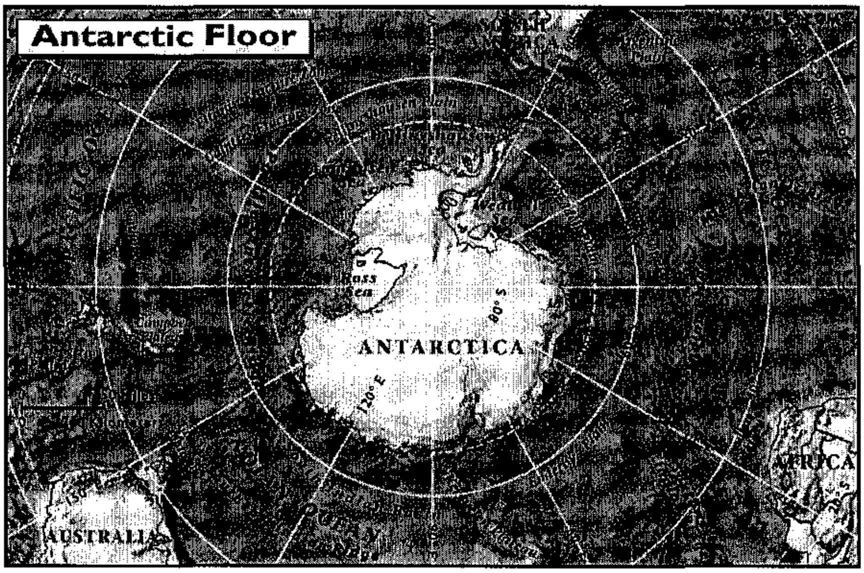


FIGURE 2.9 Bathymetry of Antarctic Ocean

In this project, the forecasting of tsunami travel time will covered these five oceans.

CHAPTER 3
TSUNAMIS

3.0 INTRODUCTION TO TSUNAMI

*Tsunamis are generated when an earthquake or volcanic eruption moves a section of seafloor or coast and produces abrupt displacement of the ocean water. Tsunamis are not related to tides, but are often incorrectly called "tidal waves". [4]The term tsunami was adopted for general use in 1963 by an international scientific conference. Tsunami is a Japanese word represented by two character : "tsu" and "nami". The character "tsu" means harbour, and the character "nami" means wave.

Tsunamis consist of a series of waves with extremely long wavelengths (typically 100 to 200 km) and periods (typically 10 to 30 minutes). Only a very small fraction of the ocean basin is deeper than 6 km and half of the ocean floor is less than 4 km deep. Hence, the water depth is almost always less than one twentieth of the tsunamis wavelength, which causes tsunamis to behave as shallow water waves. The speed of a shallow water wave is determined by the water depth. In water 4 km deep, tsunamis travel at approximately 200 m/s (720 km/hr), nearly the speed of a jet airliner. Because tsunamis are shallow water waves, their speed changes with depth and they are refracted as they pass over seafloor topography. Tsunamis can be spread out or focused by undersea ridges or depressions, just as wind waves are as they approach a coastline.

When the tsunami is over deep ocean waters, its wave height rarely exceeds one or two meters. Therefore, ships at sea are not affected by tsunamis. Indeed, it is almost impossible to detect a tsunami at sea because of its very long wavelength and limited wave height.

*For details on the life of tsunami refer Appendix 1

As a tsunami enters shallower water, it slows and its wavelength is reduced but its period is unchanged, as is true for any other wave. As a wave slows, the wave height increases. Because water depth is very small in comparison to a tsunami's wavelength, wave height builds very rapidly. The tsunami does not break like wind waves because its wavelength is so long that even a large increase in wave height does not produce steep unstable waves. Nevertheless, the leading edge of the tsunami wave can produce tremendous surf as it flows turbulently across the shore and coast.

The tsunami reaches shore as a wave that can be tens of meters high and can take 5 to 10 minutes to pass from trough to crest. As the tsunami moves inshore, sea level rises several meters above normal and enormous quantities of water are transported onshore and into any estuaries or rivers. The water simply keeps pouring onshore for several minutes as the wave crest approaches. The enormous energy stored in the wave is released as the water in the wave flows turbulently onto land and past any structures it encounters. Very strong currents and the equivalent of large breaking waves are generated as the water is concentrated in flows through harbours and channels and between structures. If the ocean is not calm when the tsunami arrives, wind waves will add to the tsunami wave and may contribute to the destruction as they break far inland from the normal surf zone.

[5]The impact that creates a tsunami may cause either a trough or a crest to be formed initially. At the coast, the first indication of the tsunami's arrival may be a rise in the normal level of the sea or a recession of the sea that lasts for several minutes and exposes large areas of seafloor that are not normally exposed. Regardless of whether a trough or crest arrives at the coast first, the tsunami will consist of several waves may be larger, but they eventually decrease in height. Waves can continue to arrive for 12 hours or more.

[4]The National Tsunami Hazard Mitigation Program
[5]Segar A.D., 1997

3.1 CAUSES OF TSUNAMIS

Tsunamis can be caused by a few different means:

1) the down drop or upthurst of the Earth's crust which results in an earthquake;
2) a large-scale undersea landslide;
3) a submarine volcanic eruption of a certain degree; or potentially,
4) a large meteor impact at sea.

The vast majority of tsunamis result from earthquakes.

How Earthquakes Cause Tsunamis

A tsunami begins with an undersea earthquake. The force jolts the ocean floor, displaces water, and produces waves. Slowing as they enter shallow water, the waves begin to pile up. The waves can rise 100 feet (30 1/2 meters) or higher. Sweeping onshore, the fearsome walls of water wreck property and take lives. Warning centers around the Pacific Ocean detect approaching waves and alert people so they can head for high ground.

Figure 3.1 below shows a subduction earthquake (one where a denser plates shifts below its neighboring plate, at left). Energy is transferred and the displaced water forms a wave. As the wave travels and enters shallower water in the coastal area, it begins to increase in amplitude.

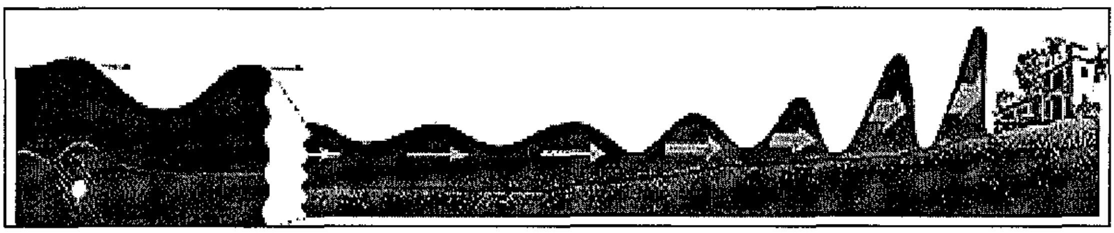


FIGURE 3.1 Killer wave
(*Source* : Tsunami- National Geographic Kids)

Tsunamis are not always colossal waves when they come into the shore. In fact, "...[6]most tsunamis do not result in giant breaking waves (like normal surf waves at the beach that curl over as they approach shore). Rather, they come in much like very strong and very fast tides (i.e., a rapid, local rise in sea level)". Nevertheless, there is destruction of life and of property by floating debris and impact of water. The tsunami produces a series of rushing waves and also a series of withdrawals.

In Figure 3.2 below, it can be seen that a tsunami is very fast (the speed often compared with that of a jet) and it has a height of 20 inches.

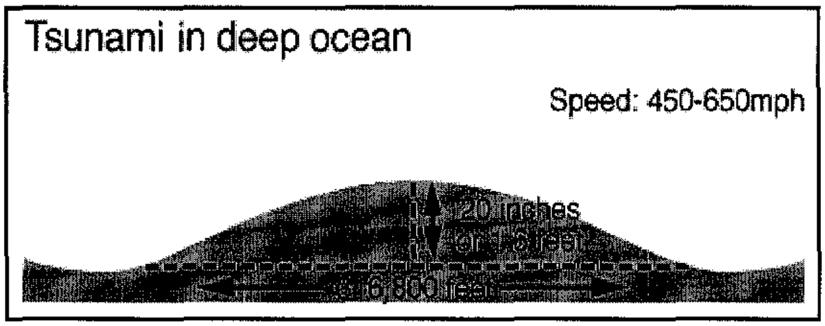


FIGURE 3.2 Tsunami in deep ocean

However, the effect of the tsunami reaching the shore is what needs to take into consideration. The speed is diminished but the wave height is increased drastically.

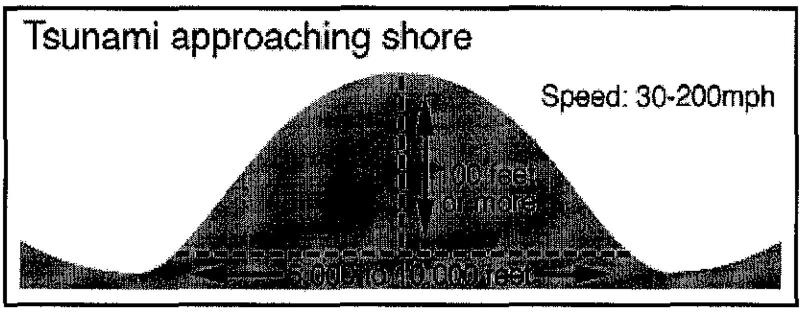


FIGURE 3.3 Tsunami as approaching shore
(*Source* : The Physics Behind The Wave)

[6]USGS, Western Coast and Marine Geology

How Volcanoes Cause Tsunamis

[7]There are two different ways that volcanoes can cause seismic waves. One possibility is for a land-based volcano to break down and collapse, forcing large amounts of ash and debris into the water. This sudden change and displacement of the water column, transfers to kinetic energy and results in waves. More debris can create a bigger increase in wave amplitude and number. Tsunamis can also be induced by submarine volcanoes. These underwater volcanoes can collapse downwards or spew forth lava heating the surrounding water quickly.

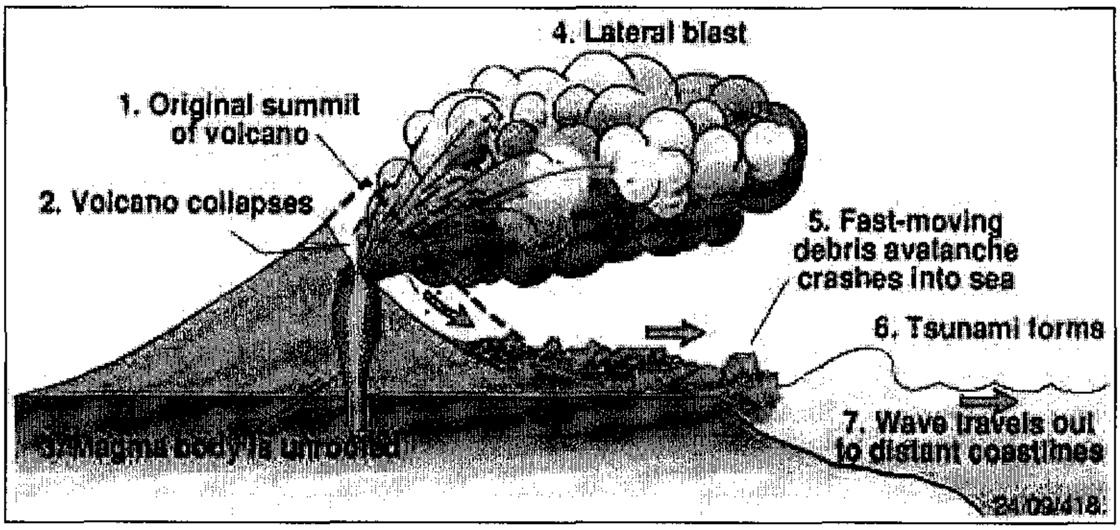


FIGURE 3.4 Schema of a volcanic eruption

How Landslides Cause Tsunamis

Less frequently, tsunami waves can be generated from displacements of water resulting from rock falls, icefalls and sudden submarine landslides or slumps. Such events may be caused impulsively from the instability and sudden failure or submarine slopes. Landslides are similar to volcanoes that avalanche into the sea. They occur in the water and often are triggered by earthquakes.

[7]Lindsay Springer,

There is an instance in 1958 where a tsunami was caused by rockfall in Lituya Bay, Alaska. In this instance, a gigantic boulder was loosed by an earthquake along the Fairweather fault and [8]approximately 40 million m^3 rock fell into the bay causing a tsunami that went out to sea. The generated wave reached an incredible height of 520 m on the opposite side of the inlet. An initial huge solitary wave of about 180 m raced at about 160 km/hr within the bay debarking trees along its path. However, the tsunami's energy and height diminished rapidly away from the source area.

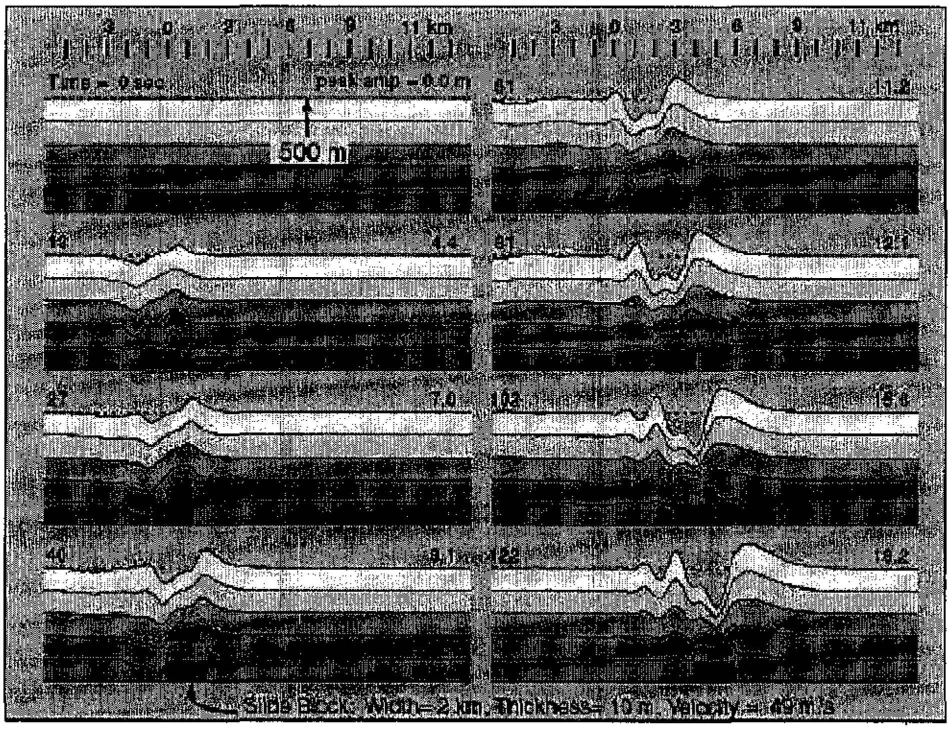


FIGURE 3.5 Tsunami generated form seafloor landslide

3.2 GEOGRAPHY OF TSUNAMIS

[9]81 percent of the world's largest earthquake and about 90 percent of all tsunamis occur in the Pacific Ocean, where it is encircled by a 40,000 km long of the Ring of Fire, shown in Figure 3.6. Ring of Fire is a zone of frequent earthquake and volcanic eruptions. It is associated with a nearly continuous series of oceanic trenches, island arcs, and volcanic mountain ranges and/or plate movements.

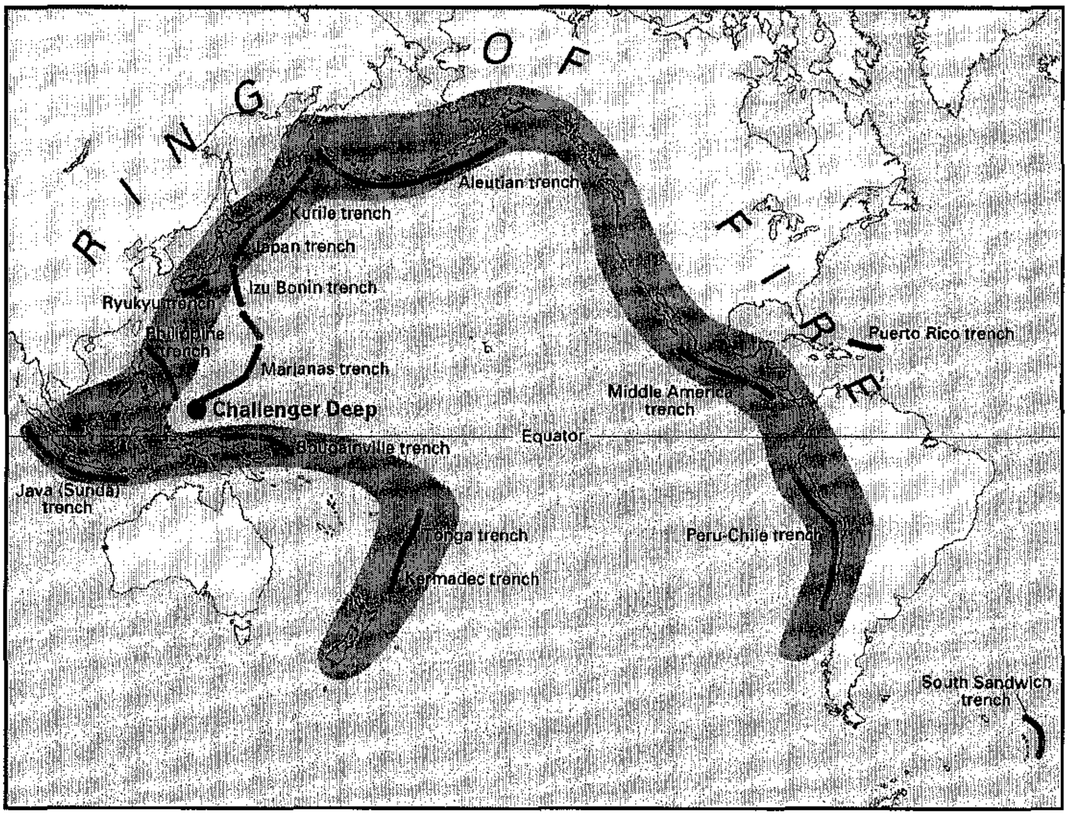


FIGURE 3.6 The Pacific Ring of Fire
(*Source* : US Geological Survey (USGS))

Statistical data extracted from the National Oceanic and Atmospheric Administration (NOAA) indicates that most of the source of tsunami is caused by earthquake. Figure 3.7 below shows the allocation of causes of tsunamis from the year before century up to 2005. By far, the most destructive tsunamis are generated from large, shallow earthquakes with an epicentre or fault line near or on the ocean floor. Second largest contributor to tsunami is identified as null due to lack of proved evidence on the causes where most of these events occurred at the early years of before century.

[8]http://www.extremescience.com/BiggestWave.htm
[9]http://en.wikipedia.org/wiki/Pacific_Ring_of_Fire

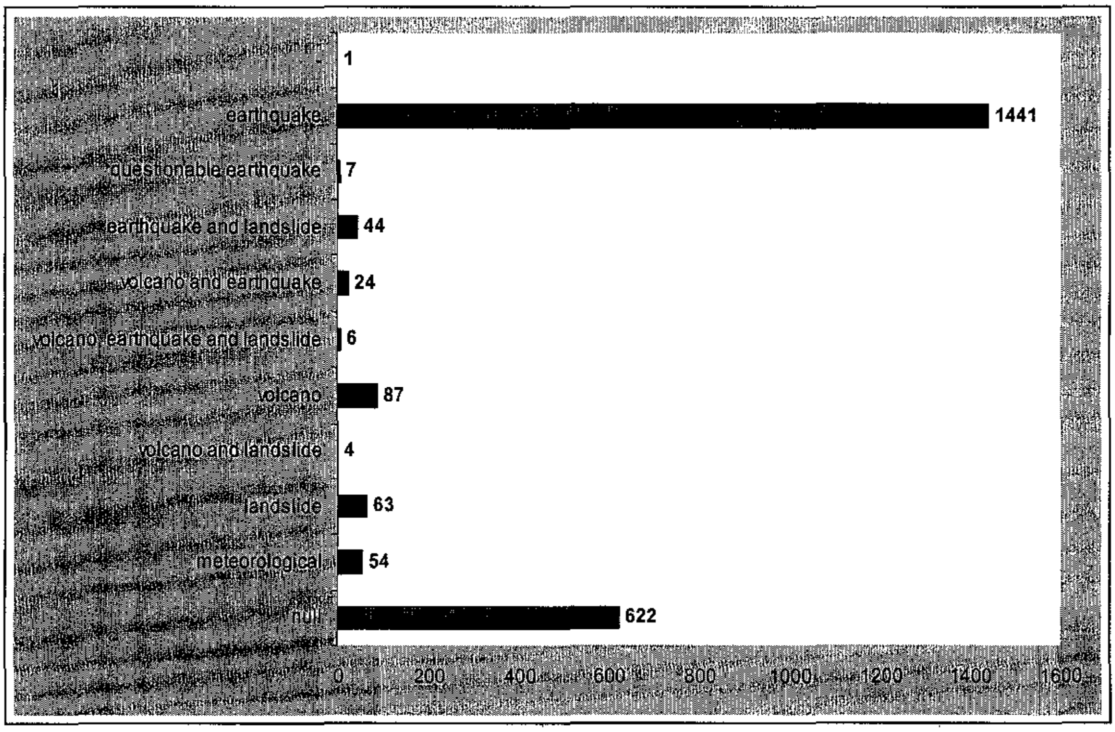


FIGURE 3.7 Tsunami data from -2000BC to 2005

(*Source* : National Oceanic and Atmospheric Administration (NOAA))

Data shown below representing the distribution of tsunamis in the world's oceans and seas :

TABLE 3.1 Location and percentage distribution of tsunami

Location	Percentage, %
Atlantic East Coast	1.6
Atlantic West Coast	0.4
Mediterranean	10.1
Caribbean	13.8
Bay of Bengal	0.8
East Indies	20.3
Oceania	25.4
Japan-Russia	18.6
Pacific East Coast	8.9

(*Source* : http://www.smithsonianmag.com/)

3.3 TSUNAMI WARNING SYSTEM

A tsunami warning system is a system to detect tsunamis and issue warnings to prevent loss of life and property. It consists of two equally important components : a network of sensors to detect tsunamis and a communications infrastructure to issue timely alarms to permit evacuation of coastal areas.

