PDHonline Course G207 (3 PDH)

Tsunamis: Basic Principles

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Tsunamis: Basic Principles

Samir G. Khoury, Ph.D., P.G.

Course Outline

This course on "Tsunamis" is presented as a complement to course G175 on "Earthquakes: Basic Principles" for the benefit of those students who want to learn more about this particularly devastating natural phenomenon. Course G175, however, is not a pre-requisite for taking this course. This course is a stand-alone presentation that can be taken independently of course G175.

In this course you will learn that any number of large-scale, short duration disturbances of the ocean floor can generate tsunamis. Most frequently, however, it is the strong, shallow submarine earthquakes that are the most likely triggering mechanism of these monstrous sea waves.

Following a brief explanation of the origin of the word, you will learn how to describe the geometry and general behavior of water waves and what distinguishes wind-generated waves from tsunamis. The geologic concept of plate tectonics is then presented, which explains that the earth's crust is divided into a number of rigid plates that interact with one another causing seismic activity along their boundaries. In fact, it is the interaction between the oceanic and continental plates that most frequently trigger the large seismic events that deform the ocean floor and spawn the most devastating tsunamis. A step by step illustration of this process is presented along with an explanation of how the initial tsunami wave splits into two waves that start traveling in opposite directions. The wave that travels out to the deep ocean is known as the distant tsunami, while the other wave that travels towards the nearby coast is referred to as the local tsunami. The wave transformations that occur at shallow oceanic depths are explained as they control the ensuing wave run-up that occurs all along the coastline. The equations used to compute the velocity of tsunamis are presented in an appendix at the end of the course.

The characteristics of the most notable tsunamis that occurred since 1900 are presented and discussed. Experiences gained from the study of these events led the US National Oceanic and Atmospheric Administration (NOAA) to develop and deploy several tsunami-warning stations in the Pacific Ocean in the mid-1990s. When data collected from these stations confirm the detection of a tsunami, scientists begin immediately to predict the propagation course and velocity of the waves. Warnings are then issued to the most susceptible areas likely to be affected. Following the devastating tsunami of December 26, 2004, several additional tsunami detection stations have been added to the existing network.

Finally, other mechanisms that could also trigger tsunamis are presented and explained. Examples from the historical and geological records are presented as evidence that tsunamis have occurred in the past and are therefore one of the recurring and potent geologic hazards of our planet.

A glossary of terms and acronyms used is provided at the end of this course as a reference to assist the student in following the concepts that are discussed throughout the text.

The information presented in this course is based on the professional experience gained by the author in dealing with various aspects of seismic issues he dealt with in association with the major engineering projects he managed around the world.

Learning Objective

In this course you will learn that large earthquakes that affect the ocean floor are capable of generating immense sea waves called "tsunamis", a Japanese word that means "harbor wave". You will also understand why this is an appropriate descriptive term for this phenomenon. In the open ocean these waves have relatively low heights, but are of enormous longitudinal dimension (at right angle to the direction of propagation). As they approach the coast, these waves undergo significant transformations that determine the ensuing wave run-up above mean sea level along the coastline. Tsunamis can travel at great speed for very large distances such as across the entire widths of oceans, inflicting significant damage to far away coastal towns. You will specifically learn:

1) How the wavelength, wave height and period are used to describe the geometry and behavior of wind generated waves and tsunamis,
2) That wind generated waves and tsunamis are easily distinguishable,
3) That the earth's crust is formed of interlocking rigid plates that interact with each other,
4) That the cycles of strain accumulation and slippage along these plate boundaries is the most common mechanism for the triggering of large earthquakes and tsunamis,
5) How the near shore transformations of tsunamis determine the ultimate run-up of the waves above the coastal mean sea level,
6) That the devastating effects of tsunamis led NOAA to develop an early tsunami warning system that was first deployed in the Pacific Ocean in the mid-1990s,
7) That the initiation of a tsunami can be readily detected by the monitoring stations of the warning system,
8) How to compute the propagation velocity of a tsunami in open water,
9) That tsunamis can also be generated by massive submarine landslides, the collapse of marine volcanoes, and even by the impact of large meteorites or asteroids, and
10) That tsunamis occurred periodically throughout the geologic record indicating that these events represent one of the most potent recurring natural hazards of our planet.