There are two distinct types : international tsunami warning systems, and regional warning systems. Both depend on the fact that, while tsunamis travel at between 500 and 1,000 km/h in open water, earthquakes can be detected almost at once as seismic waves travel with a typical speed of 4 km/s. This gives time for a possible tsunami forecast to be made and warnings to be issued to threatened areas, if warranted. Unfortunately, until a reliable model able to correlate earthquakes to tsunami is available alarms raised measuring only seismic waves should be considered only as warnings. To be sure, tsunami waves must be observed in open water as far as possible by the coast, using real time operating seafloor observatories.

3.3.1 International Warning Systems (IOC)

Pacific Ocean

Tsunami warnings for most of the Pacific Ocean are issued by the Pacific Tsunami Warning Center (PTWC), operated by the United States's NOAA in Ewa Beach, Hawaii. NOAA's West Coast/Alaska Tsunami Warning Center (WC/ATWC) in Palmer, Alaska issues warnings for the west coast of North America, including Alaska, Canada, and the western coterminous United States. PTWC was established in 1949, following the 1946 Aleutian Island earthquake and a tsunami that resulted in 165 casualties on Hawaii and Alaska; WC/ATWC was founded in 1967. International coordination is achieved through the International Coordination Group for the Tsunami Warning System in the Pacific, established by the Intergovernmental Oceanographic Commission of UNESCO.

Indian Ocean (ICG/IOTWS)

In response to the 2004 Indian Ocean Tsunami which killed more than 200,000 people, a United Nations conference was held in January 2005 in Kobe, Japan, and decided that as an initial step towards an International Early Warning Programme, the UN should establish an Indian Ocean Tsunami Warning System.

North Eastern Atlantic, the Mediterranean and connected Seas (ICG/NEAMTWS)

The First Session of the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and connected Seas (ICG/NEAMTWS), established by the Intergovernmental Oceanographic Commission of UNESCO Assembly during its 23rd Session in June 2005, through Resolution XXIII.14, took place in Rome on 21st and 22nd November, 2005. The Meeting, hosted by the Government of Italy (Italian Ministry of Foreign Affairs and Ministry for Environment and Protection of the Territory), was attended by more than 150 participants from 24 countries, 13 organizations and numerous observers.

3.3.2 Regional warning systems

Regional (or local) warning system centres use seismic data about nearby earthquakes to determine if there is a possible local threat of a tsunami. Such systems are capable of issuing warnings to the general public (via public address systems and sirens) in less than 15 minutes. Although the epicenter and moment magnitude of an underwater quake and the probable tsunami arrival times can be quickly calculated, it is almost always impossible to know whether underwater ground shifts have occurred which will result in tsunami waves. As a result, false alarms can occur with these systems, but due to the highly localised nature of these extremely quick warnings, disruption is small.

Few of the organizations are given in Appendix 2 for reference.

3.4 PREVIOUS TSUNAMIS

Tsunamis occur most frequently in the Pacific Ocean, but are a global phenomenon; they are possible wherever large bodies of water are found, including inland lakes, where they can be caused by landslides. Very small tsunamis, non-destructive and undetectable without specialized equipment, occur frequently as a result of minor earthquakes and other events. List of past tsunamis are shown in the Appendices 3 to 8 attached. Since most of the tsunamis are caused by earthquakes, Appendix 9 shows lists of significant earthquakes occurred for the past decades.

3.5 TSUNAMIS SYNDROME AND ITS LOCAL EFFECTS

Tsunamis are always triggered by the simultaneous or advance occurrence of a large earthquake, a volcanic eruption or caldera collapse, an earth landslide, or a submarine slumps, among other possible causes. Near the source, the arrival of a local tsunami resembles the concurrence of several phenomena running together, whose noticeable effects may happen almost simultaneously. [10]The main effects of the interaction of this tsunami syndrome with the coast are :

a. Sinking or rising sea-level and/or land-level in short (hours) or long term (years)
b. Inundation and currents
c. Earth landslide and/or submarine slumps
d. Soil deformation and/or liquefaction
e. Sediment : erosion-transport-deposition
f. Vegetation : uprooting-destruction-immersion
g. Exposure of the subaqueous (below inter-tidal level) marine life
h. Salt water penetration into the inland soil
i. Shoreline alteration
j. Destruction and damage to human life, man-made structures and infrastructure
k. Inland and seaward transport of objects (ships, vehicles, structures)

[10] Woo G., 1999

Example of disastrous damage is the Asian Tsunami (3.316°N, 95.854°E) where a great earthquake occurred at 6.58am local time, on Sunday, 26 December 2004. The magnitude 9.0 event was located off the West coast of Northern Sumatra. By 30 December 2004 the death toll from the Asian tsunami disaster has risen to over 100,000 people, and by 05 January 2005 the number approaches 150,000.

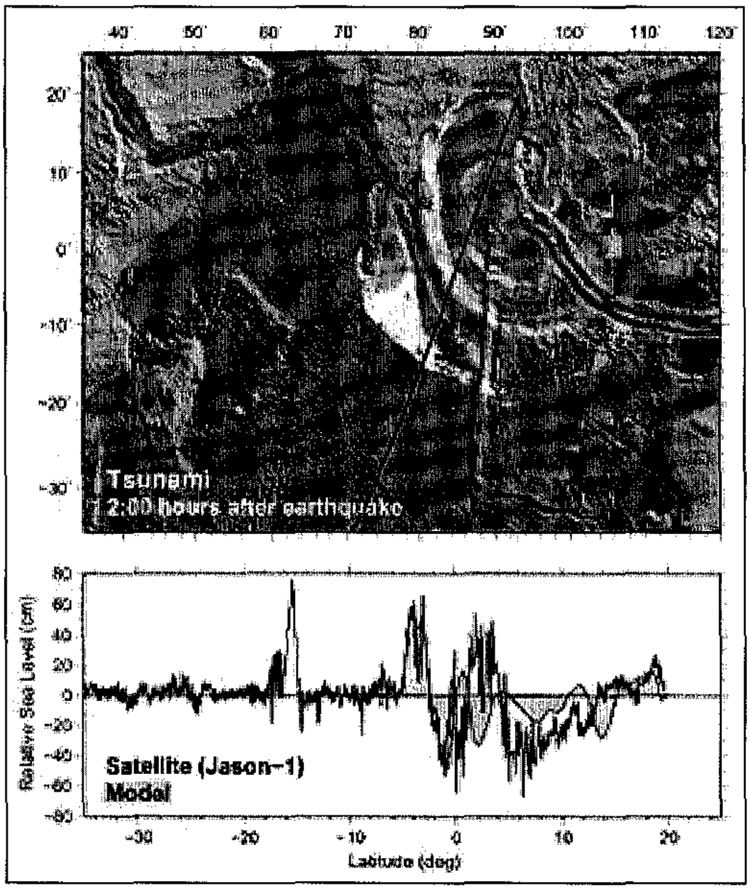


FIGURE 3.8 Radar imaging of the tsunami two hours after the earthquake
(*Source* : Wikipedia)

[11]In Sri Lanka, the southeastern coastline coastline was the worst hit. Almost the entire seafront was obliterated, with no buildings within 100 meters of the waterfront escaping undamaged. In India the Andaman Islands, Nicobar Islands, Kerala, Tamil Nadu, Chennai, Andhra Pradesh were all affected.

[11] All information on the damages is from GlobalSecurity.org

With half of the casualties being reported from Sumatra, Indonesia-the region nearest to the earthquake's epicenter-international relief organization officials warn that the overall casualty figures could rise to over 100,000. The death toll in Indonesia's Aceh province from a quake and tsunami that struck on Sunday might reach between 50,000 and 80,000. There were about 10,000 deaths in Meulaboh, the south-coast town nearest to the epicenter. Surveillance from flights over the town indicated it had been "wiped out", with up to 80 percent of buildings destroyed, raising fears for the fate of the area's 100,000 residents.

In Thailand, this caused great loss of life and destruction to buildings and infrastructure in Phuket, Phi Phi Island, Krabi, and other smaller islands in that vicinity. Along the eastern coast of Phuket island, waves crashed over Rassada Pier as passengers were waiting to board ferries for Phi Phi Island. The Laguna Phuket was protected from a direct hit by the headland to its South and thus spared the serious damage reported from other areas of the island. Other areas affected included Bang Tao Beach, Kamala Beach, Patong Beach, Kata Beach, Karon Beach, Nai Harn Beach and Phuket Fantasea. There was total destruction of resort properties and infrastructure on the Phi Phi islands, and all operations had ceased. Phuket's Patong beach along the west of the island took the bulk of the damage, and two-thirds of Thailand's fatalities occurred there.

The Maldives's only international airport on the tiny island of Hulule reopened early on 27 December, after workers pumped out water that had inundated the runway. The entire island of Dhiffushi, a prime tourist destination, was submerged and would have to be rebuilt.

In Myanmar damage was reported only in the southern archipelago, with minimal to no impact reported at Ngapali, Chauntha, and Ngwe Saung beaches. Praslin Island in Seychelles was also hit

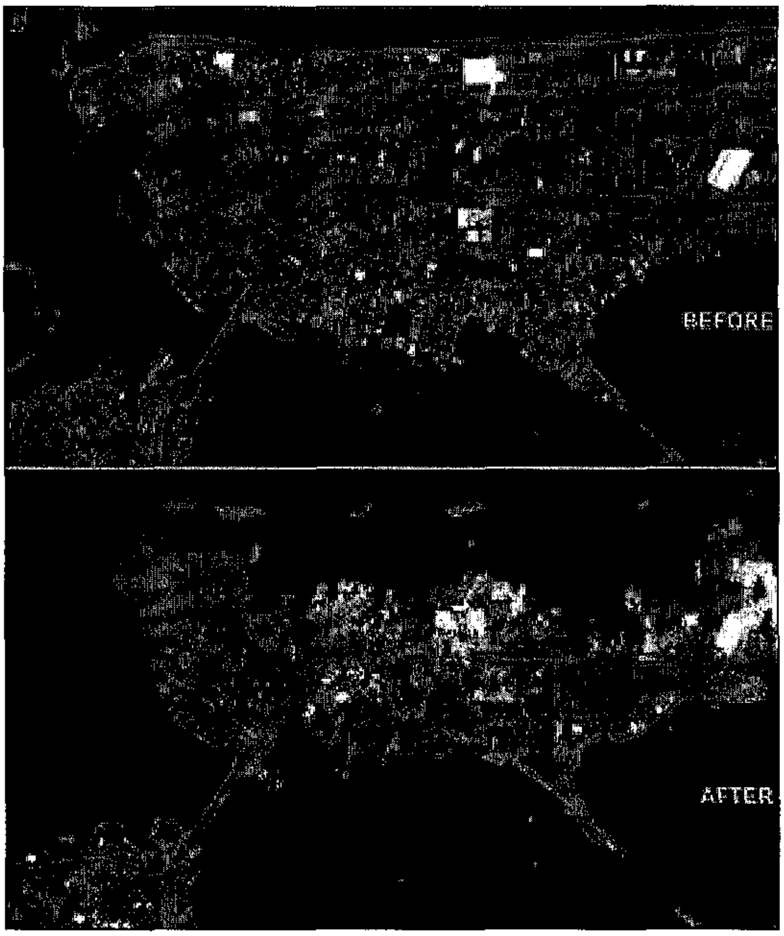


FIGURE 3.9 Part of the devastation of Banda Aceh on the island of Sumatra
(*Source* : Wikipedia)

In April 2005 the number of people killed in the December 26 tsunami disaster which devastated 11 Indian Ocean countries has been revised down to 217,000 after Indonesia drastically reduced its number of missing.

CHAPTER 4
TSUNAMI'S SPEED AND HEIGHT

Tsunami waves can engulf a coastal community within minutes of their birth and cause loss of life, catastrophic destruction to structures and infrastructure, and severe erosion of the shoreline by hours of repeated attack of waves many minutes apart.

Tsunami is a large sea wave that can be generated by a major disturbance producing a vertical displacement of the sea floor resulting in the displacement of a large volume of water. Once formed, this wave surges outward in all direction.

Tsunamis are shallow-water waves, which mean that the ratio between water depth and wavelength is very small. Its speed depends upon the depth of the water, and consequently the waves undergo accelerations or decelerations in passing respectively over an ocean bottom of increasing or decreasing depth. By this process the direction of wave propagation also changes, and the wave energy can become focused or defocused.

To simulate the progress of the tsunami, several hydrodynamic models are required. The first is a model for ocean propagation of the tsunami. For a large earthquake, a tsunami will be tens of kilometres wide, and of the order of 100 km long, and have a height typically around 10 m or less. [10]Given that the ocean depth y is generally not more than a few kilometres, the use is justified of shallow-water (long wave) fluid dynamical theory as a first-order approximation, yielding gravity waves travelling with speed shown in equation 1 below. This equation will be used throughout this study in order to achieve the objective of the project.

[10]Woo G., 1999

$$v = \sqrt{gy} \qquad (1)$$

where v is the speed of tsunami

g is the acceleration of gravity

y is the ocean depth

[12]A useful measure of depth effect is the scattering index, S, derived from the theory of lineal ridge scattering.

$$S = 1 - T_{min} \qquad (2)$$

Here $T_{min} = 2\epsilon / (1 - \epsilon^2)$, where $\epsilon \equiv \sqrt{H_1 / H_O}$. This index provides an effective tool for identifying those topographic features in the ocean that are likely to scatter or reflect significant tsunami wave energy.

The initial height of tsunami wave is usually the order of vertical bottom displacement, while the initial length of tsunami wave is the size of the disturbed area. As the tsunami travels to nearshore, the water depth decreases, the tsunami waves slow down and become compressed, causing them to grow in height (shoaling process).

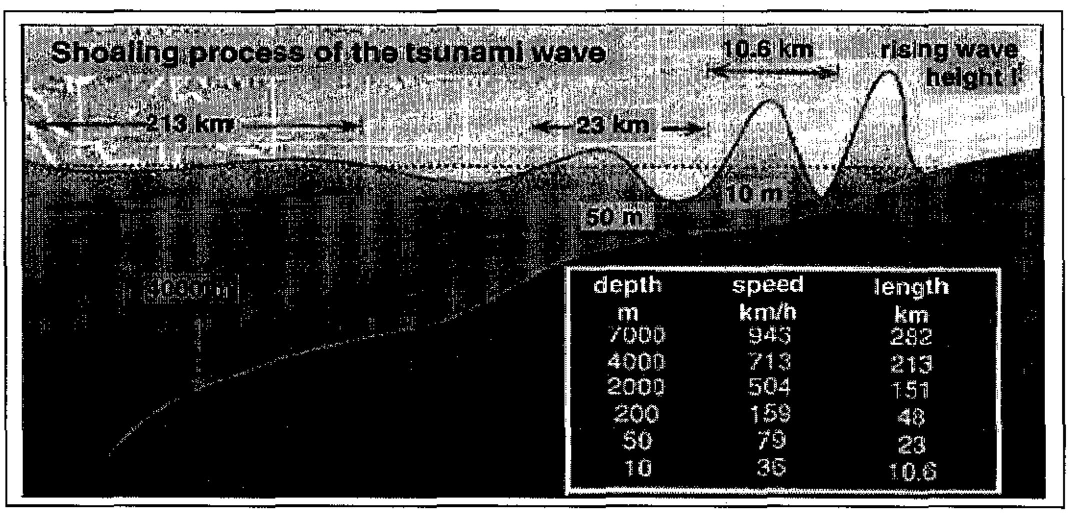


FIGURE 4.1 The shoaling process of tsunami wave

(*Source* : Indian Ocean Tsunami)

As a tsunami enters shallow water and approaches a shore, it increases in height, steepness, and curvature of water surface, as kinetic energy is transformed to gravitational potential energy. To compute the runup of a tsunami onshore, it is necessary to calculate the motion of an offshore long wave evolving over variable depth. This calls for solution of the nonlinear shallow-water equations in the nearshore region. If u and v are depth-averaged velocities in the onshore x and offshore y directions, and h is the tsunami wave height :

$$\begin{aligned} \frac{\delta h}{\delta t} + \frac{\delta(uh)}{\delta x} + \frac{\delta(vh)}{\delta y} &= 0 \\ \frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} + g\frac{\delta h}{\delta x} &= g\frac{\delta d}{\delta x} \\ \frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} + g\frac{\delta h}{\delta y} &= g\frac{\delta d}{\delta y} \end{aligned} \tag{3}$$

In the deep ocean, tsunami waves can travel at speeds of 500 to 1,000 kilometres per hour. Near shore, however, a tsunami slows down to just a few tens of kilometres per hour. For example, at the deepest ocean depths the tsunami wave speed will be as much as 800 km/hr, about the same as that of a jet aircraft. Since the average depth of the Pacific Ocean is 4000m, tsunami wave speed will average about 200m/s or over 700km/hr.

As the tsunami wave reaches the shallower water above the continental shelf, friction with the shelf slows the front wave. The wavelength shortens, and the height increases. As the wave approaches shore, large volume of water is withdrawn as wave rises seaward. As the leading edge of the tsunami encounters shallow water so it slows down faster than the trailing edge (Figure 4.2). This then increases the height.

[12]Mofjeld H. O., 2000

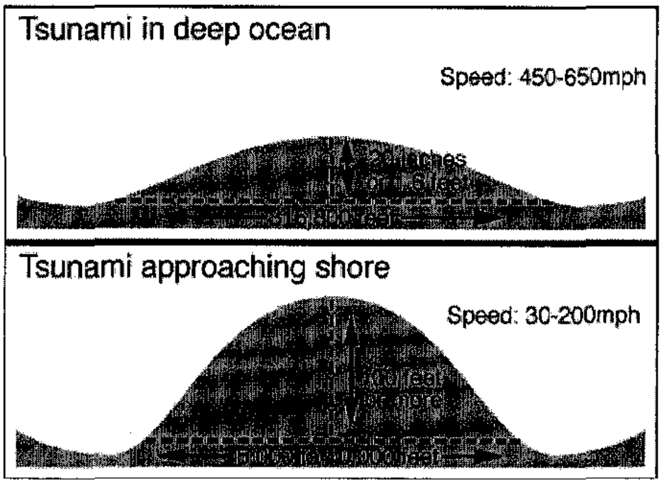


FIGURE 4.2 In deep water the Tsunami cannot be noticed, but in shallow water it rapidly increases in height as it slows.
(*Source* : Annunziato A., Best C., 2005)

[13]From conservation of energy, wave height varies with depth as in equation below. A tsunami that is just a meter in height in the deep ocean can grow to tens of meters at the shoreline. Unlike familiar wind-driven ocean waves that are only a disturbance of the sea surface, the tsunami wave energy extends to the ocean bottom. Near shore, this energy is concentrated in the vertical direction by the reduction in water depth, and in the horizontal direction by a shortening of the wavelength due to the wave slowing down.

$$H_2 = H_1 \sqrt{(c_1 / c_2)} = H_1 \, (y_1 / y_2)^{1/4} \qquad (4)$$

where H is the wave height
c is the speed of tsunami
y is the ocean depth

Another equation obtained from Lab Math, Indonesia (No. 1 Vol. 1, September 2005), it simply states the result that amplitude is related to depth according to

$$a^2 \sqrt{y} = \text{constant}$$

and so

$$a \sim 1 / \sqrt[4]{y} \qquad (5)$$

The relationship of equation (5) shows that the wave height of a tsunami wave travelling into shallow water is increasing by wave shoaling. In addition, the wave length is decreasing resulting in a steeper wave. Thus, shoaling is an important effect to be considered.

The bay effect can be calculated by Green's law :

$$\frac{H_x}{H_o} = \sqrt[2]{\frac{b_o}{b_x}} \sqrt[4]{\frac{d_o}{d_x}} \qquad (6)$$

where H is wave height

b is width of the bay

d is water depth

index o is offshore

index x is onshore

Based on a compilation of historic, largely Pacific Ocean, data, Abe (1979) proposed the following equation for estimating the wave height, H, of a tsunami at a distant shore due to an earthquake of magnitude M_w

$$H = 10\text{\^{}}(M_w - B) \qquad (7)$$

where B is a parameter that varies for each site and earthquake source. B can be determined using either historical data, or numerical modeling, or a combination of both. The data that Abe (1979) based this equation on has considerable scatter, so the relationship has significant uncertainty.

[13]Hinwood J., 2005

Height of wave at shoreline is dependent on the coastline topography as well.

1. A submerged valleys cause refraction outward making smaller wave at shoreline at head of submerged valley.
2. Platform extending seaward causes inward refraction, making larger wave at shoreline behind the extension.
3. Coastal valleys funnel wave into increasingly narrow area causing wave height to increase inland.

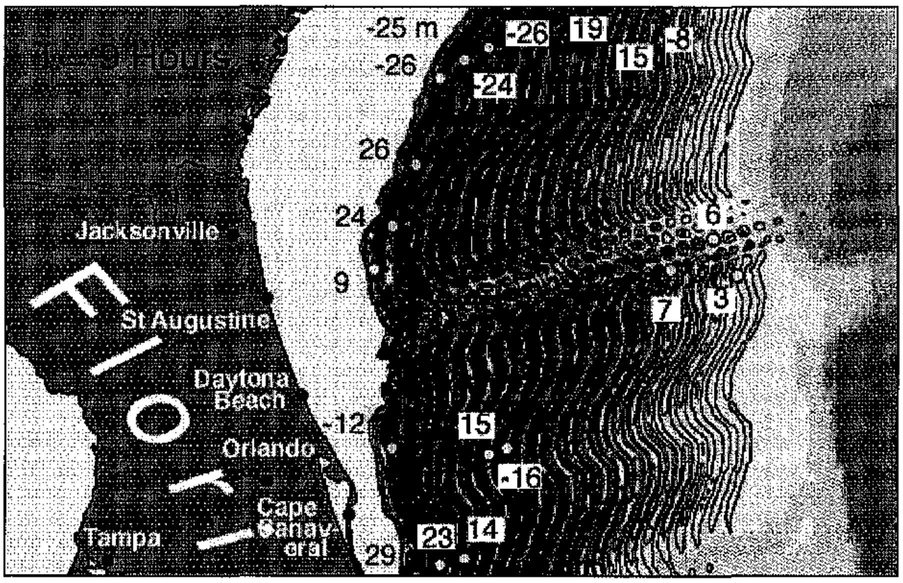


FIGURE 4.3 Evolution of wave height, in meters, as it is approaching shoreline (*Source* : Ward S. N., Day S.)

Tsunamis have periods (the time for a single wave cycle) range from just a few minutes to as much as an hour or exceptionally more. At the shore, a tsunami can have a wide variety of expressions depending on the size and period of the waves, the near-shore bathymetry and shape of the coastline, the state of the tide, and other factors. Other features which influence the size of a tsunami along the coast are the shoreline configuration, the velocity of the sea floor deformation, the slope of the basin and the efficiency which energy is transferred from the earth's crust to the water column.

CHAPTER 5
DATA COLLECTED

5.0 MAJOR SEA PORTS

38 main ports and terminals around the world have been identified as shown in Appendix 10. Most of these ports and terminals were selected based on their position and exposure to open seas as well as their economic activities. Ports exposed to open seas have the potential to be badly damaged once hit by a destructive tsunami. Ports surrounded by headlands and channel are selected as well considering the effect of refraction, reflection and diffraction of water waves towards these ports. However, further studies need to be carried out to determine the impact of tsunami towards these later ports.

5.1 ETOPO-2

As mentioned earlier in Chapter 4, the tsunami's speed and height are both affected by the ocean's floor profile. ETOPO-2 software developed by National and Atmospheric Administration, NOAA is used in obtaining the profile of the oceans especially for Pacific, Atlantic and Indian oceans. It is a digital database of seafloor and land elevations on a 2-minute latitude/longitude grid. (1 minute of latitude = 1 nautical mile, or 1.852 km). Figure 5.1 to 5.3 below show examples of the software.

ETOPO-2 covers 360 degrees of longitude from 180 West eastward to 180 East and latitude coverage is from 90 degrees North to 90 degrees South. The resolution of the grid data varies from true 2-minute for the Atlantic, Pacific, and Indian Ocean floors and all land masses to 5 minutes for the Arctic Ocean floor.

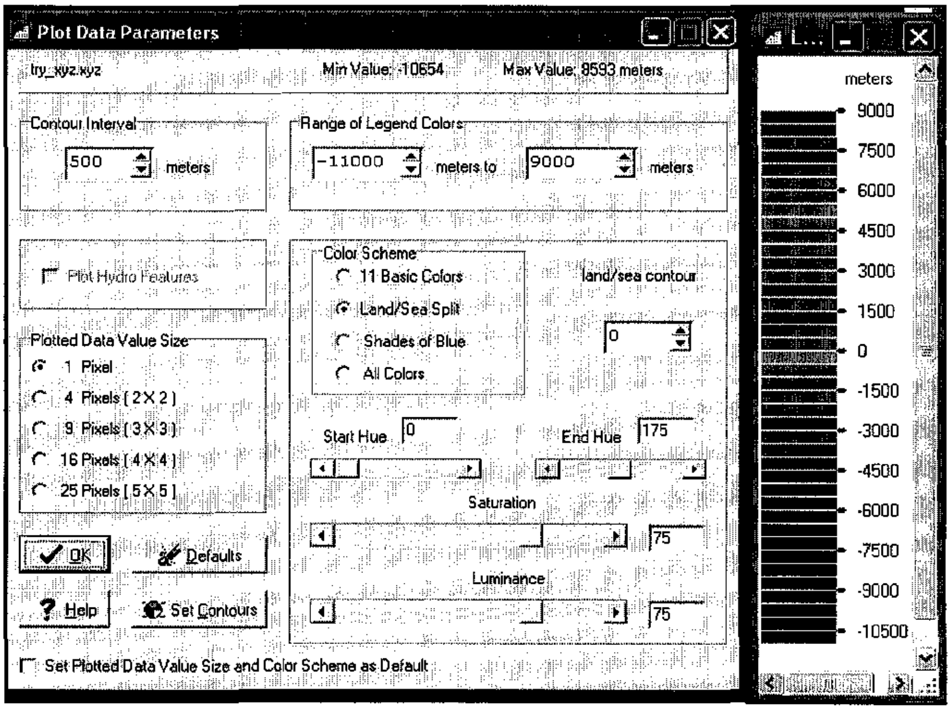


FIGURE 5.1 Example of ETOPO-2 Software

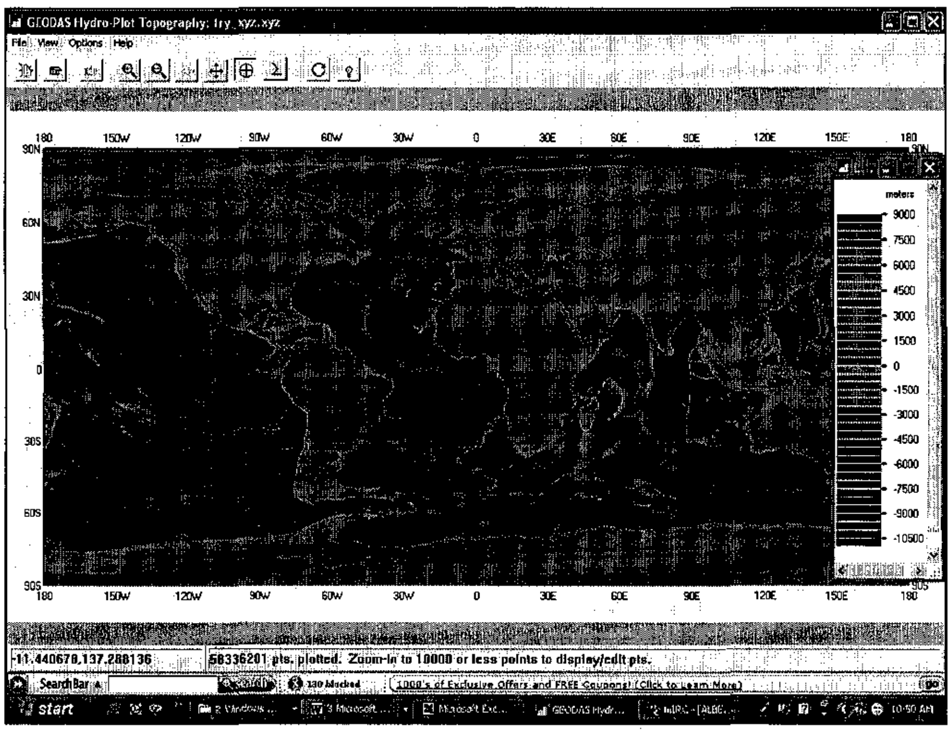


FIGURE 5.2 View of 58336201 points plotted on ETOPO-2

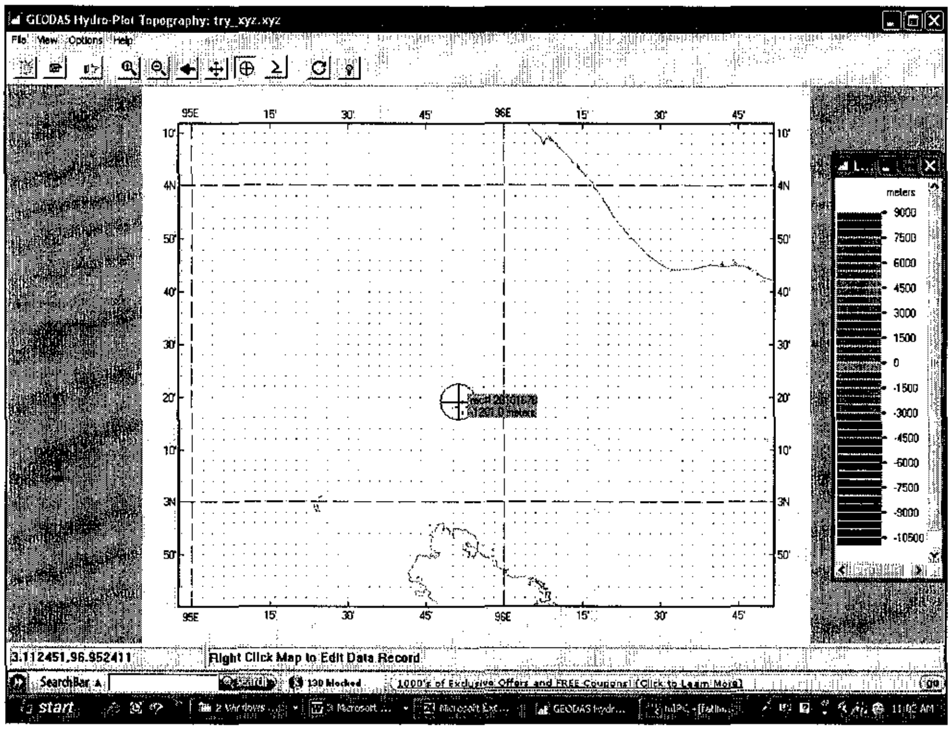


FIGURE 5.3 Zoom to 10000 or less points to display or edit points

5.2 RELATIONSHIP BETWEEN BATHYMETRIC AND TRAVEL TIME

Throughout this chapter, only the speed of a tsunami wave will be discussed based on equation (1) in Chapter 4. Figure 5.4 below shows the Asian Tsunami travel time obtained from JRC Model; an online tsunami propagation model, that occurred on December 26, 2004 with an epicentre 3.316^{o} N 95.854^{o} E.

Four locations (L1, L2, L3 and L4) were selected and the bathymetric profile along these rays where plotted by using ETOPO-2 (Figure 6.1). Equation of $v = \sqrt{gy}$ is used to calculate the tsunami's speed from this epicenter towards each four rays. The travel time can be calculated where $dt = dx / v$, which will be discussed in Chapter 6. The same procedures were done on various historic tsunamis to come out with a conclusion. The locations selected are actually the countries affected by the tsunamis and their actual travel time will then be compared with the calculated one.

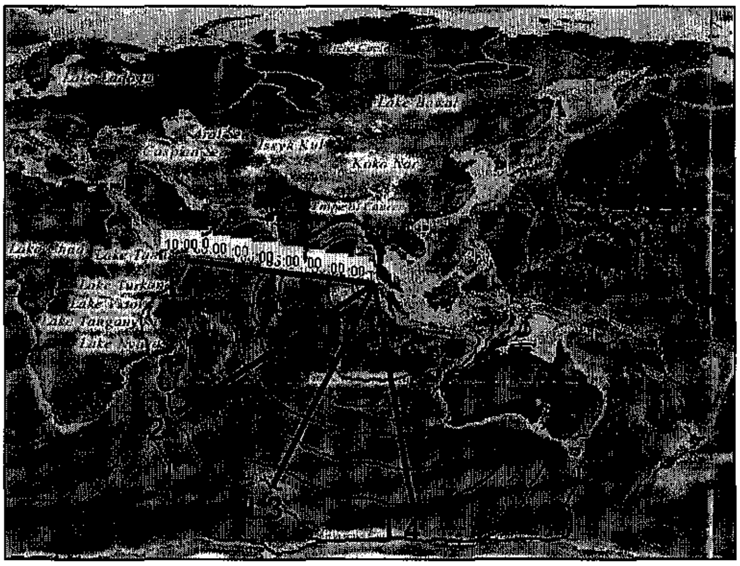


FIGURE 5.4 Asian Tsunami travel time

(*Source* : http://www.tsunami.jrc.it/model)

Tsunamis have the potential to threaten harbours or ports due to its location; closer to open ocean. Travel time of various tsunamis observed towards a selected port namely Port Los Angeles is compared with the equation of $v = \sqrt{gy}$ by conducting the same procedures mentioned above.

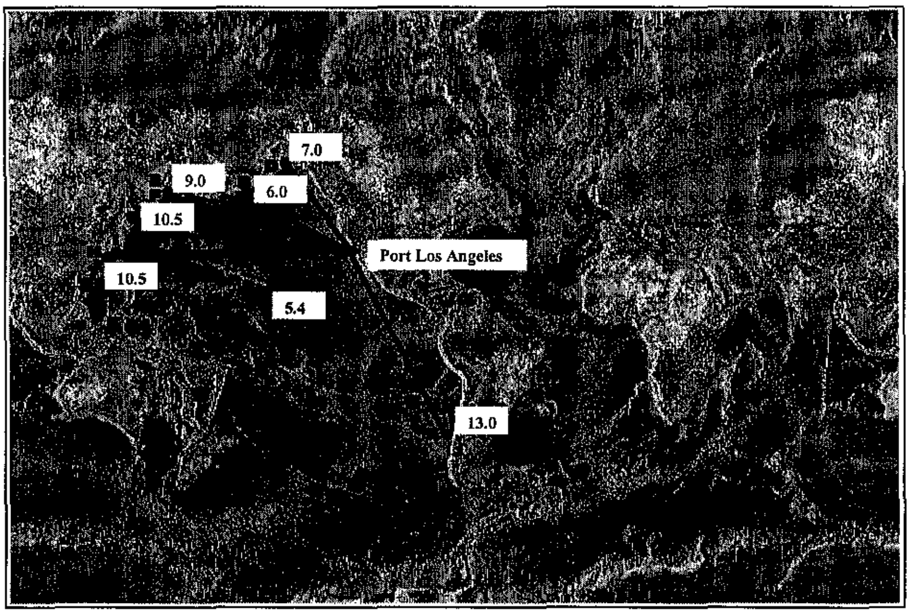
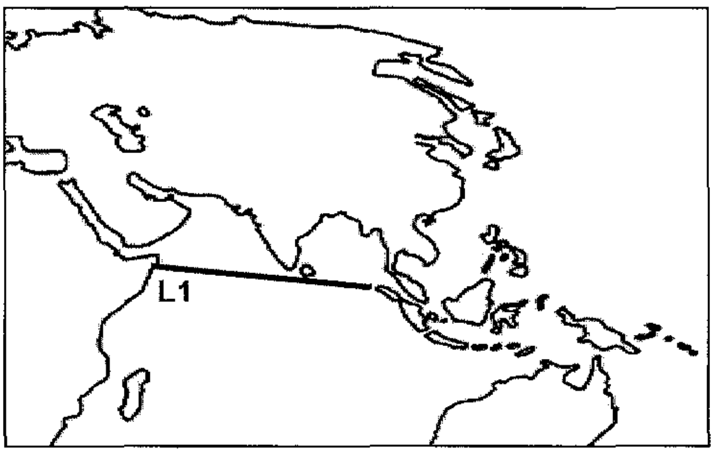


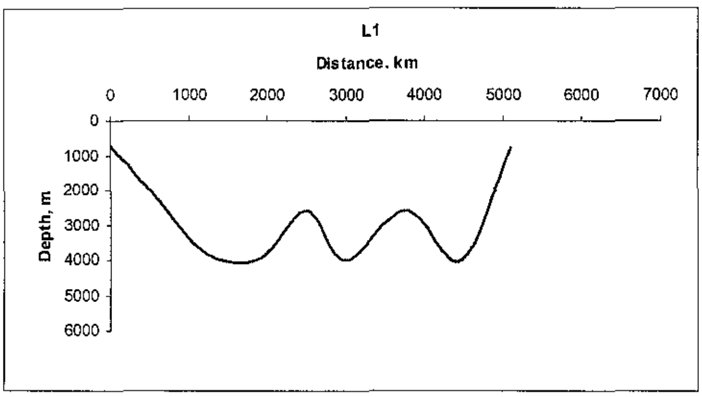
FIGURE 5.5 Past tsunamis travel time, hr, towards port Los Angeles

CHAPTER 6
DATA ANALYSIS

Figure 6.1 shows the result obtained from Asian tsunami data. By using the bathymetry profile (Figure 6.1 (b) to (e)), the travel time is calculated, $dt = dx / v$, where dt is the travel time differences, dx is the distance differences and v is the speed at average depth between the distance differences. Step by step procedures are as shown below. From Figure 6.1 (a), the relation between distance and travel time indicates that the travel time increases with the distance. The travel time for the wave to reach the further distance is higher compared to the nearest distance. The speed of tsunami wave is given



1. A line is drawn from the epicentre of source of tsunami towards the location selected



2. Bathymetry profile along the line is constructed based on ETOPO-2

Location : L1			
dx	**depth**	***v* (km/h)**	***dt* (hr)**
250	1150	382.37	0.65
500	2000	504.26	0.50
750	2750	591.29	0.42
1000	3700	685.86	0.36
1250	3900	704.16	0.36
1500	4100	721.99	0.35
1750	4000	713.13	0.35
2000	3750	690.48	0.36
2250	3000	617.59	0.40
2500	2500	563.78	0.44
2750	3400	657.47	0.38
3000	4050	717.57	0.35
3250	3200	637.84	0.39
3500	2800	596.65	0.42
3750	2900	607.21	0.41
4000	3100	627.79	0.40
4250	3800	695.07	0.36
4500	4000	713.13	0.35
4750	2100	516.71	0.48
5000	750	308.79	0.81
Total time			**8.55**

3. Travel time calculated based on bathymetry profile

by the slope of this graph. The steeper the slope is, the faster the tsunami waves travelled.

v = slope = dx / dt

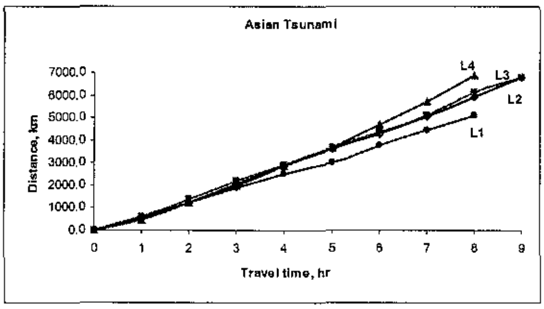
where v is the speed of tsunami, km/h

dx is the changes in distance, km

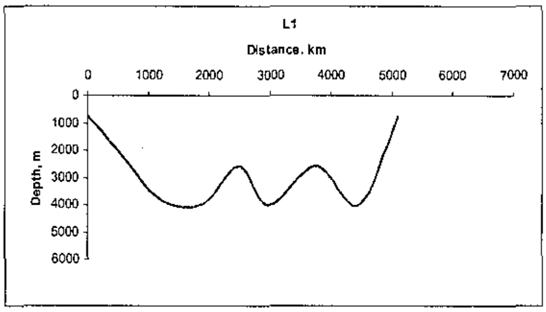
dt is the changes in travel time, hr

Theoretically $v = \sqrt{gy}$ (Equation (1) in Chapter 4) and from the above relations, since $v = dx \; / \; dt$ it can be seen that the tsunami's speed increases as the ocean's depth increases. Take line L1 and L4 from Figure 6.1 (a) for example, where the slope is steeper in line L4 compared to L1. This is due to the bathymetry profile where L4 has deeper ocean's depth than LI. The same results were obtained for other historic tsunamis where the Equation (1) is applied.