Course Content

Introduction

A tsunami, also known as a seismic sea wave, seismic surge or earthquake sea wave, is produced by any large-scale, short duration disturbance of the ocean floor. As all of the alternate names imply, it is the strong, shallow submarine earthquakes that are by far the most prevalent causes for the generation of these potentially devastating sea waves. However, sudden submarine earth movements such as massive landslides into oceans, submarine volcanic eruptions, the sudden collapse of volcanic structures, and even the impact of large cosmic bodies into oceans can also generate tsunamis.

In the past, tsunamis were often referred to as "tidal waves." The use of the term "tidal wave" in this context is incorrect because tides, which are the periodic rise and fall in sea level, result from the gravitational influences of the moon, sun, and planets. Although a tsunami is not a tidal event, a tsunami striking a coastal area can be influenced by the state of the tide at the time of impact.

Origin of the Word

Japanese fishermen upon returning to port and finding the area surrounding the harbor devastated first used the word tsunami to describe the scene. A few moments earlier, however, these same fishermen had not been aware of any wave passing under them in the open ocean.

Two characters represent the word: "tsu" and "nami." The character "tsu" means harbor, and the character "nami" means wave. These two Japanese characters are shown below.

Figure 1: The Japanese characters that represent the word Tsunami

The term “tsunami” was formally adopted for general use in 1963 by an international scientific conference to describe the devastating sea waves that are triggered by major oceanic earthquakes. In Japanese, the same characters are used for both the singular and the plural form of the word. In English, however, the plural form “tsunamis” is well established and is frequently used to refer to the waves from multiple events. Sometimes the descriptor “tsunami wave” is encountered in articles on the subject. The use of the word “wave” in this context is superfluous because it is a repetition of the word “nami” and would be equivalent to writing “harbor wave wave”.

Wave Descriptors

Waves in water are periodic variations in the height of the water surface about its equilibrium position. A wave is generally described by three fundamental properties: 1) its height (the vertical distance between normal sea level and wave crest), 2) its wavelength (the horizontal distance between two successive wave crests in the direction of propagation), and 3) its velocity (the speed at which the wave travels). In addition, the period of a wave is defined as the interval between the passage of adjacent crests by a reference mark. The period is equal to the wavelength divided by the velocity. The wave height and wavelength are shown on the following figure.

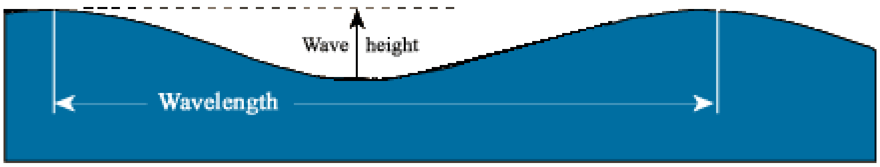

Figure 2: The Wave height and Wavelength of Sea Waves

Most waves in water bodies are generated by wind. Wind induced turbulence and random fluctuations of air pressure on the water surface, aided by wind shear, cause the formation of wind-generated waves. As these random pressure fluctuations cause the sea surface to rise and fall, forces that tend to restore the surface back to its original level come into play. The restoring forces are surface tension and gravity. Surface tension is effective only on very small waves, whose dimensions are measured in centimeters. This is the reason why most ocean waves are considered gravity waves.

Wind-Generated Waves v/s Tsunamis

Both wind-generated waves and tsunamis are described using the same geometrical properties of waves shown on Figure 2, above. However, although the two types of waves (tsunami- and wind-generated) have the same geometrical features and are measured in the same way, there are many differences between the two. The chart below presents some of these differences.

Wind-Generated Waves v/s Tsunamis		
Wave Feature	**Wind-generated Waves**	**Tsunamis**
Wave Speed (Velocity)	5-60 mph (8-100 km/h)	300-600 mph (500 - >1,000 km/h)
Wave Period (time required for two wave crests to pass a reference point in space)	5 to 20 seconds apart	10 minutes to 2 hours apart
Wave Length (horizontal distance between two successive wave crests)	300-600 feet (100-200 meters)	65-330miles (100-500 kms)

Offshore, the wave heights of tsunamis are usually small and their wavelengths are very long. This is why ships traveling in the high seas hardly feel the passage of tsunamis.