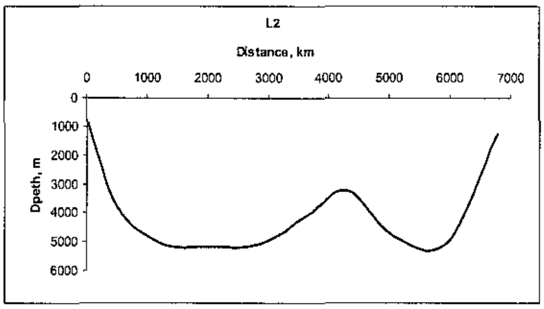
Since $v = \sqrt{gy}$, where g is the acceleration of gravity and y is the ocean's depth, decreasing in depth as the tsunami approaches shore caused slower tsunami wave. This relationship can be seen in Figure 6.2 below.



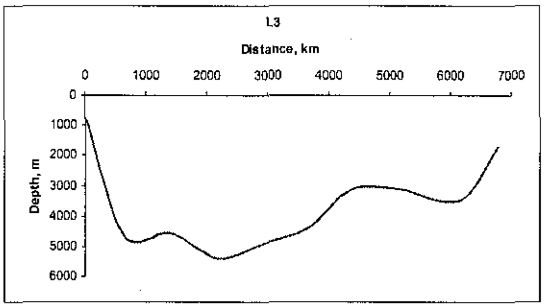
(a)



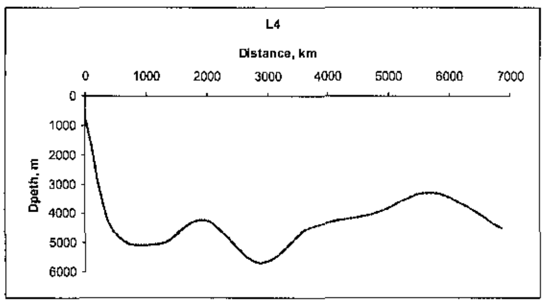
(b)



(c)



(d)



(e)

FIGURE 6.1 Relationship between bathymetry and travel time (a) Graph of distance versus wave travel time (b) to (e) Bathymetric profile along each four rays

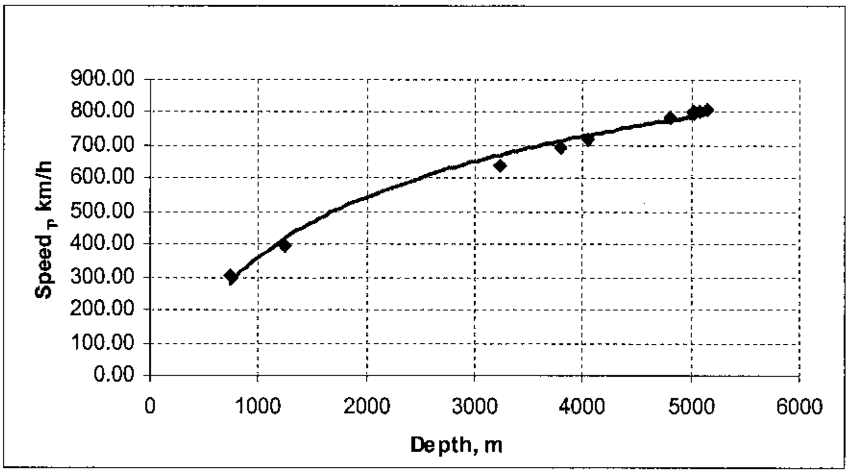


FIGURE 6.2 Tsunami speed calculated by v = sqrt (gy)

From the Asian tsunami data, 16 countries identified to have been affected by the tsunami. However, only four countries, namely, Sri Lanka, India, Indonesia and Somalia were provided with the actual travel time. The differences in both actual and calculated time are shown in Table 6.1

Percentage difference between the actual and calculated travel time for Indonesia is significantly high, 109%. This is due to the barrier encountered by the wave during its propagation. The effects of refraction, reflection and diffraction need to be considered for this situation and thus the simple wave's speed equation used will be modified. Another reason for such error is due to fact that the wave period is within 10 to 20 minutes and by using this basic shallow-water equation, the model will not be able to predict any tsunamis below the wave period or location closest to the source of tsunami.

When constructing the bathymetry profile along the lines of various tsunamis toward Port Los Angeles (Figure 5.5), ETOPO-2 is used. Equation of $v = \sqrt{gy}$ is used to calculate the theoretical travel time (from the bathymetry profile constructed) shown in Table 6.2.

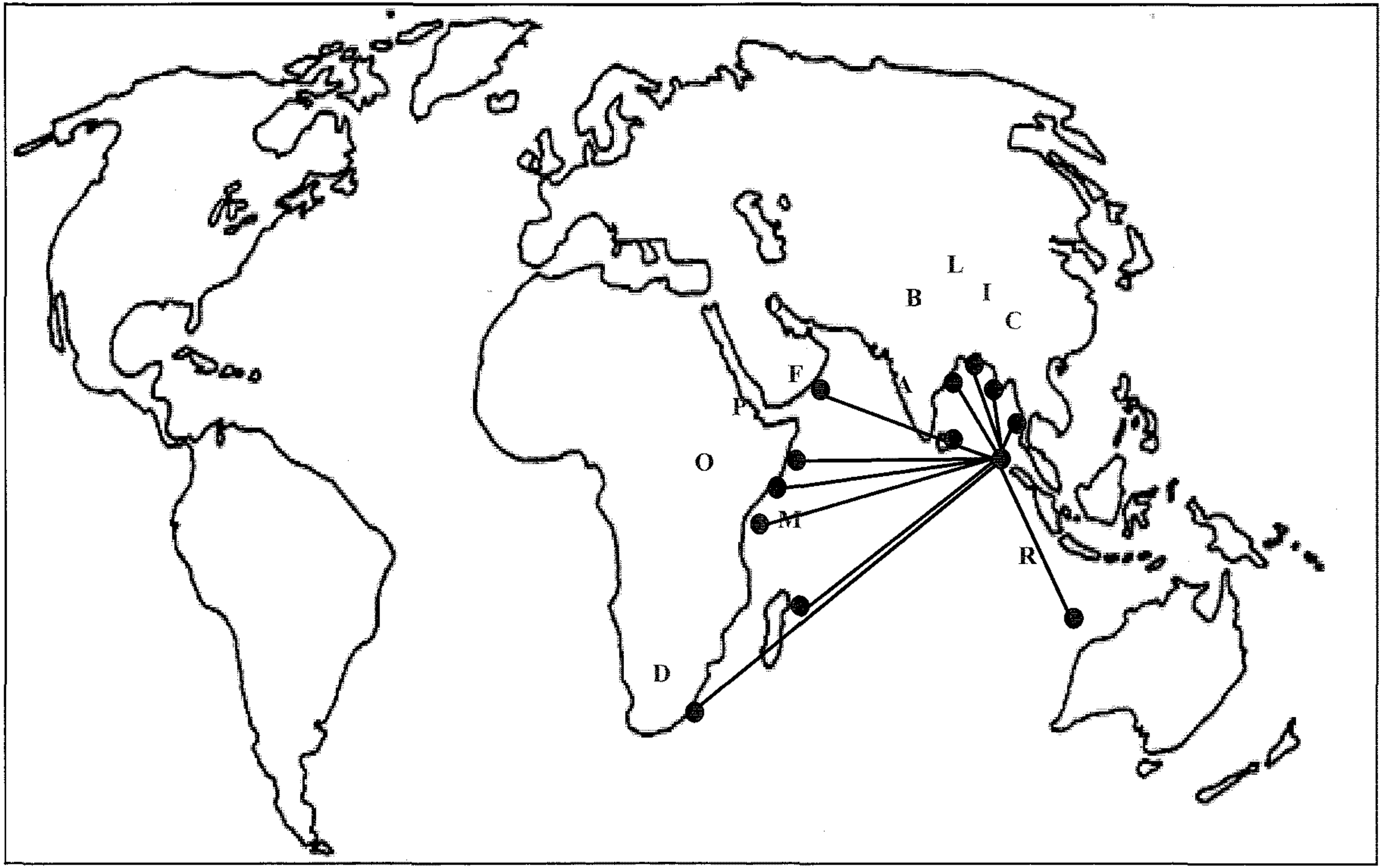


FIGURE 6.3 Countries affected by Asian tsunami

TABLE 6.1 Travel time observed and calculated for Asian tsunami

Location	Earthquake	Travel time Observed, hr	Travel time Calculated, hr	% Difference
A	Colombo, Sri Lanka	2.333	1.793	23.15
B	India	2.000	1.961	1.95
E	Aceh, Indonesia	0.167	0.349	108.98
F	Somalia	7.000	4.423	36.81
G	Manzanillo, Mexico	nil	-	-
H	Maldives	nil	-	-
I	Myanmar	nil	-	-
J	Malaysia	nil	-	-
K	Seychelles	nil	-	-
L	Bangladesh	nil	-	-
M	Madagascar	nil	-	-
N	Mauritus	nil	-	-
O	Tanzania	nil	-	-
P	Kenya	nil	-	-
Q	Oman	nil	-	-
R	Australia	nil	-	-

TABLE 6.2 Travel time observed and calculated of various historical tsunamis towards Port Los Angeles

Location	Earthquake	Travel time Observed, hr	Travel time Calculated, hr	% Difference
A	1975, Hawaii	5.4	4.64	14.07
B	1946, Unimak Island, Alaska	6.0	5.64	6.00
C	1957, Aleutian Island, Alaska	6.4	6.25	2.34
D	1964, Prince William Sound, Alaska	7.0	5.31	24.14
E	1923, Kamchatka, Russia	9.0	7.62	15.33
F	1952, Kamchatka, Russia	9.0	8.06	10.44
G	1952, Hokkaido, Japan	10.5	10.10	3.81
H	1968, Honshu, Japan	10.5	9.90	5.71
I	1944, Kii Peninsula, Japan	12.0	11.26	6.17
J	1946, Honshu, Japan	12.3	12.64	2.76
K	1960, Southern Chile	13.0	12.28	5.54

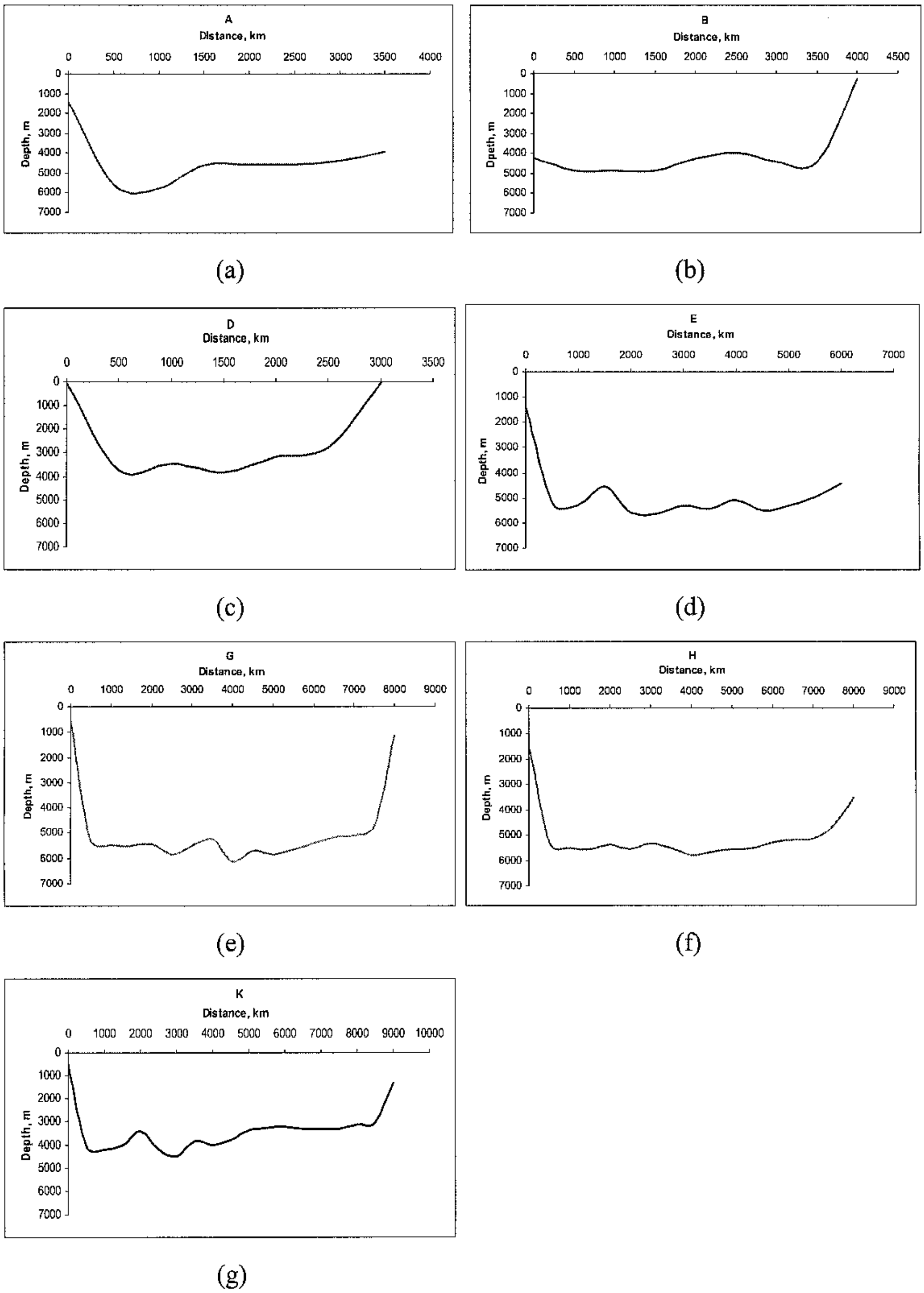


FIGURE 6.4 Relationship between bathymetry and travel time

From Figure 5.5, tsunami travel time for G and H tsunamis are similar even though distance of H is much further. This is due to the effect of bathymetry profile as shown in Figure 6.4 (e) and (f) where both rays have similar bathymetry depths. While for B and D tsunamis, even though the distance is quite similar, bathymetry along B ray is deeper compared to D thus giving it higher tsunami speed and shorter travel time. However, further studies on this equation will be conducted and may be modified depending on the results obtained.

CHAPTER 7
PROGRAM DECSRIPTION

The calculations previously shown are very detailed but they cannot be used for a large repetition of events involving numerous locations. In this study, a rather simplified model able to predict the correct time of arrival of the wave in the various location close to the epicenter is developed. The model is written in C for the calculation part.

The aim of this project is to rapidly estimate travel times of a hypothetical tsunami risk for inclusion in any warning or alert system available. The simulation is simply based on the shallow water approximation for velocity of gravity driven waves. It uses a fine 2-minute Ocean Bathymetry (generally known as ETOPO-2 data) to calculate the local velocity at each point on the wave front. No wave diffraction or hydrodynamic effects are currently included. Its purpose is to rapidly predict arrival times for line of selected ports.

Starting from the literature equation $v = \sqrt{gy}$, a fast running predictive model has been developed, based on the above formula and detailed bathymetry data. The calculation is performed for each intersection of grid starting from the source of tsunami calculating, step by step, the local velocity. The distance dx from the epicenter at time dt, is a function of the grid intersection, which represent in Figure 7.1.

The operation is repeated until the distance reached the selected port. The arrival time is the total time of dt calculated. The model is extremely sensitive to the bathymetry, which therefore has to be specified very carefully. Example of program calculation is attached in Appendix 11.

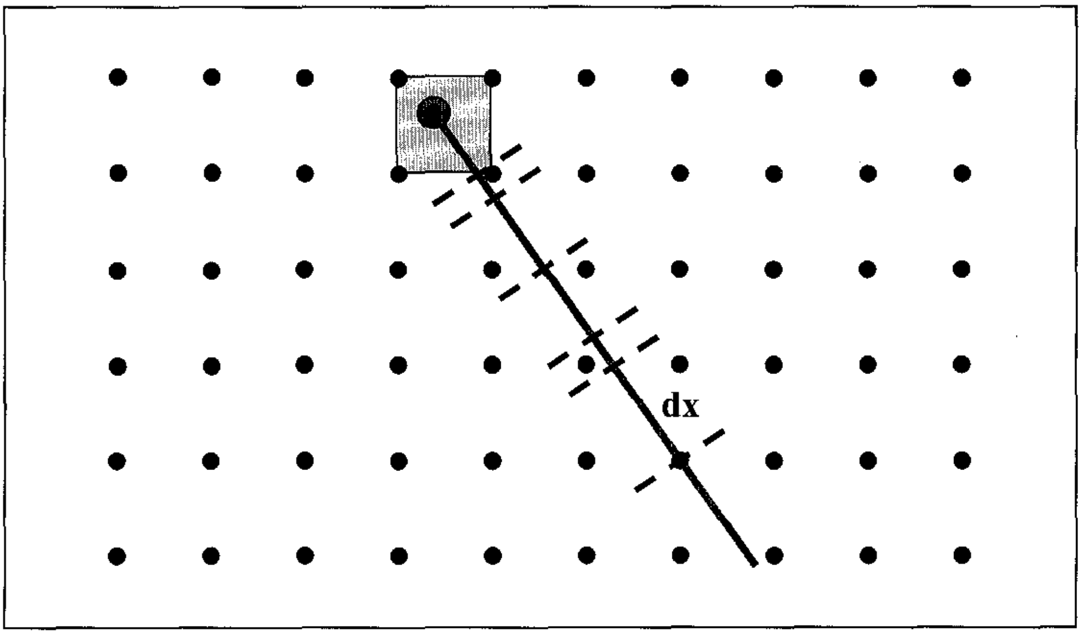


FIGURE 7.1 Logic for the propagation model

Two problems of this program are the presence of land mass and short distance of affected ports. The model does not take diffraction into account (i.e. it doesn't curve the wave front round obstacles). Hence when it hits land it appears to have bigger difference in travel time calculated compared to observe. This problem can be resolved with a much detailed calculation which considers the diffraction and refraction. For the short distance situation, by considering the wave front movement in deeper topography, the calculations can be more accurate.

CHAPTER 8
CONCLUSION

Great effort is being dedicated in various countries to the understanding of the characteristics of the devastating tsunami in order to prepare early warning tools and systems which may allow an effective alerting mechanism for the population. The report compared the calculated model of the 26th December Tsunami propagation as well as various historic tsunamis with available data to check whether the models could predict the tsunamis arrival times. In general it was found that the formulation of speed used in the model requires modification to include effects of waves refraction.

The aim of this project is proposed to develop a simple mathematical model for tsunami travel. A formulation of the speed and height capable of giving quantitative is required. Due to time and facilities constrained, the height of a tsunami is unable to be studied. It is hope that in future, this study can be further continued by another student to possibly improve the model to include the evaluation of the effect of the tsunami.

Towards the study of tsunami, the bathymetric configuration is known to affect the speed of tsunamis as shown in the equation of $v = \sqrt{gy}$ where y is the ocean's depth.

Tsunamis can be caused by a few different means:
1) the down drop or upthurst of the Earth's crust which results in an earthquake
2) a large-scale undersea landslide
3) a submarine volcanic eruption of a certain degree; or potentially
4) a large meteor impact at sea.

However, the majority of tsunamis are resulted from earthquakes where 81 percent of them occurred in Pacific Ocean.