As shown on the table, the velocity of wind-generated waves and tsunamis differ greatly. Observations indicate that wind blowing at 50 Km/hr over open water produces waves that are about 7 meters high and have wavelengths of 75 meters. These waves travel at about 40 km/hr. With wind blowing at 110 km/hr the wind-generated waves are about 15 meters high, 375 meters in wavelength, and travel at about 85 km/hr. Larger waves can be generated by the wind where it can blow over an extensive water surface. For example, in the open ocean hurricanes can generate wave heights on the order of 20 to 25 meters. Also, the velocity of a wind-generated wave decreases exponentially with depth. Particle velocity at a depth equal to half the wavelength is generally less than five percent of the velocity at the surface.

In the case of a tsunami, the height of the wave in the open ocean is on the order of one to two meters only but the wavelength, on the other hand, is on the order of 100 to 500 km. A tsunami with a wavelength of 100 Km would travel at over 900 km/hr in deep water. As a marked difference, a tsunami disturbs the entire water column from the surface all the way down to the ocean floor.

The mathematical relationships used to compute the velocity of waves in open water are presented in an Appendix at the end of this course.

Triggering a Tsunami

As explained in the introduction of this course, any type of large-scale, short duration disturbance of the ocean floor can trigger a tsunami. For example, massive landslides, submarine volcanic eruptions, the sudden collapse of oceanic volcanic structures, and even the impact of large cosmic bodies in oceans can generate tsunamis. However, by far the most common mechanism for the generation of these monstrous sea waves is the occurrence of strong and shallow submarine earthquakes that occur along plate boundaries. The concept of “plates” is explained below.

With the development of the theory of plate tectonics in the 1960s, it is now known that the crust of the earth is divided into a number of rigid plates that move and interact with each other along their boundaries. The plates of the earth’s crust are about 4 to 5 miles thick beneath the oceans and about 20 to 40 miles thick beneath the continents. Many of these plates meet and interact with each other beneath the ocean floor, in relative close proximity to continental masses. It is the continuous movement and interaction between the plates that cause the seismic activity along their boundaries. The type of movement that is of primary interest to us here is that of one plate moving and sliding under another plate. This spatial relationship is illustrated in the following figure.

Figure 3: An Oceanic Plate (left) shown descending beneath a thicker Continental Plate (right)

Stages of Strain Accumulation and Slippage

The continuous push by the oceanic plate that is resisted by friction between the two plates results in the build-up of elastic strain energy in the rocks along their common boundary. The following diagram illustrates this process.

Figure 4: Elastic Strain build-up (red color) along the boundary between an Oceanic Plate (left) and a Continental Plate (right).

As the strain accumulates, it eventually exceeds the frictional forces that prevent slippage and movement along the boundary is suddenly initiated. Once started, movement propagates from the point of initiation along the plate boundary resulting in the displacement of rocks and the generation of an earthquake. Refer to course “G175, Earthquakes: Basic Principles” for more information about this process.

Near the source of such submarine earthquakes the seafloor is "permanently" uplifted or down-dropped, pushing the entire water column above the boundary up or down generating the initial wave of a tsunami as shown on the following figure.

Figure 5: Triggering of the first tsunami above the plate-boundary at the moment of strain release.

Tsunami Propagation

Once a tsunami is generated, the potential energy that results from pushing water above mean sea level is then transferred to kinetic energy that drives the horizontal propagation and the tsunami begins its race towards the shore. The amount of energy can be very large because the energy released by a strong earthquake is very large and the length of the initial wave parallel to the plate boundary, along which movement occurred, can also be very large (in some cases exceeding 1,000 kms). For information about the relationship between earthquake magnitude and energy released refer to course “G175, Earthquakes: Basic Principles”.

Within several minutes of the earthquake, the initial tsunami, shown on Figure 5, splits into two waves that start traveling in opposite directions as shown below.

Figure 6: Within several minutes following the earthquake, the initial tsunami, shown on Figure 5, splits into two waves that travel in opposite directions

The height above mean sea level of the two oppositely traveling tsunamis is approximately half that of the initial tsunami (Figure 5). The wave that travels out to the deep ocean is known as the distant tsunami. The other wave that travels towards the nearby coast is referred to as the local tsunami. The speed at which both waves travel is proportional to the square root of the water depth. Therefore the deep-ocean (distant) tsunami will travel faster than the near shore (local) tsunami. The equations used to compute the velocity of tsunamis are presented in the appendix at the end of this course.

Near Shore Transformation

As the local tsunami travels towards the nearest landmass, the depth of the ocean decreases and the height of the wave increases. In addition, the wavelength also decreases. As a result, the front of the leading wave becomes significantly steeper, an important factor that controls the ensuing wave run-up at the coast.

During the time it takes the local tsunami to reach a nearby shore, the distant (deep ocean) tsunami will have traveled much farther because of its higher propagation speed. However, as the deep ocean tsunami approaches a distant shore, the same amplification and shortening of the wave will also occur, just as with the local tsunami

Tsunami Run-up

Tsunami run-up begins when the first wave reaches shore. Run-up is a measurement of the height of the water observed onshore above a reference elevation (mean sea level). A tsunami run-up is shown diagrammatically on the following figure.

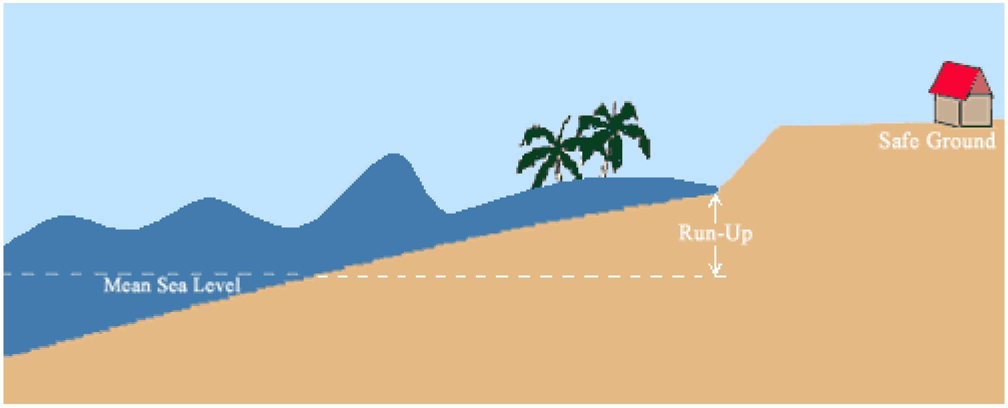

Figure 7: Diagrammatic Representation of a Tsunami Run-up

Most tsunamis do not result in giant breaking waves. Rather, they come rushing in with tremendous force much like very fast tides and manifest themselves as a very rapid, local rise in sea level. Much of the damage inflicted by tsunamis is caused by strong currents and floating debris. Upon reaching shore, a small number of tsunamis do break to form vertical walls of turbulent water that can reach heights of 10 to 20 m (30 to 60 feet). These monstrous shallow water waves, with a steep breaking front, are called bores. Tsunamis will travel much farther inland than normal tides and wind-generated waves causing a great deal of devastation. Safety is only gained at higher elevations, well above the initial tsunami run-up.

Because these waves have a long period, other waves will follow the initial onslaught and will continue to pound the same area over and over until all the potential energy is dissipated. The maximum run-up may therefore be attained with the arrival of the later waves, and people should not return to the lower elevations until all the energy of the tsunami has been dissipated and depleted.

Examples of Notable Tsunamis

Some of the largest magnitude earthquakes in the World since 1900 are the 1960 Chile earthquake, the 1964 Alaska earthquake and the 2004 Southeast Asia earthquake. Their locations are shown on the following figure.