CHAPTER 9
REFERENCE

Books and Journals

(2005), *Reference Atlas of The world,* 6th edition, Dorling Kindersley Limited, London

(2005), *Review of Tsunami Hazards and Risk in New Zealand*, Institute of Geological and Nuclear Sciences Limited

Abdul Basith, et. al. (2005), *Application of Tsunami Numerical Model for Estimating Height and Travel Time of Tsunami Wave At Nangroe Aceh Darussalam*, Gadja Mada University

Annunziato A., Best C., (2005), *The Tsunami Event, Analyses and Models*, Joint Research Centre, European Commission

Bernard E. N., (2001), *Recent Developments In Tsunami Hazard Mitigation*, NOAA, Pacific Marine Environmental Laboratory, USA

Choi B. H. et. al. (2003), *Simulation of the trans-oceanic tsunami propagation due to 1983 Krakatau volcanic eruption*, National Hazards and Earth System Sciences

Day T., (1999), *Oceans*, Facts On File Inc., New York

Duxbury A.C. et al., (2000), *An Introduction to The World's Oceans*, 6th edition, McGraw-Hill, USA

Garrison T., (2002), *Oceanography : An Invitation to Marine Science*, fourth edition, Thomson Learning, USA

Heathfield R., Kirby L., et al., (2000), *C Unleashed*, Sams Publishing, Indiana

Helena O., Yamashita M. T., (2006), *Understanding the Tsunami with A Simple Model*, PACS, Brazil

Hinwood J., (2005) *Design for tsunamis – Coastal engineering considerations*, Structural Engineering International, Australia

James F., Lander, Lowell S., Whiteside, Patricia A., (2003) *Tsunami Data Issue : Two Decades of Global Tsunamis -1982 - 2002*, The International Journal of The Tsunami Society, Colorado

Johnsonbaugh R., Kalin M., (1997), *C for Scientist and Engineers*, Prentice Hall, New Jersey

Kenneth A. R., (1998), *Pointers on C*, Addison Wesley, USA

Mofjeld H. O., Titov V. V., Gonzalez F. I., Newman J. C., (2000), *Analytic Theory of Tsunami Wave Scattering in the Open Ocean with Application to the North Pacific*, NOAA Technical Memorandum OAR PMEL-116, Seattle

Ross D. A., (1995), *Introduction to Oceanography*, HarperCollins, New York

Segar A. D., (1997), *Introduction to Ocean Sciences*, Wadsworth Publishing Company, USA

Schildt H., (2000), *C : The Complete Reference*, fourth edition, McGraw-Hill Company, California

Ward S. N., Day S., (2001), *Cumbre Vieja Volcano, Potential collapse and tsunami at La Palma, Canary Islands*

Ward S. N., (2000), *Tsunamis*, Encyclopedia of Physical Science and Technology

Woo G., (1999), *The Mathematics of Natural Catastrophes*, Imperial College Press, London

Relevant Websites

<http://www.solcomhouse.com/tsunamis.html>

<http://wcatwc.arh.noaa.gov/physics.html>

<http://www.e11th-hour.org/resources/backgrounders/tsunami>

<http://www.extremescience.com/BiggestWave.html>

Atlas of The World, <http://www.welt-atlas.de/worldatlas/>

European Commission, Joint Research Centre, <http://www.tsunami.jrc.it/model>

Map Quest, <http://go.hrw.com/atlas/norm_htm/world.htm>

History Map of Tsunami, <http://www.mapsofworld.com>

How A Tsunami Happens, <http://academic.evergreen.edu/g/grossmaz/SPRINGLE/>

How Stuff Works, <http://science.howstuffworks.com/tsunami.htm>

National Geophysical Data Centre, <http://www.ngdc.noaa.gov>

National Weather Service Forecast Office, <http://www.erh.noaa.gov/er/phi/reports/tsunami.htm#intro>

Oxford Brookes University, <http://www.brookes.ac.uk/geology/8361/1998/craig/craig.html>

The Physics Behind The Wave, <http://observe.arc.nasa.gov/nasa/exhibits/tsunami/tsun_physics.html>

The National Tsunami Hazard Mitigation Program, <http://www.pmel.noaa.gov/tsunami-hazard/index.html>

The Tsunami Page, <http://www.drgeorgepc.com/Tsunami2004IndianOcean.html>

Tsunami, <http://hyperphysics.phy-astr.gsu.edu/hbase/waves/tsunami.html#c1>

Tsunami, <http://www.acehtsunami.com/index.php?option=com_content&task=blogsection&id=5&Itemid=27>

Tsunami Background, <http://www.globalsecurity.org/eye/andaman-back.htm>

Tsunami Generation, Propagation and Inundation, <http://www.tsunami.org/summary.htm>

Tsunami History of Tidal Waves, <http://www.important.ca/tsunami_history.html>

Tsunamis On The Move, <http://www.wsspc.org/tsunami/HI/Waves/waves03.html>

Tsunami - The National Geographic Kids,
<http://www.nationalgeographic.com/ngkids/9610/kwave/how.html>

USGS, Western Coast and Marine Geology,
<http://walrus.wr.usgs.gov/tsunami/basics.html>

USC Tsunami Research Group,
<http://www.usc.edu/dept/tsunamis/alaska/1958/webpages/lituyacloseup.html>

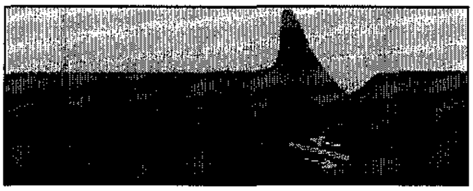
US Water News Online
<http://www.uswaternews.com/archives/arcglobal/5resestud8.html>

Wikipedia – The Free Encyclopedia, <http://en.wikipedia.org/wiki/>

APPENDIX 1 The Life of A Tsunami

Initiation

Earthquakes are commonly associated with ground shaking that is a result of elastic waves travelling through the solid earth. However, near the source of submarine earthquakes, the seafloor is "permanently" uplifted and down-dropped, pushing the entire water column up and down.



The potential energy that results from pushing water above mean sea level is then transferred to horizontal propagation of the tsunami wave (kinetic energy). For the case shown above, the earthquake rupture occurred at the base of the continental slope in relatively deep water. Situations can also arise where the earthquake rupture occurs beneath the continental shelf in much shallower water.

Note: *In the above figure, the waves are greatly exaggerated compared to water depth. In the open ocean, the waves are at most several meters high, spread over many tens to hundreds of kilometres in length.*

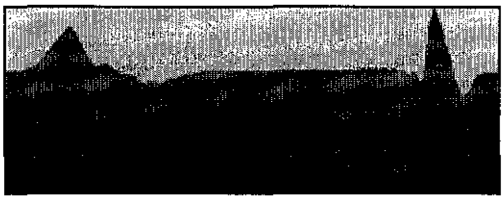
Split

Within several minutes of the earthquake, the initial tsunami is split into a tsunami that travels out to the deep ocean (distant tsunami) and another tsunami that travels towards the nearby coast (local tsunami).

The height above mean sea level of the two oppositely travelling tsunamis is approximately half that of the original tsunami. The speed at which both tsunamis travel varies as the square root of the water depth. Therefore the deep-ocean tsunami travels faster than the local tsunami near shore.

Amplification

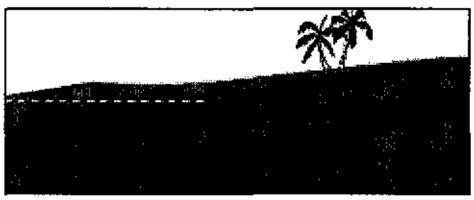
Several things happen as the local tsunami travels over the continental slope. Most obvious is that the amplitude increases. In addition, the wavelength decreases. This results in steepening of the leading wave—an important control of wave runup at the coast.



Note also that the deep ocean tsunami has travelled much farther than the local tsunami because of the higher propagation speed. As the deep ocean tsunami approaches a distant shore, amplification and shortening of the wave will occur, just as with the local tsunami shown above.

Runup

As the tsunami wave travels from the deep-water, continental slope region to the near-shore region, tsunami runup occurs. Runup is a measurement of the height of the water onshore observed above a reference sea level.



Contrary to many artistic images of tsunamis, most tsunamis do not result in giant breaking waves (like normal surf waves at the beach that curl over as they approach shore). Rather, they come in much like very strong and very fast tides (i.e., a rapid, local rise in sea level). Much of the damage inflicted by tsunamis is caused by strong currents and floating debris. The small number of tsunamis that do break often form vertical walls of turbulent water called bores. Tsunamis will often travel much farther inland than normal waves.

Do tsunamis stop once on land? After runup, part of the tsunami energy is reflected back to the open ocean. In addition, a tsunami can generate a particular type of wave called edge waves that travel back-and forth, parallel to shore. These effects result in many arrivals of the tsunami at a particular point on the coast rather than a single wave. Because of the complicated behaviour of tsunami waves near the coast, the first runup of a tsunami is often not the largest, emphasizing the importance of not returning to a beach several hours after a tsunami hits.

APPENDIX 2 Tsunami Warning Systems and Centres

No.	Organization	Operation	Establish	Contact No.
1	Western States Seismic Policy Council (WSSPC)	• Promote understanding & study of seismic hazards • Provide advise & recommendations regarding seismic hazards & risk • Coordinates & implements tsunami hazards mitigation plans • Develop policies based on current technology & science • Translate knowledge into action • Considers need & requirements of seismic building codes	1977	**Address :** 801 K Street, Suite 1436 Sacramento, CA 95814 **Tel :** 916 – 444 – 6816 **Fax :** 916 – 444 – 8077 **Email :** wsspc@wsspc.org
2.	West Coasts / Alaska Tsunami Warning Center (WA / ATWC)	• Locating & sizing earthquake • Earthquake analysis, review & modification • Obtain sea level data • Calibrate models • Disseminating information	1967	**Address :** West Coast & Alaska Tsunami Warning Center 910 S. Felton St. Palmer, AK 99645 USA **Tel :** :907 – 745 – 4212 **Fax :** :907 – 745 – 6071
3.	Pacific Tsunami Warning Center (PTWC)	• Detect & locate major earthquakes • Provide timely & effective tsunami information & warnings	1949	**Address :** National Weather Service Pacific Tsunami Warning Center 91-270 Fort Weaver Rd Ewa Beach, HI 96706-2928 **Tel :** 808 – 689 – 8207 **Fax :** 808 – 689 – 4543 **Email :** ptwc@ptwc.noaa.gov webmaster@ptwc.noaa.gov

4.	International Tsunami Information Center (ITIC)	• Provide information & expertise • Provide training & capacity building in enhancing tsunami warning & mitigation systems		hosted by the US National Weather Service of NOAA, Honolulu, Hawaii
5.	National Oceanic and Atmosphere Administration (NOAA)	• Focused on condition of oceans & atmosphere • Supply information on state of oceans & atmosphere	1970	**Address :** 14th Street & Constitution Avenue, NW, Room 6217 Washington, DC 20230 **Tel :** 202 – 482 – 6090 **Fax:** 202 – 482 – 3154 **Email** (eduacator/students) noaa-outreach@noaa.gov.
6.	Pacific Marine Environmental Laboratory (PMEL)	• Research & development activities in improving tsunami warning & mitigation		**Address :** Pacific Marine Environmental Laboratory NOAA /R/PMEL 7600 Sand Point Way NE Seattle, WA 98115 **Tel :** 206 – 526 – 6239 **Fax :** 206 – 526 – 6815
7.	NOAA Center for Tsunami Research (NCTR)	• Research & design of optimal tsunami monitoring networks • Develop & implementation of improved models • Research & develop improved method to predict tsunami impacts		**Email :** oar.pmel.tsunami-webmaster@noaa.gov
8.	USC Tsunami Research Center (TRC)	• inundation field surveys • numerical & analytical modelling • hazard assessment, mitigation & planning		**Address :** Tsunami Research Center Biegler Hall, University of Southern California, Los Angeles, California 90089-2531 **Tel :** 213 – 740 – 5129 **Fax :** 213 – 744 – 1426

APPENDIX 3 List of tsunamis

(*Source* : Wikipedia)

No.	Date	Place	Remarks
1	Circa 65 million years B.C		• Meteor impact created the Chicxulub Crater and caused the Cretaceous-Tertiary extinction event • Tsunami more than one kilometre high
2	Circa 1,500 B.C		• Eruption of Santorini volcano • Tsunami estimated at 600 feet
3	1607	England and Wales	• Tsunami caused Bristol Channel floods
4	26/01/1700	Vancouver Island, Canada	• Cascadia Earthquake (one of largest earthquake on records) • Create tsunami logged in Japan and oral traditions of the Native Americans
5	1755	Lisbon, Portugal	• Tsunami followed 30 minutes after earthquake • Killed more than 91,667 people
6	1883	Krakatau	• Explosion of an island volcano caused series of large tsunamis • Height reached over 40 m above sea level • Tsunami waves were observed throughout the Indian Ocean, Pacific Ocean, American West Coast, South America, and as far away as English Channel • Killed 36,000 people

No.	Date	Place	Remarks
7	18/11/1929	Newfoundland	• Earthquake of magnitude 7.2 occurred beneath the Laurentian Slope on the Grand Banks • Tsunami measured over 7 m in height • 2.5 hrs to reach the Burin Peninsula on the south coast of Newfoundland • Killed 28 people
8	1946	Aleutian Island	• Killed 165 people in Hawaii and Alaska
9	1960	Chile	• Magnitude 9.5 Great Chilean Earthquake (strongest earthquake ever recorded) • Spread across the entire Pacific Ocean • Waves up to 25 metres high • The first tsunami arrived at Hilo, Hawaii approximately 14.8 hrs after it originated with highest wave 10.7 m • Tsunami hit Onagawa, Japan, almost 22 hrs after the quake, the wave height was 3 m above high tide • Killed 490 to 2,290 people
10	1963	Italy	• Enormous landslide struck reservoir behind Vajont Dam • Killed nearly 2,000 people
11	1964	Prince William Sound, Alaska	• Magnitude 9.2 Good Friday Earthquake • Tsunamis struck Alaska, British Columbia, California and coastal Pacific Northwest towns • Killed 121 people • The tsunamis were up to 6 m tall

No.	Date	Place	Remarks
12	16/08/1976	Mindanao, Philippines	• Earthquake of 7.9 hit the island of Mindanao, Philippines • Created tsunami that devastated more than 700 km of coastline bordering Moro Gulf in the North Celebes Sea • Killed 5,000 people
13	12/12/1979		• Magnitude-7.9 earthquake along the Pacific coast of Colombia and Ecuador • Killed 259 people
14	12/07/1993	Hokkaido, Japan	• Tsunami occurred off the coast of Hokkaido in Japan as a result of an earthquake • Killed 202 people
15	26/12/2004	Simulue Island, Indonesia	• Earthquake with magnitude of 9.15 • Killed approximately 230,000 people (deadliest tsunami in recorded history)

Other tsunamis in South Asia

(*Source* : Amateur Seismic Centre, India)

No.	Date	Location
1	1524	Near Dabhol, Maharashtra
2	02/04/1762	Arakan Coast, Myanmar
3	16/06/1819	Rann of Kachchh, Gujarat, India
4	31/10/1847	Great Nicobar Island, India
5	31/12/1881	Car Nicobar Island, India
6	26/08/1883	Krakatau
7	28/11/1945	Mekran coast, Balochistan
8	26/12/2004	Banda Aceh, Indonesia; Tamil Nadu, Kerala, Andhra Pradesh, Andaman and Nicobar Island, India; Sri Lanka; Thailand; Malaysia; Maldives; Somalia; Kenya; Tanzania

Other historical tsunamis

(*Source* : Wikipedia)

No.	Date	Place	Remarks
1	Circa 500 B.C	Poompuhar, Tamil Nadu, India, Maldives	
2	1541	Sao Vicente	• No record of deaths or injuries
3	20/01/1606	England and Wales	• Along the coast of the Bristol Channel thousands of people were drowned
4	26/01/1700	Vancouver Island, Canda	• Magnitude-9.0 Cascadia Earthquake • Massive tsunamis across the Pacific Northwest
5	1896	Sanriku, Japan	• Wave about 20 m high • Drowned 26,000 people
6	1946	Aleutian Island	• Earthquake in the Aleutian Islands sent a tsunami to Hawaii • Killed 159 people (five died in Alaska)
7	9/07/1956		• Huge landslip caused a tsunami in the fjord shaped Lituya Bay, Alaska, USA • It travelled at over 150 km/h
8	26/05/1983		• Killed 104 people in western Japan
9	17/07/1998	Papua New Guinea	• Killed approximately 2,200 people • A 7.1 magnitude earthquake 24 km offshore was followed within 11 minutes by a tsunami about 12 m tall • The earthquake generated an undersea landslide

APPENDIX 4 Casualties resulted from Asian Tsunami

Country where deaths occurred	Deaths		Injured	Missing	Displaced
	Confirmed	Estimated[1]			
Indonesia	126,915	126,915+	~100,000	37,063	400,000-700,000
Sri Lanka	30,957	38,195	15,686	5,637[2]	~573,000
India	10,749	16,413	—	5,640	380,000
Thailand	5,395[3]	11,000	8,457	2,932	—
Somalia	298	298	—	—	5,000
Myanmar (Burma)	61	290– 600	45	200	3,200 confirmed
Maldives	82	108	—	26	12,000– 22,000
Malaysia	68 – 74	74	299	—	—
Tanzania	10	10+	—	—	—
Seychelles	1 – 3	3	—	—	—
Bangladesh	2	2	—	—	—
South Africa	2[4]	2	—	—	—
Yemen	2	2	—	—	—
Kenya	1	2	2	—	—
Madagascar	—	—	—	—	1,000+
Total	174,542	~193,623	~125,000	~51,598	~1.5 million

Note: All figures are approximate and subject to change.

[1] Includes those reported under 'Confirmed'. If no separate estimates are available, the number in this column is the same as reported under 'Confirmed'

[2] Does not include approximately 19,000 missing people initially declared by Tamil Tiger authorities from regions under their control

[3] Data includes at least 2,464 foreigners

[4] Does not include South African citizens who died outside of South Africa (eg, tourists in Thailand). For more information on those deaths

APPENDIX 5 Tsunamis out of Pacific Area

Date	Location	Damage & Effects
Aug. 6, 1983	Aegean Sea	Weak wave.
Nov. 30, 1983	Seychelles Is., Indian Ocean	Wave damage near the southeastern tip of the island.
Feb. 11, 1984	West Corinthos Gulf – Greece	Intensity 3 tsunami at Sergoula.
Mar. 16, 1985	Leeward Islands	Small tsunami at Basse Terre, Guadeloupe.
Apr. 20, 1988	Tyrrhenian Sea	A wave 5.5 meters in height was seen in the Porto di Levante.
Nov. 1, 1989	Puerto Rico	Small tsunami in Cabo Rojo.
Dec. 13, 1990	Italy	Road flooded at Augusta.
Jan. 4, 1991	Karia Island, Greece	Tsunami intensity of 3 at Evdilas.
Apr. 22, 1991	Costa Rica	Tsunami effects from north of Limon to Panama, 2 m in Cahuito Puerto Viejo, Costa Rica.
Jan. 5, 1992	Hainan Island, China	A number of waves up to 80 cm damaged fishing boats. Effects at Beibu Bay, and Sanya Port.
May 7, 1993	Greece	Aseismic tsunami or storm surge at Leros Island.
May 13, 1995	Greece	Earthquakes caused ship to move in harbor near Gevena-Kozani. No runup reported on land.
Jun. 15, 1995	Gulf of Corinth, Greece	Tsunami had a height of 0.4 to 0.5 m at Eratini. Probably a landslide tsunami.
Nov. 22, 1995	Aqaba, Jordan	Possible tsunami from Egypt earthquake.
Dec. 31, 1995	Western Corinthos Gulf	Heights of 1.5 to 2 m at Aeghio City. Flooded cultivated areas.
Jul. 9, 1997	Tobago, Venezuela	Large wave observed.
Dec. 26, 1997	White River Valley, Montserrat	Eruption generated a tsunami that was 3 m at Old Road Bay.
Aug. 17, 1999	Bay of Izmit	150 deaths from tsunami. Waves up to 2 meters.
Jun. 18, 2000	South Indian Ocean	30 cm tsunami in the Cocos Islands.

APPENDIX 6 Damaging Tsunamis

Date	Location	Damage & Effects
May 26, 1983	Minehama, Japan	Tetrapods scattered and broken.
	Noshiro, Japan	Caissons translated and dislocated, 40 ships destroyed, houses destroyed.
	Oga Peninsula	Much damage.
	Total for Japan	52 homes washed away, 3,513 homes destroyed, 225 vessels sunk, 251 vessels washed away, 1,187 vessels damaged $800 million total damage.
	Korea	70 boats damaged, numerous roads and dwellings damaged and boats damaged. $500,000 damage.
	Primorsky Russia	Several small fishing boats washed ashore. Some ships had lines broken. Boxes and barrels washed ashore.
Nov. 30, 1983	Diego Garcia Island, Indian Ocean	Significant damage.
Sep. 19, 1985	Lazaro Cardenos, Mexico	1,500 m of railway destroyed, bridge washed out, fishing boats missing.
	Michoacan, Mexico	Palapa restaurants washed away.
	Playa Azul, Mexico	Other restaurants and hotels flooded.
	Ixtapa Zihuatenejo, Mexico	Many beach front restaurants destroyed.
Oct. 16, 1987	New Britain	Wharf destroyed, 2 jetties damaged.
Aug. 10, 1988	Solomon Islands	100 homes washed away in 13 villages.
Apr. 22, 1991	Limon, Costa Rica	7,439 homeless and severe damage in the Limon-Pandora area.
Jan. 5, 1992	Hainan Island, South China Sea	Damage to fishing boats.
Apr. 25, 1992	Trinidad, California	Boats flooded, vehicle stuck in sand.
Sep. 2, 1992	El Transito, Nicaragua	80% of buildings were swept away.
	El Popoyo, Nicaragua	Damage.
	Marsella, Nicaragua	Scoured beach.
Dec. 12, 1992	Riangkroko, Indonesia	Village destroyed.
	Pagaraman, Babi Islands, Flores	Settlement destroyed.
	Maumere	Minor damage.
	Pmoana Besar Island	Villages flooded.
	Sumba Island	Damage.
	Wuring	80% of stilt houses collapsed.
	Sumba Island	Damage.
	Lewobele	Damage.
July 12, 1993	Sea of Japan	Destroyed several hundred homes and caused 1.2 billion dollars in damage. 71 ports were damaged.
	Aonae, Japan	340 homes destroyed by flames spread by waves.
	Inaho, Okushiri Island	All houses destroyed.
	Kamenka, Sakhalin	Factory damaged.
	Vladivostok, Russia	Damage ($6.5 million).
	Korea	$0.5 million damage.
Aug. 8, 1993	Guam	Washed truck into Papo Bay and other vehicles washed into Klig Bay.