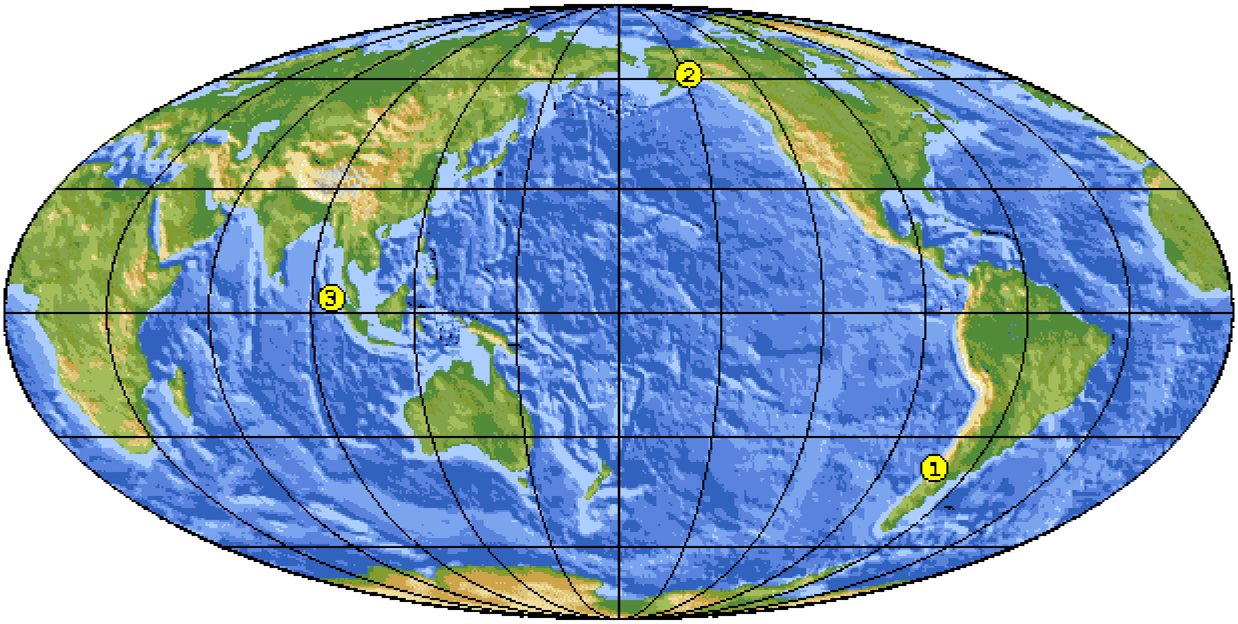

Figure 8: Map of the world showing the locations of the 1960 Chilean earthquake (1), the 1964 Alaska earthquake (2), and the 2004 Southeast Asia Earthquake (3).

It is interesting to note that all of these three earthquakes occurred beneath the ocean, in proximity to a continental margin. Because of the large underwater disturbances they caused, all three earthquakes triggered large tsunamis that caused widespread devastation both near and far from the source of the disturbance.

The Great Chilean Earthquake and Tsunami of 1960

In May 1960, a series of large and damaging earthquakes shook southern Chile. The first earthquake, which occurred at 10:02 GMT (UTC) on the 21st of May 1960, had a magnitude of 8.0. Between this initial event and December 1960 eight more earthquakes, all of magnitude greater than 7.0, jolted the region. The worst of these events occurred at 19:10 UTC on the 22nd of May 1960. That earthquake had a magnitude of 9.5, the largest magnitude ever assigned to an earthquake in the 20th century. A map of Southern Chile showing the epicenter of the 22nd of May 1960 event is presented below.

Figure 9: Map of Southern Chile showing the epicenter of the 22nd of May, 1960 earthquake.

Important modifications to the coastal relief were observed. The 1960 earthquake lowered the coastal landscape by about 1.5 m. and the subsidence killed forests and changed pastures into tidal flats. In addition, significant rock falls and massive landslides occurred in the Andes.

The earthquake generated a major tsunami. The local tsunami struck the coast of South America within a very short time, while the distant tsunami proceeded to cross the Pacific, where it struck the coasts of Australia, New Zealand, Japan, the Philippines, Hawaii and the western U.S. many hours later. In Japan, 138 people were killed on the Eastern Shore of Honshu and Hokkaido. The city of Ofunato was devastated. More than 855 people were injured and 1,678 homes were destroyed. The wave had a maximum run-up of 6 meters. In the Philippines 32 people were killed.