Jan. 21, 1994	Halmahera, Indonesia	Two meter damaging tsunami.
Feb. 15, 1994	Sumatera, Indonesia	$160 million US.
Jun. 2, 1994	Area south of Java, Indonesia	Several villages destroyed.
Nov. 4, 1994	Skagway, Alaska	$25 million damage.
Nov. 14, 1994	Mindoro Is., Philippines	804 houses destroyed, 3,288 damaged.
May 14, 1995	Flores Sea, Indonesia	Homes and fishing boats destroyed.
Jul. 30, 1995	Northern Chile	$131,000 damage.
Oct. 9, 1995	Jalisco, Mexico	Extensive damage in Manzanillo Bay.
Dec. 31, 1995	Western Corinthos Gulf	Flooding, road partially destroyed.
Jan. 1, 1996	Sulawesi, Indonesia	9 killed by wave at Tonggolobibi.
Feb. 17, 1996	Irian Jaya, Indonesia	Tsunami damaged 5,043 houses.
Feb. 21, 1996	North coast of Peru	Tsunami destroyed 15 houses, & 2 boats, killed 12.
Apr. 21, 1997	Santa Cruz Islands	7 houses washed away.
Jul. 17, 1998	NW coast of Papua New Guinea	Two villages destroyed.
Aug. 17, 1999	Izmit Bay, Turkey	Several coastal villages incurred damage.
Nov. 26, 1999	Vanuatu	Baie Martelli village destroyed.
Nov. 16, 2000	New Ireland PNG	Tsunami damage on SW shore of New Ireland.
Jun. 23, 2001	Southern coast of Peru	Tsunami swept over the town of Camana.

Damaging Teletsunamis

Date	Generating Location	Affected Location(s)	Damage
May 26, 1983	Sea of Japan	Korea	70 boats damaged, numerous roads and dwellings damaged $500,000 damage.
		Russia	Fishing boats washed ashore, Ship lines broken.
July 12, 1993	Sea of Japan	Korea	$0.5 million damage.
July 30, 1995	Northern Chile	Tahauku Bay, Marquesas islands	Sank 2 boats.

APPENDIX 7 Fatalities from Tsunamis

Date	Location	Fatalities+
May 26, 1983	Japan	100
	South Korea	3
Aug. 10, 1988	Solomon Islands	1
Sep. 2, 1992	Nicaragua	169
Dec. 12, 1992	Indonesia	2,080
July 12, 1993	Sea of Japan	*330
Feb. 15, 1994	Sumatera, Indonesia	7
Jun. 2, 1994	Area south of Java, Indonesia	223
Nov. 4, 1994	Skagway, Alaska	1
Nov. 14, 1994	Mindoro Is., Philippines	*87
Jan. 1, 1996	Sulawesi, Indonesia	9
Feb. 17, 1996	Irian Jaya, Indonesia	108
Feb. 21, 1996	North coast of Peru	12
Jul. 17, 1998	NW coast of Papua New Guinea	2,182
Aug. 17, 1999	Izmit Bay, Turkey	150
Nov. 26, 1999	Vanuatu	5
Jun. 23, 2001	South Peru	96
TOTAL		5,562

+Includes missing
*Earthquake and tsunami

APPENDIX 8 Origin Source Parameters for Tsunamis 1982-2002

Event #	Year	Month	Date	Hour (UT)	Minute	Second	Latitude	Longitude	Depth (km)	Max runup (m)
1	1982	1	11	6	10	8	13.732	124.358	46	0.1
2	1982	2	24	4	22	40	4.374	97.755	52	0.1
3	1982	3	11	10	32	27	-9.265	118.479	33	0.1
4	1982	3	21	2	32	8	42.158	142.361	44	1.3
5	1982	7	23	14	23	53	36.194	141.702	37	0.4
6	1982	12	19	17	43	54	-24.133	-175.864	33	0.2
7	1982	12	25	12	28	3	-8.405	123.08	33	0.1
8	1982	12	28	6	37	42	33.826	139.434	22	0.4
9	1983	3	12	1	36	36	-4.056	127.924	17	3.0
10	1983	3	18	9	5	50	-4.883	153.581	89	0.3
11	1983	5	26	2	59	60	40.462	139.102	24	14.9
12	1983	6	9	12	49	4	40.237	139.023	31	0.6
13	1983	6	21	6	25	27	41.346	139.099	10	1.0
14	1983	8	6	15	44	51	40.142	24.766	2	0.1
15	1983	8	17	10	55	54	55.867	161.287	63	0.1
16	1983	8	17	12	17	56	18.231	120.86	29	0.1
17	1983	10	4	18	52	13	-26.535	-70.563	15	0.2
18	1983	11	30	17	46	1	-6.852	72.11	10	1.5
19	1984	1	8	15	24	0	-2.9	118.7	95	0.1
20	1984	2	11	8	2	51	38.396	22.094	29	0.1
21	1984	3	24	9	44	3	44.117	148.192	44	0.2
22	1984	6	13	2	29	25	31.448	140.036	41	0.1
23	1984	8	6	19	6	38	32.386	131.945	46	0.2
24	1984	9	18	17	2	44	34.006	141.5	48	0.1
25	1984	12	28	10	37	54	56.194	163.46	33	0.2
26	1985	3	3	22	47	7	-33.135	-71.871	33	3.0
27	1985	3	16	14	54	1	17.013	-62.448	13	0.1
28	1985	4	13	1	6	0	-9.245	114.185	99	2.0
29	1985	7	3	4	36	52	-4.439	152.828	46	1.3
30	1985	9	19	13	17	47	18.19	-102.533	28	3.0
31	1985	9	21	1	37	13	17.802	-101.647	31	2.5
32	1986	5	7	22	47	11	51.52	-174.776	33	1.4
33	1986	10	20	6	46	10	-28.117	-176.367	29	0.2
34	1987	2	6	13	16	18	36.988	141.689	48	0.1
35	1987	2	8	18	34	0	-6.1	147.7	62	1.5
36	1987	3	5	9	17	5	-24.388	-70.161	62	0.2
37	1987	3	18	3	36	30	32.034	131.837	54	0.1
38	1987	3	24	12	49	47	37.447	137.865	23	0.1

Event #	Year	Month	Date	Hour (UT)	Minute	Second	Latitude	Longitude	Depth (km)	Max runup (m)
39	1987	6	18	14	3	15	-10.707	162.326	73	0.1
40	1987	7	6	2	49	43	-14.074	167.828	48	0.1
41	1987	10	6	4	19	6	-17.94	-172.225	16	0.3
42	1987	10	12	13	57	5	-7.288	154.371	25	0.1
43	1987	10	16	20	48	2	-6.266	149.06	48	0.1
44	1987	11	17	8	46	53	58.586	-143.27	10	0.1
45	1987	11	26	1	43	14	-8.247	124.155	33	0.1
46	1987	11	30	19	23	20	58.679	-142.786	10	0.9
47	1988	2	5	14	1	3	-24.753	-70.433	37	0.1
48	1988	3	6	22	35	38	56.953	-143.032	10	0.4
49	1988	4	20	0	0	0	40	13	10	5.5
50	1988	6	24	2	6	26	18.606	121.013	53	0.6
51	1988	7	5	20	32	7	-5.964	148.78	53	0.1
52	1988	8	10	4	38	26	-10.366	160.819	34	0.2
53	1989	5	23	10	54	46	-52.341	160.568	10	0.2
54	1989	6	26	3	27	4	19.362	-155.083	9	0.6
55	1989	9	4	13	14	58	55.543	-156.835	11	0.1
56	1989	10	18	0	4	15	37.036	-121.883	19	0.4
57	1989	10	29	5	25	38	39.571	143.333	10	0.1
58	1989	11	1	10	25	52	18.986	-68.833	26	0.1
59	1989	11	1	18	25	35	39.837	142.76	29	0.9
60	1990	2	20	6	53	39	34.706	139.252	14	0.3
61	1990	3	25	13	16	6	9.814	84.828	27	0.3
62	1990	4	5	21	12	36	15.125	147.596	11	0.6
63	1990	5	0	0	0	0	7	126	0	0.1
64	1990	9	23	21	13	7	33.287	138.643	10	0.2
65	1990	12	13	0	24	25	37.3	15.438	11	0.1
66	1991	1	4	0	0	0	38	27	0	0.1
67	1991	2	9	16	18	58	-9.929	159.139	10	0.1
68	1991	2	16	1	23	40	48.268	154.238	39	0.1
69	1991	2	21	2	35	34	58.427	-175.45	20	0.3
70	1991	4	22	21	56	52	9.685	-83.073	10	2.0
71	1991	10	14	15	58	12	-9.094	158.442	23	0.2
72	1992	1	5	14	30	0	19	109	0	0.8
73	1992	4	25	18	6	4	40.368	-124.316	15	1.8
74	1992	5	17	10	15	31	7.191	126.762	33	0.1
75	1992	5	27	5	13	39	-11.122	165.239	19	0.1
76	1992	7	18	8	36	59	39.419	143.33	29	0.3
77	1992	9	2	0	16	2	11.742	-87.34	45	10.0
78	1992	12	12	5	29	26	-8.48	121.896	28	26.2
79	1993	2	7	13	27	42	37.634	137.245	11	0.5
80	1993	5	7	0	0	0	38	26	0	0.5
81	1993	6	8	13	3	36	51.218	157.829	71	0.1

Event #	Year	Month	Date	Hour (UT)	Minute	Second	Latitude	Longitude	Depth (km)	Max runup (m)
82	1993	7	12	13	17	12	42.851	139.197	17	10.0
83	1993	8	8	8	34	25	12.982	144.801	59	2.1
84	1993	11	13	1	18	4	51.934	158.347	34	0.1
85	1994	1	17	12	30	55	34.213	118.537	18	0.1
86	1994	1	21	2	24	30	1.015	127.733	20	2.0
87	1994	2	15	17	7	43	-4.967	104.302	23	0.1
88	1994	4	8	1	10	41	40.608	143.683	13	0.2
89	1994	6	2	18	17	34	-10.477	112.835	18	9.5
90	1994	6	3	21	6	59	-10.362	112.892	26	3.7
91	1994	6	4	0	57	51	-10.777	113.366	11	3.0
92	1994	9	1	15	15	53	40.402	-125.68	10	0.1
93	1994	9	19	0	0	0	-4.238	152.214	0	1.2
94	1994	10	4	13	22	56	43.773	147.321	14	11.0
95	1994	10	8	21	44	7	-1.258	127.98	17	3.0
96	1994	10	9	7	55	40	43.905	147.916	33	0.2
97	1994	11	5	4	10	0	59.5	-135.32	0	2.0
98	1994	11	14	19	15	31	13.525	121.067	32	7.3
99	1994	12	28	12	19	23	40.525	143.419	27	1.1
100	1995	1	16	20	47	52	34.583	135.018	22	0.2
101	1995	4	7	22	6	57	-15.199	-173.529	21	0.3
102	1995	4	21	0	34	46	12.059	125.58	21	0.2
103	1995	4	21	5	17	1	12.047	125.92	27	0.2
104	1995	5	13	8	47	13	40.149	21.695	14	0.1
105	1995	5	14	11	33	19	-8.378	125.127	11	1.5
106	1995	5	16	20	12	44	-23.008	169.9	20	0.5
107	1995	5	27	13	3	53	52.629	142.827	11	0.1
108	1995	6	15	0	15	49	38.401	22.283	14	0.5
109	1995	7	30	5	11	24	-23.34	-70.294	46	3.0
110	1995	8	16	10	27	29	-5.799	154.178	30	0.6
111	1995	9	14	14	5	31	16.779	98.597	23	0.4
112	1995	10	9	15	35	54	19.055	-104.205	33	5.1
113	1995	10	18	10	37	26	27.929	130.175	28	2.6
114	1995	10	19	2	41	36	28.094	130.148	20	1.5
115	1995	11	1	0	35	32	-28.906	-71.417	20	0.1
116	1995	11	22	4	15	12	28.826	34.799	10	0.1
117	1995	12	3	18	1	9	44.663	149.3	33	1.1
118	1995	12	31	0	0	0	38.1	22.4	0	2.0
119	1996	1	1	8	5	12	0.724	119.981	33	2.9
120	1996	1	2	15	40	0	54.45	159.318	33	30.0
121	1996	2	17	5	59	30	-0.95	137.027	33	7.7
122	1996	2	21	12	51	4	-9.62	-79.568	33	5.1
123	1996	2	25	3	8	16	15.978	-98.07	21	0.1
124	1996	6	10	4	3	35	51.564	-177.632	33	1.0

Event #	Year	Month	Date	Hour (UT)	Minute	Second	Latitude	Longitude	Depth (km)	Max runup (m)
125	1996	6	10	15	25	56	51.478	-176.847	26	0.3
126	1996	9	4	18	16	2	31.555	139.931	33	0.3
127	1996	9	5	8	14	14	-22.118	-113.436	10	0.2
128	1996	10	18	10	50	21	30.568	131.093	10	0.2
129	1996	10	19	14	44	41	31.885	131.468	22	1.1
130	1996	11	12	16	59	44	-14.993	-75.675	33	0.4
131	1996	12	2	22	17	59	31.789	131.314	49	0.2
132	1997	4	10	0	0	0	13.1	-87.6	49	15.0
133	1997	4	18	15	6	0	-29	167.6	49	0.1
134	1997	4	21	12	2	26	-12.584	166.676	33	1.0
135	1997	7	9	19	24	13	10.598	-63.486	20	1.0
136	1997	10	14	9	53	18	-22.101	-176.772	167	0.1
137	1997	12	5	11	26	55	54.841	162.035	33	1.5
138	1997	12	15	15	0	0	54.841	162.035	33	8.0
139	1997	12	26	8	0	0	16.7	-62.2	33	3.0
140	1998	3	25	3	12	25	-62.877	149.527	10	0.1
141	1998	5	3	23	30	22	22.306	125.308	33	0.1
142	1998	7	17	8	49	13	-2.961	141.926	10	15.0
143	1998	11	29	14	10	31	-2.071	124.891	33	2.8
144	1999	8	17	0	1	39	40.748	29.864	17	2.5
145	1999	11	26	13	21	16	-16.423	168.214	33	6.6
146	2000	1	26	0	0	0	5.2	120.3	26	20.0
147	2000	3	29	0	0	0	38	-123.2	26	15.0
148	2000	5	4	4	21	16	-1.105	123.573	26	6.0
149	2000	6	18	14	44	13	-13.802	97.453	10	0.3
150	2000	7	1	7	1	56	34.221	139.131	10	0.1
151	2000	11	4	0	0	0	43	-127	10	7.0
152	2000	11	16	4	54	56	-3.98	152.169	33	1.0
153	2000	11	16	7	42	17	-5.233	153.102	33	1.0
154	2001	6	23	20	33	17	-16.1	-73.4	33	4.0
155	2002	3	5	21	16	9	6.17	124.28	114	1.5
156	2002	3	26	03	:45		23.47	124.06	33	0.1
157	2002	3	31	6	52	50	24.4	122.21	42	0.2

APPENDIX 9 Lists of Significant Earthquakes

USGS list of significant earthquakes

This is a list of significant earthquakes as listed by the USGS. For other ancient or recent earthquakes not listed here, see the tables below.

Date	Timeâ €ǀ	Place	Lat.	Long.	Fatalities	M	Mxâ€ (M reference)
January 23, 1556		Shaanxi, China	34.5	109.7	830,000	~8	
August 17, 1668		Anatolia, Turkey	40	36	8,000	~8	
January 26, 1700		Cascadia subduction zone from Northern California to Vancouver Island				~9	M (Satake et al, 1996)
November 1, 1755	10:16	Lisbon, Portugal	36	-11	c. 80,000	~8.7	M_l (Johnston, 1996)
December 16, 1811	8:00	New Madrid, Missouri, USA	36.6	-89.6		~8.1	M_l (Johnston, 1996)
January 23, 1812	15:00	New Madrid, Missouri, USA	36.6	-89.6		~7.8	M_l (Johnston, 1996)
February 7, 1812	9:45	New Madrid, Missouri, USA	36.6	-89.6		~8	M_l (Johnston, 1996)
June 2, 1823	8:00	south flank of Kilauea, Hawaii, USA	19.3	-155		~7	M_l (Klein and Wright, 2000)
June 10, 1836	15:30	south San Francisco Bay region, California, USA	36.9	-121.5		~6.5	M_l (Bakun, 1999)
June 1838		San Francisco Peninsula, California, USA	37.3	-123.2		~6.8	M_l (Bakun, 1999)
January 5, 1843	2:45	Marked Tree, Arkansas, USA	35.5	-90.5		~6.3	M_l (Johnston, 1996)
January 9, 1857	16:24	Fort Tejon, California (San Andreas fault from Parkfield to Wrightwood)			1	~7.9	M (Grant and Sieh, 1993; Stein and Hanks, 1998)
December 16, 1857	21:00	Naples, Italy	40.3	16	11,000	~6.9	M_l
October 8, 1865	20:46	San Jose, California, USA	37.2	121.9		~6.5	M_l (Bakun, 1999)
April 3, 1868	2:25	Hilea, southeast Hawaii, Hawaii, USA	19.2	-155.5	77	~7.9	M_l (Klein and Wright, 2000)
October 21, 1868	15:53	Hayward, California, USA	37.7	-122.1	30	~6.8	M_l (Bakun, 1999)
February 20, 1871	8:42	Molokai, Hawaii, USA	21.2	-156.9		~6.8	M_l (Klein and Wright, 2000)
March 26, 1872	10:30	Owens Valley, California, USA	36.5	-118	27	~7.6	M (Beanland and Clark, 1994)

December 15, 1872	5:40	north Cascades, Washington, USA	47.9	-120.3		~7.3	M_l (Malone and Bor, 1979; Rogers et al., 1983)
November 23, 1873	5:00	California-Oregon coast	42.2	-124.2		~7.3	M_l (Bakun, 2000)
August 31, 1886	2:51	Charleston, South Carolina, USA	32.9	-80	60	~7.3	M_l (Johnston, 1996)
April 24, 1890	11:36	California, California, USA	37	121.8		~6.3	M_l (Bakun, 1999)
October 27, 1891	21:38	Mino-Owari, Japan	35.6	136.6	7,273	~8	M_S
April 19, 1892	10:50	Vacaville, California, USA	38.5	-121.8	1	~6.4	M_l (Bakun, 1999)
April 21, 1892	17:43	Winters, California, USA	38.6	-122		~6.4	M_l (Bakun, 1999)
October 31, 1895	11:08	Charleston, Missouri, USA	37	-89.4		~6.6	M_l (Johnston, 1996)
June 15, 1896	19:32	Sanriku, Japan	39.5	144		~8.5	M
June 12, 1897	11:06	Assam, India	26	91	1,500	~8.3	
June 20, 1897	20:14	Calaveras fault, California, USA	37	-121.6		~6.3	M_l (Bakun, 1999)
March 31, 1898	7:43	Mare Island, California, USA	38.1	122.4		~6.3	M_l (Bakun, 1999)
April 15, 1898	7:07	Mendocino County, California, USA	39.3	-123.9		~6.8	M_l (Bakun, 2000)
September 4, 1899	0:22	Cape Yakataga, Alaska, USA	60	-142		7.9	M_S
September 10, 1899	21:41	Yakutat Bay, Alaska, USA	60	-142		8	M_S
October 9, 1900	12:28	Kodiak Island, Alaska, USA	57.1	-153.5		7.7	M_S
March 3, 1901	7:45	Parkfield, California, USA	36.2	-120.7		6.4	M_S (Abe, 1988)
August 27, 1904	21:56	Fairbanks, Alaska, USA	64.7	-148.1		7.3	M_S
July 9, 1905	9:40	Mongolia	49	99		8.4	M
January 31, 1906	15:36	Colombia-Ecuador	1	-81.5	1,000	8.8	M
April 18, 1906	13:12	San Francisco, California (San Andreas fault from Cape Mendocino to San Juan Bautista)			3,000	7.8	M (Bakun, 1999)
August 17, 1906	0:40	ValparaÃso, Chile	-33	-72	20,000	8.2	M

December 28, 1908	4:20	Messina, Italy	38.3	15.6	70,000	7.2	M_S
July 1, 1911	22:00	Calaveras fault, California, USA	37.39	-121.8		6.5	M_S
October 3, 1915	6:52	Pleasant Valley, Nevada, USA	40.5	-117.5		7.1	M (Stover and Coffman, 1993)
October 11, 1918	14:14	Puerto Rico	18.47	-67.63	116	7.5	M_S (McCann, 1985)
December 6, 1918	8:41	Vancouver Island, British Columbia, Canada	49.62	-125.92		7	M_L (Gutenberg and Richter, 1954: Rogers, 1983)
December 16, 1920	12:05	Ningxia-Gansu, China	36.6	105.32	200,000	8.6	M_S
January 31, 1922	13:17	offshore, Cape Mendocino, California, USA	40.7	-125.55		7.3	M_{G-R} (Ellsworth, 1990)
March 10, 1922	11:21	Parkfield, California, USA	35.9	120.9		6.1	M (Bakun and McEvilly, 1984)
January 22, 1923	9:04	offshore, Cape Mendocino, California, USA	40.49	-125.32		7.2	M_{G-R} (Ellsworth, 1990)
September 1, 1923	2:58	Kanto, Japan	35.4	139.08	143,000	7.9	M
March 1, 1925	2:19	Charlevoix, Quebec, Canada	47.76	-69.84		6.3	M (Bent, 1992)
June 28, 1925	1:21	Clarkston Valley, Montana, USA	46.32	-111.52		6.6	M (Dosier, 1989)
June 29, 1925	14:42	Santa Barbara, California, USA	34.3	-119.8	13	6.8	M (Stein and Hanks, 1998)
October 22, 1926	12:35	Monterey Bay, California, USA	36.62	-122.35		6.1	M_{G-R} (Ellsworth, 1990)
October 22, 1926	13:35	Monterey Bay, California, USA	36.55	-122.18		6.1	M_{G-R} (Ellsworth, 1990)
March 7, 1927	9:27	Tango, Japan	35.8	134.92	3,020	7.6	M_S
May 22, 1927	22:32	Tsinghai, China	37.39	102.31	200,000	7.9	M_S
November 4, 1927	13:51	offshore Lompoc, California, USA	34.92	-121.03		7.1	M (Stein and Hanks, 1998)
November 18, 1929	20:32	Grand Banks, Newfoundland, Canada	44.69	-56.01		7.3	M (Bent, 1995)
December 21, 1932	6:10	Cedar Mountain, Nevada, USA	38.51	-118.08		7.2	M
March 2, 1933	17:31	Sanriku, Japan	39.22	144.62	2,990	8.4	M
March 11, 1933	1:54	Long Beach, California, USA	33.6	-118	115	6.4	M (Hauksson & Gross, 1991)