This tsunami was also experienced along the western coast of the United States. The largest wave height in California, measured at the Crescent City tide gage, was 1.7 m, and the wave height was more than 1.4 m at Santa Monica. The tsunami was recorded widely further north along the pacific coast with amplitudes less than 1 m. The travel time curves of this tsunami are presented below:

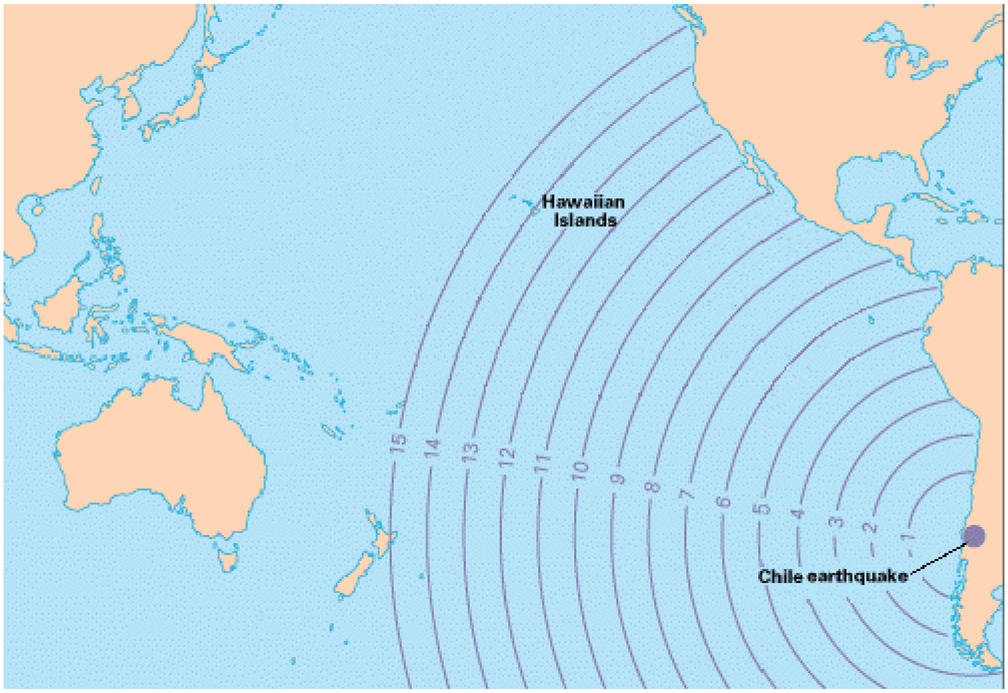

Figure 10: Hourly travel-times (purple curves) of the tsunami generated by the 1960 Chilean earthquake (Modified from a map published by the United States Geological Survey).

The Great Alaska Earthquake and Tsunami of 1964

One of the largest earthquakes to have occurred during the 20th century is the 1964 Prince William Sound, Alaska event. It occurred on Good Friday, March 27, 1964 at 05:36:14 p.m. local time (March 28, at 03:36:14 UTC). This earthquake was assigned a Magnitude of 9.2 and was felt over 500,000 square miles. The epicenter was about 10 km east of the mouth of College Fiord, approximately 90 kilometers west of Valdez and 120 kilometers east of Anchorage. The epicenter was located at Latitude 61.04N, Longitude 147.73W, at a depth of approximately 25 kilometers.

The ground motion near the epicenter, above the origin of the earthquake, was so violent that the tops of trees were snapped off. About 125 people died as a result of this event. Had Alaska been more populated, certainly a lot more people would have lost their lives. A map of Alaska showing the epicenter of the Good Friday 1964 earthquake is presented below.

Figure 11: Map of Alaska showing the epicenter of the Good Friday, 1964 earthquake (Base map modified from MapQuest, Inc.).