November 20, 1933	23:21	Baffin Bay, Canada	73	-69.98		7.4	M (Stein et al. 1979)
January 15, 1934	8:43	Bihar, India	27.55	87.09	10,700	8.1	M (Chen and Molnar, 1977)
June 8, 1934	4:47	Parkfield, California, USA	35.9	-120.9		6.1	M (Bakun and McEvilly, 1984)
November 1, 1935	6:03	Timiskaming, Quebec, Canada	48.89	-79		6.2	M (Bent, 1996)
July 22, 1937	17:09	Salcha, Alaska, USA	64.49	-146.85		7.3	M_S
January 23, 1938	8:32	Maui, Hawaii, USA	20.96	-156.18		6.8	M_S (Klein and Wright, 2000)
November 10, 1938	20:18	Shumagin Islands, Alaska, USA	55.33	-158.37		8.2	M
December 26, 1939	23:57	Erzincan, Turkey	39.77	39.53	32,700	7.8	M_S
May 19, 1940	4:36	Imperial Valley, California, USA	32.73	-115.5	9	7.1	M (Ellsworth, 1990)
December 7, 1944	4:35	Tonankai, Japan	33.75	136	1,223	8.1	M
April 1, 1946	12:28	Unimak Island, Alaska, USA	52.75	-163.5	165	7.3	M_S (Stover and Coffman, 1993)
June 23, 1946	17:13	Vancouver Island, British Columbia, Canada	49.75	-124.5		7.3	M_L (Gutenberg and Richter, 1954; Rogers, 1983)
August 4, 1946	17:51	Dominican Republic	19.25	-69	100	8	M_S (Abe, 1981)
December 20, 1946	19:19	Nankaido, Japan	32.5	134.5	1,330	8.1	M
October 16, 1947	2:09	Fairbanks, Alaska, USA	64.2	-148.3		7.2	M
April 13, 1949	19:55	Olympia, Washington, USA see Nisqually Earthquake	47.1	-122.7	8	7.1	M_L (Baker and Langston, 1987)
August 22, 1949	4:01	Queen Charlotte Islands, British Columbia, Canada	53.62	-133.27		8.1	M_S (Gutenberg and Richter, 1954)
August 15, 1950	14:09	Assam-Tibet	28.5	96.5	1,526	8.6	M
August 21, 1951	10:57	Kona, Hawaii, USA	19.5	-155.95		6.9	M_S (Klein and Wright, 2000)
July 21, 1952	11:52	Kern County, California, USA	34.95	-119.05	12	7.3	M (Stein and Hanks, 1998)
November 4, 1952	16:58	Kamchatka, Russia	52.76	160.06		9	M
March 29, 1954	6:17	Spain	37.03	-3.51		7.9	M

July 6, 1954	11:13	Rainbow Mountain, Nevada, USA	39.42	-118.53		6.6	M (Ellsworth, 1990)
August 24, 1954	5:51	Stillwater, Nevada, USA	39.58	-118.45		6.8	M (Ellsworth, 1990)
December 16, 1954	11:07	Fairview Peak, Nevada, USA	39.32	-118.2		7.1	M (Ellsworth, 1990)
December 16, 1954	11:11	Dixie Valley, Nevada, USA	39.5	-118		6.8	M (Ellsworth, 1990)
October 24, 1955	4:10	Concord, California, USA	38	-122.1	1	5.4	M_L (Bolt and Miller, 1975)
March 9, 1957	14:22	Andreanof Islands, Alaska, USA	51.56	-175.39		9.1	M
December 4, 1957	3:37	Gobi-Altai, Mongolia	45.15	99.21	30	8.1	M
April 7, 1958	15:30	Huslia, Alaska, USA	65.94	-156.37		7.3	M
July 10, 1958	6:15	Fairweather, Alaska, USA	58.37	-136.66	5	7.7	M
August 18, 1959	6:37	Hebgen Lake, Montana, USA	44.6	-110.64	28	7.3	M (Dosier, 1985)
February 29, 1960	23:40	Agadir, Morocco	30.5	-9.3	10,000	5.7	M
May 22, 1960	19:11	Chile	-38.24	-73.05	5,700	9.5	M
March 28, 1964	3:36	Prince William Sound, Alaska, USA	61.02	-147.65	125	9.2	M
June 16, 1964	4:01	Niigata, Japan	38.43	139.23	26	7.5	M
February 4, 1965	5:01	Rat Islands, Alaska, USA	51.21	-178.5		8.7	M
April 29, 1965	15:28	Seattle-Tacoma, Washington, USA	47.32	-122.33	7	6.5	M_L (Algermissen and Harding, 1965)
June 28, 1966	4:26	Parkfield, California, USA	35.88	-120.49		6.1	M (Tsai and Aki, 1969)
September 12, 1966	16:41	Truckee, California, USA	39.38	-120.22		5.9	M (Tsai and Aki, 1970)
December 10, 1967	22:51	Koyna, India	17.39	73.77		6.3	M (Langston, 1976)
October 2, 1969	6:19	Santa Rosa, California, USA	38.3	-122.76	1	5.7	M_L (Bolt and Miller, 1975)
May 31, 1970	20:23	Peru	-9.25	-78.84	66,000	7.9	M
July 31, 1970	17:08	Colombia	-1.49	-72.56		8	M_S
February 9, 1971	14:00	San Fernando, California, USA	34.4	-118.39	65	6.7	M (Heaton, 1982)

February 4, 1975	11:36	Haicheng, China	40.72	122.73	10,000	7	M (Cipar, 1979)
August 1, 1975	20:20	Oroville, California, USA	39.5	-121.39		5.8	M
November 29, 1975	14:47	south flank of Kilauea, Hawaii, USA	19.45	-155.03	2	7.2	M_S (Klein and Wright, 2000)
February 4, 1976	9:01	Guatemala	15.3	-89.14	23,000	7.5	M
July 27, 1976	19:42	Tangshan, China	39.61	117.89	242,419*	7.6	M
August 6, 1979	17:05	Coyote Lake, California, USA	37.11	-121.52		5.7	M (Ellsworth, 1990)
October 15, 1979	23:17	Imperial Valley, California, USA	32.82	-115.65		6.4	M (Hartzell and Heaton, 1983)
January 24, 1980	19:00	Livermore, California, USA	37.71	-121.73		5.8	M (Bolt et al., 1981)
May 25, 1980	16:33	Mammoth Lakes, California, USA	37.6	-118.83		6.1	M (Ellsworth, 1990)
May 25, 1980	16:49	Mammoth Lakes, California, USA	37.65	-118.9		5.9	M_L (Ellsworth, 1990)
May 25, 1980	19:44	Mammoth Lakes, California, USA	37.55	-118.82		5.8	M (Ellsworth, 1990)
May 27, 1980	14:50	Mammoth Lakes, California, USA	37.48	-118.8		6	M (Ellsworth, 1990)
November 8, 1980	10:27	Gorda Plate, California, USA	41.12	-124.67		7.2	M (Ellsworth, 1990)
May 2, 1983	23:42	Coalinga, California, USA	36.23	-120.32		6.5	M (Ellsworth, 1990)
October 28, 1983	14:06	Borah Peak, Idaho, USA	44.09	-113.8	2	7	M (PDE Monthly Listing)
November 16, 1983	16:13	Kaoiki, Hawaii, USA	19.44	155.38		6.7	M (PDE Monthly Listing)
April 24, 1984	21:15	Morgan Hill, California, USA	37.3	-121.71		6.2	M (PDE Monthly Listing)
November 23, 1984	18:08	Round Valley, California, USA	37.45	-118.6		5.7	M (Ellsworth, 1990)
September 19, 1985	13:17	MichoacÃ¡n, Mexico	18.44	-102.36	9,500	8	M (PDE Monthly Listing)
December 23, 1985	5:16	Nahanni, Northwest Territories, Canada	62.16	-124.31		6.8	M (Wetmiller et al., 1988)
May 7, 1986	22:47	Andreanof Islands, Alaska, USA	51.56	-174.81		8	M (PDE Monthly Listing)
July 8, 1986	9:20	north Palm Springs, California, USA	33.97	-116.78		6.1	M (Hartzell, 1989)
July 21, 1986	14:42	Chalfant Valley, California, USA	37.53	-118.43		6.2	M (Ellsworth, 1990)

October 1, 1987	14:42	Whittier Narrows, California, USA	34.06	-118.13	8	5.9	M (Hartzell and Iida, 1990)
November 30, 1987	19:23	Gulf of Alaska	58.84	-142.6		7.9	M (PDE Monthly Listing)
January 22, 1988	0:35	Tennant Creek, Australia	-19.87	133.78		6.3	M (Choy and Bowman, 1990)
January 22, 1988	3:57	Tennant Creek, Australia	-19.88	133.83		6.4	M (Choy and Bowman, 1990)
January 22, 1988	12:04	Tennant Creek, Australia	-19.9	133.83		6.6	M (Choy and Bowman, 1990)
March 6, 1988	22:35	Gulf of Alaska	57.26	-142.75		7.8	M (PDE Monthly Listing)
November 25, 1988	23:46	Saguenay, Quebec, Canada	48.06	-71.27		5.9	M (Boatwright and Choy, 1992)
December 7, 1988	7:41	Spitak, Armenia	40.93	44.11	25,000	6.8	M (PDE Monthly Listing)
October 18, 1989	0:04	Loma Prieta, California, USA	37.14	-121.76	63	6.9	M (Wald et al., 1991)
December 25, 1989	14:24	Ungava, Quebec, Canada	60.07	-73.54		6	M (Bent, 1994)
June 28, 1991	1:43	Sierra Madre, California, USA	34.25	-117.95	2	5.6	M (Wald et al., 1991)
August 17, 1991	22:17	Honeydew, California, USA	41.79	-125.58		7.1	M (PDE Monthly Listing)
April 23, 1992	4:50	Joshua Tree, California, USA	33.87	-116.55		6.1	M (Hauksson et al., 1993)
April 25, 1992	18:06	Cape Mendocino, California, USA	40.38	-124.05		7.2	M (PDE Monthly Listing)
April 26, 1992	7:41	offshore, Cape Mendocino, California, USA	40.55	-124.29		6.5	M (Oppenheimer et al., 1993)
April 26, 1992	11:18	offshore, Cape Mendocino, California, USA	40.44	-124.43		6.7	M (Oppenheimer et al., 1993)
June 28, 1992	11:57	Landers, California, USA	34.2	-116.52	3	7.3	M (Sieh et al. 1993)
June 29, 1992	10:14	Little Skull Mountain, Nevada, USA	36.77	-116.32		5.7	M (Walter, 1993)
September 2, 1992	0:16	Nicaragua	11.77	-87.35	116	7.7	M (PDE Monthly Listing)
September 29, 1993	22:25	Latur-Killari, India	18.08	76.52	9,748	6.2	M (PDE Monthly Listing)
January 17, 1994	12:30	Northridge, California, USA	34.18	-118.56	60	6.7	M (PDE Monthly Listing)
June 9, 1994	0:33	Bolivia	-13.86	-67.49	5	8.2	M (PDE Monthly Listing)
September 1, 1994	15:15	Cape Mendocino, California, USA	40.38	-125.78		7.1	M (PDE Monthly Listing)

January 16, 1995	20:46	Kobe, Japan	34.57	135.03	5,502	6.9	M (PDE Monthly Listing)
May 21, 1997	22:51	Jabalpur, India	23.07	80.12	38	5.8	M (Singh et al., 1999)
July 17, 1998	8:49	New Guinea	-2.94	142.58	2,183	7	M (PDE Monthly Listing)
January 25, 1999	18:19	Colombia	4.45	-75.65	1,185	6.2	
August 17, 1999	0:01	Izmit, Turkey	40.77	30	17,118	7.6	M (PDE Monthly Listing)
September 20, 1999	17:47	Chi-Chi, Taiwan	23.82	120.86	2,400	7.7	M (PDE Monthly Listing)
October 16, 1999	9:46	Hector Mine, California, USA	34.56	-116.44		7.2	M (PDE Monthly Listing)
November 12, 1999	16:57	Duzce, Turkey	40.82	31.23	894	7.2	M (PDE Monthly Listing)
September 3, 2000	8:36	Napa, California, USA	38.38	-122.41		5	M (BRK)
November 16, 2000	4:54	New Ireland, Papua New Guinea	-4	152.33		8	
January 13, 2001	17:33	El Salvador	13.04	-88.66	844	7.7	M (PDE Monthly Listing)
January 26, 2001	3:16	Gujarat, India	23.39	70.23	20,085	7.7	M (PDE Monthly Listing)
February 28, 2001	18:54	Olympia, Washington, USA	47.11	-122.6		6.8	M (PDE Monthly Listing)
June 23, 2001	20:33	coastal Peru	-16.3	-73.55	75	8.4	M (PDE Monthly Listing)
March 25, 2002	14:56	Hindu Kush Region, Afghanistan	36.06	69.32	1,000	6.1	M (PDE Monthly Listing)
April 20, 2002	10:50	Au Sable Forks, New York	44.51	-73.7		5.2	M (PDE Monthly Listing)
November 3, 2002	22:12	Denali National Park, Alaska, USA	63.52	-147.44		7.9	M (QED)
May 21, 2003	18:44	Boumerdes, Algeria	36.96	3.63	2,266	6.8	M (QED)
September 25, 2003	19:50	Hokkaido, Japan	41.82	143.91		8.3	M (PDE Monthly Listing)
November 17, 2003	06:43	Rat Islands, Alaska, USA	51.15	178.65		7.8	M (PDE Monthly Listing)
December 22, 2003	19:15	San Simeon, California, USA	35.71	-121.10	2	6.6	M (PDE Monthly Listing)
December 26, 2003	01:56	southeastern Iran	29.00	58.31	31,000	6.6	M (PDE Monthly Listing)
September 28, 2004	17:15	Parkfield, California, USA	35.81	-120.37		6.0	M (QED)
December 26, 2004	00:58	off west coast northern Sumatra	3.30	95.87	283,106	9.0	M (QED)

March 28, 2005	16:09	Northern Sumatra, Indonesia	2.07	97.01		1,313	8.7	M (QED)

$M_{G\text{-}R}$ = Gutenberg and Richter's (1954) magnitude, M_S = 20 s surface-wave magnitude, M = moment magnitude (Hanks and Kanamori, 1979), and M_I is an intensity magnitude, M_L is local magnitude (Richter, 1935).

GMT

* Fatalities estimated as high as 655,000.

Source: United States Geological Survey (USGS)

Other earthquakes not listed by the USGS

Date	Site	Deaths	Magnitude or intensity*	Comments
464 BC	Sparta, Greece	?	-	Led to a helot uprising and strained relations with Athens, one of the factors that led to the Peloponnesian War
226 BC	Rhodes, Greece	?	-	Destroyed Colossus of Rhodes and city of Kameiros
365	Knossos, Crete (Greece)	50,000	XI	
365	Cyrene, Libya	?	-	
May 20 526	Antiochia, Syria	250,000	-	
844	Damascus, Syria	50,000	VIII	
847	Mosul, Iraq	50,000	-	
847	Damascus, Syria	70,000	X	
856	Qumis, Damghan, Iran	200,000	-	
856	Corinth, Greece	45,000	-	
893	Caucasus	82,000	-	
893	Daipur, India	180,000	-	
893	Ardabil, Iran	150,000	-	
1036	Shanxi, China	23,000	-	
1042	Palmyra, Baalbek, Syria	50,000	X	
1057	Chihli (Hopeh), China	25,000	-	
1138	Ganzah, Aleppo, Syria	230,000	XI	
1156-1157	Syria	?	-	
1170	Sicily	15,000	-	
July 5, 1201	Upper Egypt or Syria	1,100,000	IX	

1268	Cilicia, Anatolia (Turkey)	60,000	-	
September 27 1290	Chihli (Hopeh), China	100,000	6.7	
May 20 1293	Kamakura, Japan	30,000	-	
October 18 1356	Basel, Switzerland	1,000	6.5	
January 26 1531	Lisbon, Portugal	30,000	-	
November 25 1667	Shemakha, Azerbaijan	80,000	XII	
June 7 1692	Port Royal, Jamaica	30,000	-	
January 11 1693	Catania Province, Sicily	60,000	-	
1693	Naples, Italy	93,000	-	
1707	Japan (seismic wave)	30,000	-	
December 30 1730	Hokkaido Island, Japan	137,000	-	
1731	Beijing, China	100,000	-	
October 11 1737	Calcutta, India	300,000	-	1737 Calcutta cyclone
October 16 1737	Kamchatka, Russia		9.3	Kamchatka earthquakes
June 7 1755	Northern Persia	40,000	-	
November 18 1755	Boston, Massachusetts	0	-	
February 28, 1780	Iran	200,000	-	Latitude: 38, longitude: 46.2
February 4â€"5, March 28 1783	Calabria, Italy	35,000	-	
February 4 1797	Quito, Ecuador & Cuzco, Peru	41,000	-	
February 10 1797	Sumatra, East Indies (now Indonesia)	300	8.4	
December 8, 1812 at 9:45	Wrightwood, California, USA (lat. 34.22, long. 117.39)	40	~7	Destroys church of Mission San Juan Capistrano
November 24 1833	Sumatra, East Indies (now Indonesia)		8.7	
January 23, 1855 21:11 local time	Wairarapa, New Zealand	4	~8.0	Raised sections of Wellington coastline by 2 metres
February 16 1861	Sumatra, East Indies (now Indonesia)		8.5	

February 3, 1931, 10:47 local time	Napier, New Zealand *see* Napier earthquake	258	7.9	Much of city destroyed; 40 km² of seabed raised to become dry land
December 25, 1932,	Gansu, China	70,000	7.6	
April 21, 1935, 6:02 local time	Hsinchu-Taichung, Taiwan	3,279	7.1	
December 20, 1942,	Turkey *see* NAFZ		6.9	
November 26, 1943,	Turkey *see* NAFZ		7.7	
January 15, 1944, 20:50 GTM-3	San Juan Argentina	8,000 ~ 10,000	IX (7.8)	The 30 second long earthquake destroyed 95% of the city, located 30 km form the epicentre.
February 1, 1944,	Turkey *see* NAFZ		7.5	
August 17, 1949,	Turkey *see* NAFZ		7.1	
August 13, 1951,	Turkey *see* NAFZ		6.8	
August 8- August 12, 1953	Kefalonia, Greece	476	7.2	113 tremors over five days
May 26, 1957,	Turkey *see* NAFZ		6.8	
August 19, 1966,	Turkey *see* NAFZ		6.6	
July 22, 1967,	Turkey *see* NAFZ		7.0	
May 22, 1971,	Turkey *see* NAFZ		6.8	
December 23, 1972	Managua, Nicaragua	5,000 â€" 20,000	6.3	Somoza mishandling of earthquake aid has been cited as a contributing factor to the Sandinista revolution; devastated largest city in Nicaragua (Managua)
June 30, 1975	Norris Junction, Yellowstone National Park, Wyoming, USA	0	6.1	Largest earthquake in Yellowstone Caldera since 1959 Hebgen Lake event
March 4, 1977	Bucharest, Romania see 1977 Bucharest Earthquake	1500	7.5	Lasted ~5 minutes and left the capital devastated.
June 21, 1990	Northwestern Iran	35000	7.7	Called *Manjil-Rudbar Earthquake*
March 13, 1992,	Turkey *see* NAFZ		6.5	

Note: Magnitudes are generally estimations from intensity data. When no magnitude was available, the maximum intensity, written as a Roman numeral from I to XII, is given.

Recent earthquakes not listed above

Date	Timeâ€¡	Place	Lat.	Long.	Fatalities	Comments	Magnitude
September 5, 2004	19:07 and 23:57 Japan Time	Off central Tokai region, western Japan			0	20+ injured, tsunami and flooding	6.9 and 7.4
October 8, 2004	15:35	Mindoro, Philippines	13.21	121.65	-	Sporadic blackouts	6.6
October 9, 2004	22:26	80 kilometres southwest of Managua, Nicaragua	12	86	0	Minimal damage	6.9
October 23, 2004	17:56	Ojiya, Japan see 2004 Chuetsu Earthquake	37.3	138.8	46	4801 injured; 103,000+ displaced	6.9
October 27, 2004	18:34	Vrancea, Romania			0	Telephone service interrupted; felt also in Bulgaria, Ukraine, Moldova and Turkey	5.8 (Istanbul's Kandilli Observatory reported 6.5)
November 10, 2004	22:58	Solomon Islands	9	159	0	No injuries nor damage	6.9
November 11, 2004	21:36	96 kilometres west-northwest of Dili, East Timor			6	21 injured	7.3
November 15, 2004	around 9:00	off coast of ChocÃ³, Colombia			0	11+ injured, 18 homes destroyed, half near Buenaventura	6.7
November 21, 2004		45 kilometres north-northwest of Dominica			1	Half-dozen injured, damage also in Guadeloupe	6.0
November 21, 2004		48 kilometres south-southwest of San Jose, Costa Rica			8	Half-dozen injured	6.2
November 28, 2004	18:32	900 kilometres northwest of Tokyo, Japan, 50 km below sea level			0	8 injured, utility services interrupted in hundreds of homes	7.1

Appendix

December 23, 2004	14:59	495 kilometres north of Macquarie Island, SW of New Zealand	50.24°S	160.13°E	0	Minimal damage reported in southern New Zealand	8.1
February 11, 2005	21:00:23.9	114 kilometres southwest of Haines Junction, Yukon, Canada	60.21°N	139.50°W	0	No damage nor injuries	5.5
February 22, 2005	02:25:21 UTC, 05:55:21 Local Time	Zarand, Iran	30.726°N	56.817°E	At least 790	Hundreds injured, damage in some 40 villages, centered 150 miles from Bam, Iran	6.4
March 6, 2005	19:06:52 UTC, 3:06:52 AM Local Time	Near Sua-ho, Taiwan	24.607°N	121.859°E	0	See below	5.7
March 6, 2005	19:08:00 UTC, 3:08:00 AM Local Time	Near Sua-ho, Taiwan	24.650°N	121.855°E	0	Occurred within minutes of a previous earthquake of magnitude 5.7 centered in the same area; no major injuries or damage reported from either earthquake	5.4
March 6, 2005	06:17:49 UTC, 1:17:49 AM Local Time	Gaspe Peninsula Canada	47.750°N	69.730°W	0	102 km (63 miles) WNW (303Â°) from Fort Kent, ME	5.4
March 20, 2005	01:53 UTC, 10:53 AM Local Time	Offshore of Fukuoka, Japan	33.54°N	130.12°E	1	1145 injured; 3000+ displaced	7.0
June 13, 2005	22:44:33 UTC, 18:44:33 Local Time	Tarapaca, Chile	19.896°S	69.125°W	11	115 km (70 miles) ENE of Iquique, Chile.	7.8
June 15, 2005	02:50:53 UTC, 18:50:53 Local Time June 14	Offshore of Northern California, USA	41.284°N	125.983°W	0	157 km (98 miles) WSW of Crescent City, California.	7.2

August 16, 2005	02:46:30 UTC, 11:46:30 Local Time August 16	Off the east coast of Honshu, Japan	38.259°N	148.980°E	0	95 km (60 miles) E of Sendai, Miyagi.	7.2
October 8, 2005	03:50:38 UTC, 08:50:38 Local Time October 8	Kashmir	34.43°N	73.54°E	100,000 (Nov 23/2005 estimate), can rise to 150,000	125 km (75 miles) WNW of Srinagar, Kashmir (pop 894,000)	7.6 or 7.8
December 5, 2005	12:19:55 UTC, 14:19:55 Local Time	Lake Tanganyika region	6.212°S	29.599°E		55 km (35 miles) SE of Kalemie, DR Congo	6.8
January 8, 2006	11:34:52 UTC, 13:34:52 Local Time	Southern Greece	36.250°N	23.498°E		195 km (120 miles) S of Athens, Greece	6.7
February 23, 2006	00:19 Local Time	Northern Mozambique				140 miles southwest of Beira	7.5

Largest earthquakes by magnitude

Pos.	Date	Location	Magnitude
1	May 22, 1960	Chile	9.5
2	October 16, 1737	Kamchatka, Russia	9.3
3	March 28, 1964	Prince William Sound, Alaska, USA	9.2
4	December 26, 2004	Off west coast northern Sumatra, Indonesia	9.0-9.3*
5	March 9, 1957	Andreanof Islands, Alaska, USA	9.1
6	November 4, 1952	Kamchatka, Russia	9.0
7	January 26, 1700	Cascadia subduction zone from Northern California to Vancouver Island	~9
8	January 31, 1906	Colombia-Ecuador	8.8
9	February 4, 1965	Rat Islands, Alaska, USA	8.7
10	November 24, 1833	Sumatra, Indonesia	8.7
11	November 1, 1755	Lisbon, Portugal	~8.7
12	March 28, 2005	Sumatra, Indonesia	8.5-8.7*
13	December 16, 1920	Ningxia-Gansu, China	8.6
14	August 15, 1950	Assam-Tibet	8.6

* Scientists have not yet agreed on an official magnitude.

Deadliest earthquakes on record

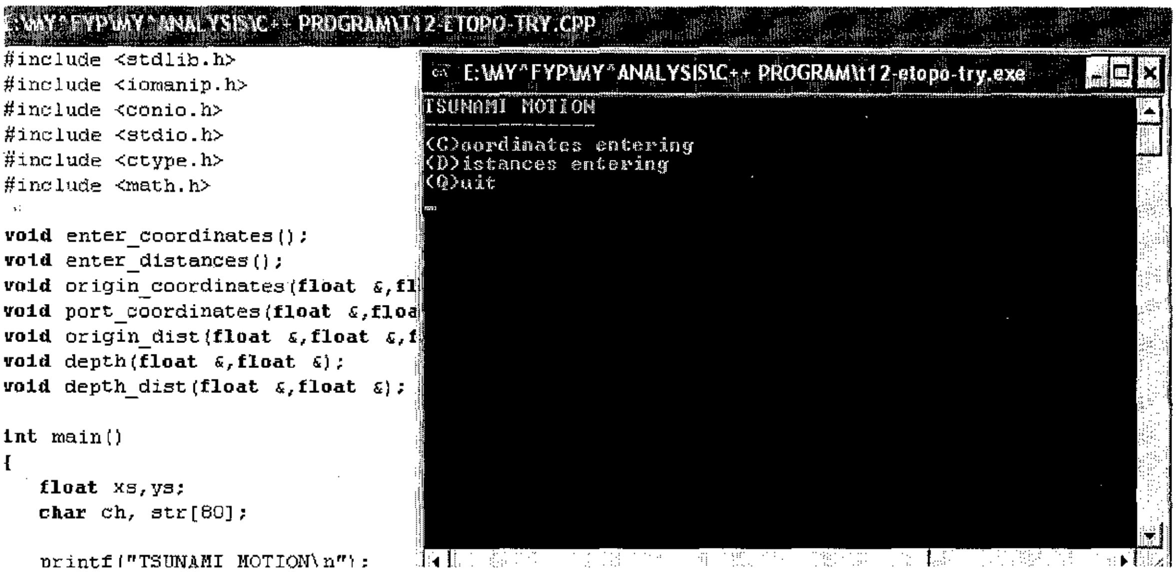
Rank	Name	Date	Location	Fatalities	Magnitude	Comments
1	Shaanxi	January 23, 1556	Shaanxi, China	830,000	~8	
2	Tangshan	July 27, 1976	Tangshan, China	255,000 (official)	7.5	Estimated death toll as high as 655,000.
3	Aleppo	August 9, 1138	Aleppo, Syria	230,000		
4	Indian Ocean	December 26, 2004	Off west coast northern Sumatra, Indonesia	230,000	9.0-9.3	Deaths from earthquake and tsunami.[2]
5	Damghan	December 22, 856	Damghan, Iran	200,000		
	Gansu	December 16, 1920	Ningxia-Gansu, China	200,000	8.6	Major fractures, landslides.
	Tsinghai	May 22, 1927	Tsinghai, China	200,000	7.9	Large fractures.
8	Ardabil	March 23, 893+	Ardabil, Iran	150,000		
9	Kanto	September 1, 1923	Kanto, Japan	143,000	7.9	Great Tokyo fire.
10	Ashgabat	October 6, 1948	Ashgabat, Turkmenistan	110,000	7.3	
11	Kashmir	October 8, 2005	Kashmir & N.W.F.P, Pakistan	100,000 (estimated) , 80,000 (official)	7.6 or 7.8	3.5 Million people homeless, 100,000 feared dead

APPENDIX 10 Lists of Selected Ports

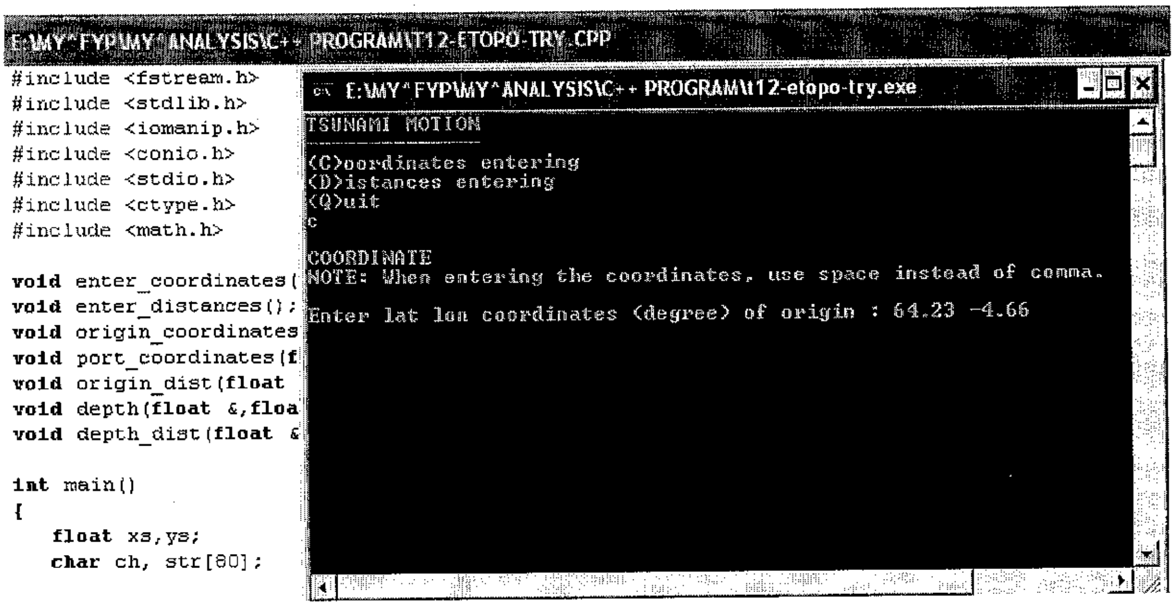
No.	Ports	Country	Ocean	Latitude	Longitude
1	Bangkok	Thailand	Pacific	13° 42' N	100° 34' E
2	Hong Kong	China	Pacific	22° 18' N	114° 10' E
3	Kao-hsiung	Taiwan	Pacific	22° 01' N	120° 15' E
4	Los Angeles	United States	Pacific	33° 42' N	118° 15' W
5	Manila	Philippines	Pacific	14° 35' N	120° 59' E
6	Pusan	South Korea	Pacific	35° 00'N	129° 00'E
7	San Francisco	United State	Pacific	37° 46' N	122° 26' W
8	Seattle	United State	Pacific	47° 39' N	122° 18' W
9	Shanghai	China	Pacific	31° 12' N	121° 26' E
10	Singapore	Singapore	Pacific	01° 18' N	103° 50' E
11	Sydney	Australia	Pacific	33° 52' S	151° 12' E
12	Vladivostok	Russia	Pacific	43° 07' N	131° 55' E
13	Wellington	New Zealand	Pacific	41° 17' S	174° 46' E
14	Yokohama	Japan	Pacific	35° 11' N	139° 22' E
15	Antwerp	Belgium	Atlantic	51° 13' N	04° 25' E
16	Buenos Aires	Argentina	Atlantic	34° 35' S	58° 29' W
17	Casablanca	Morocco	Atlantic	33° 35' N	07° 39' W
18	Colon	Panama	Atlantic	09° 20' N	80° 00' W
19	Copenhagen	Denmark	Atlantic	55° 41' N	12° 33' E
20	Dakar	Senegal	Atlantic	14° 42' N	17° 29' W
21	Hamburg	Germany	Atlantic	53° 33' N	09° 58' E
22	Lisbon	Portugal	Atlantic	38° 43' N	09° 08' W
23	Montevideo	Uruguay	Atlantic	34° 51' S	56° 13' W
24	Montreal	Canada	Atlantic	45° 30' N	73° 33' W
25	New Orleans	United State	Atlantic	29° 59' N	90° 15' W
26	New York	United State	Atlantic	42° 39' N	73° 45' W
27	Oslo	Norway	Atlantic	59° 56' N	10° 44' E
28	Rio de Janeiro	Brazil	Atlantic	22° 55' S	43° 12' W
29	Rotterdam	Netherlands	Atlantic	04° 20' N	51° 53' E
30	Bombay	India	Indian	18° 54' N	72° 49' E

31	Calcutta	India	Indian	22° 32' N	88° 20' E
32	Colombo	Sri Lanka	Indian	06° 54' N	79° 52' E
33	Durban	South Africa	Indian	29° 52' S	31° 02' E
34	Jakarta	Indonesia	Indian	06° 11' S	106° 50' E
35	Madras	India	Indian	13° 04' N	80° 15' E
36	Melbourne	Australia	Indian	37° 49' S	144° 58' E
37	Murmansk	Russia	Arctic	68° 57' N	33° 10' E
38	Prudhoe Bay	United State	Arctic	70° 15' N	148° 19' W

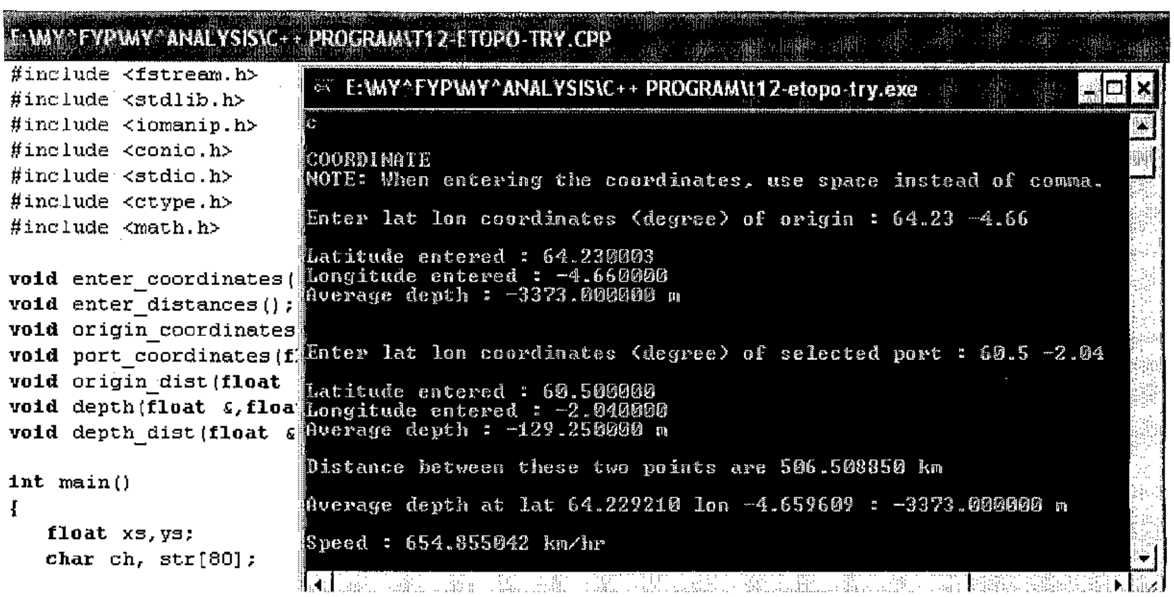
APPENDIX 11 Example of Program Calculation



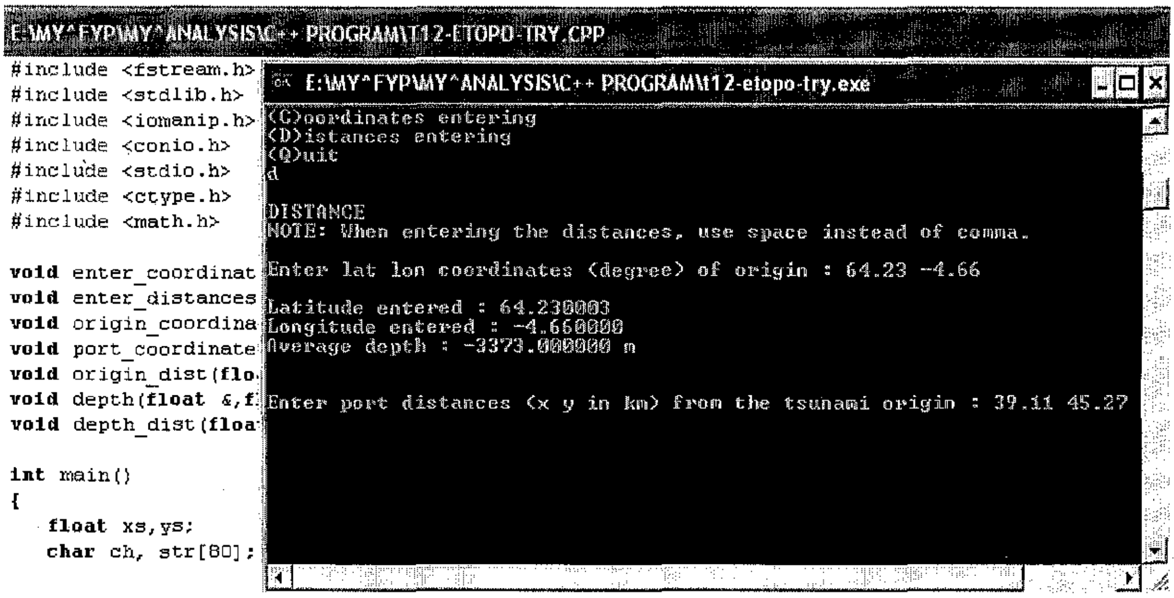
The program will ask a user to choose either to enter the coordinates of the selected port or the distance of the selected port from the source of tsunami (which is always been asked in coordinate's latitude longitude). The speed and distance between the source and the selected port are calculated and displayed by the program.



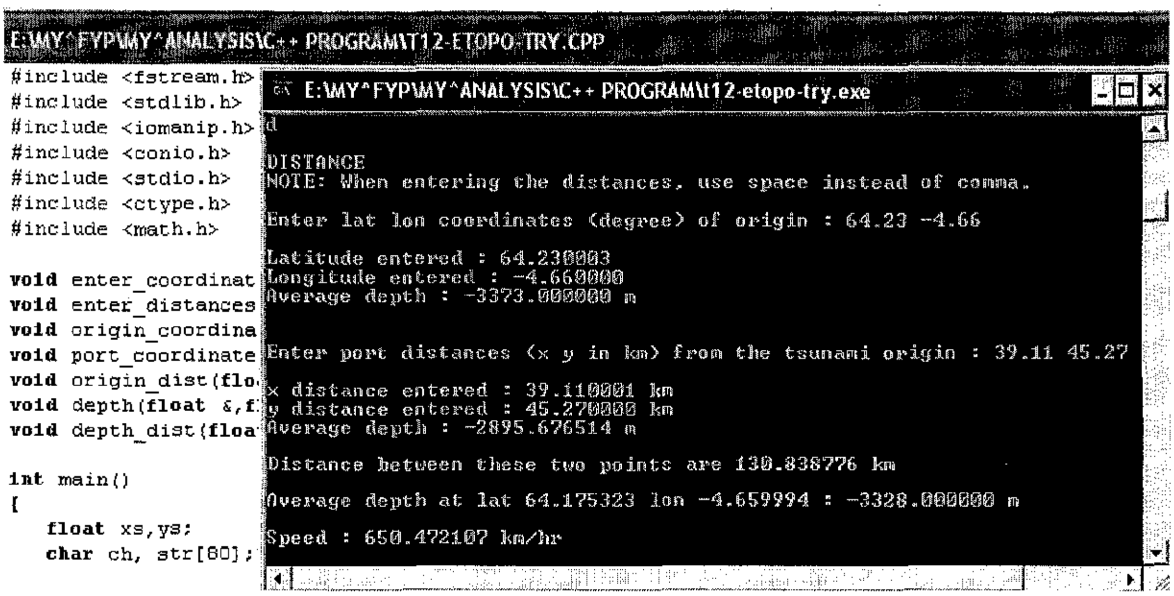
Here is an example when choosing coordinates entering. All coordinates entered should be in degrees.



Once the locations of tsunami's source and selected port have been identified, the speed starting from the source point is calculated and displayed in km/hr. It uses the simple shallow water equation where v = sqrt(g*y) and y is the average depth done by the program through interpolation. The operation of calculating speed and then time is repeated until it reached the selected port.



Here is an example when choosing a distance entering. All distances entered should be in kilometres.



The same output procedure; speed, starting from the source of tsunami is calculated and displayed by the program.