The 1964 event generated a powerful tsunami that devastated many towns along the Gulf of Alaska, and caused serious damage as far south as Kodiak and at several locations along the Western Coast of North America, where 15 people were killed. Below is a picture of the damage inflicted along the waterfront at Resurrection Bay, Kodiak, 450 kilometers (about 300 miles) southwest of the epicenter.

Figure 12: View of the tsunami damage along the waterfront at Resurrection Bay, Kodiak, Alaska, more than 450 kilometers (about 300 miles) southwest of the epicenter of the 1964 Earthquake (Source: United States Geological Survey).

The tsunami also traveled across the Pacific Ocean at speeds as great as 600 to 650 miles per hour and reached the coasts of Hawaii and Japan where it caused damage there too. On the Island of Oahu the maximum-recorded run-up was 4.8 meters (about 15 feet). The travel time curves of this tsunami are presented below:

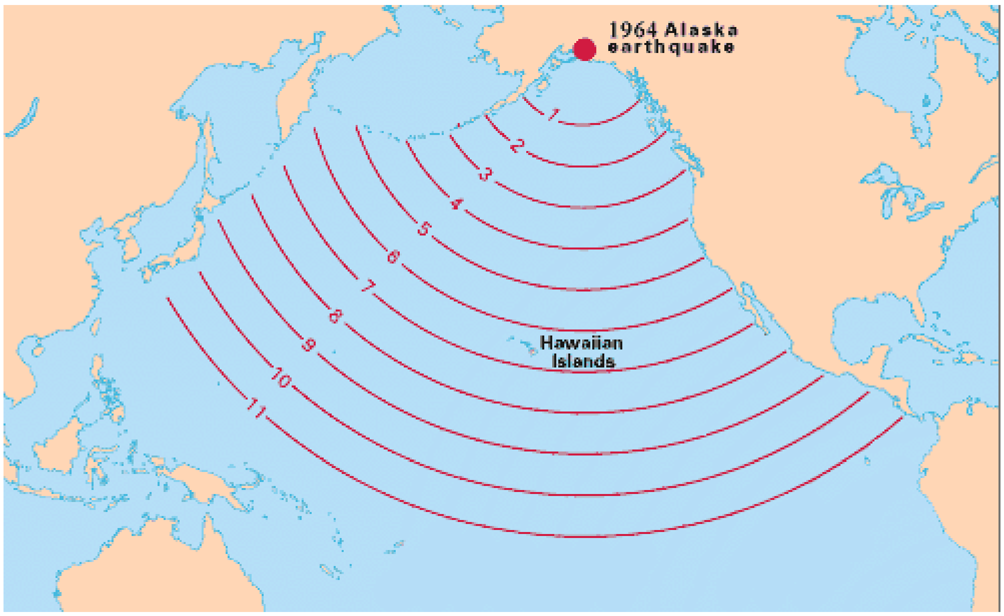

Figure 13: Hourly travel-times (red curves) of the tsunami generated by the 1964 Good Friday earthquake (Modified from a map published by the United States Geological Survey).

The Great Southeast Asia Earthquake and Tsunami of 2004

A great earthquake of magnitude 9.0 occurred at 00:58:53 (UTC), on Sunday, December 26, 2004 off the West Coast of Northern Sumatra. The epicenter was 255-km (160 miles) SSE of Banda Aceh, Sumatra, Indonesia 315-km (195 miles) West of Medan, Sumatra, Indonesia 1260-km (790 miles) SSW of Bangkok, Thailand 1590-km (990 miles) NW of Jakarta, Java, Indonesia.

The earthquake that generated the tsunami of December 26, 2004 was caused by the release of large accumulated strains that disturbed the ocean floor along the boundary between the Indian plate and the Eurasian plate. This disturbance occurred along a segment of a trench (fault trace) that lies offshore of Java and Sumatra and extends past the Nicobar and Andaman Islands. The sea floor overlying this oceanic fault zone was uplifted by several meters along the entire length of the break forming sustained waves of enormous extent (over 1,000 kms) that started racing at great speed across the Bay of Bengal and beyond. The location of the epicenter, the segment of the fault trace that ruptured and the travel time curves of the resulting tsunami are presented below:

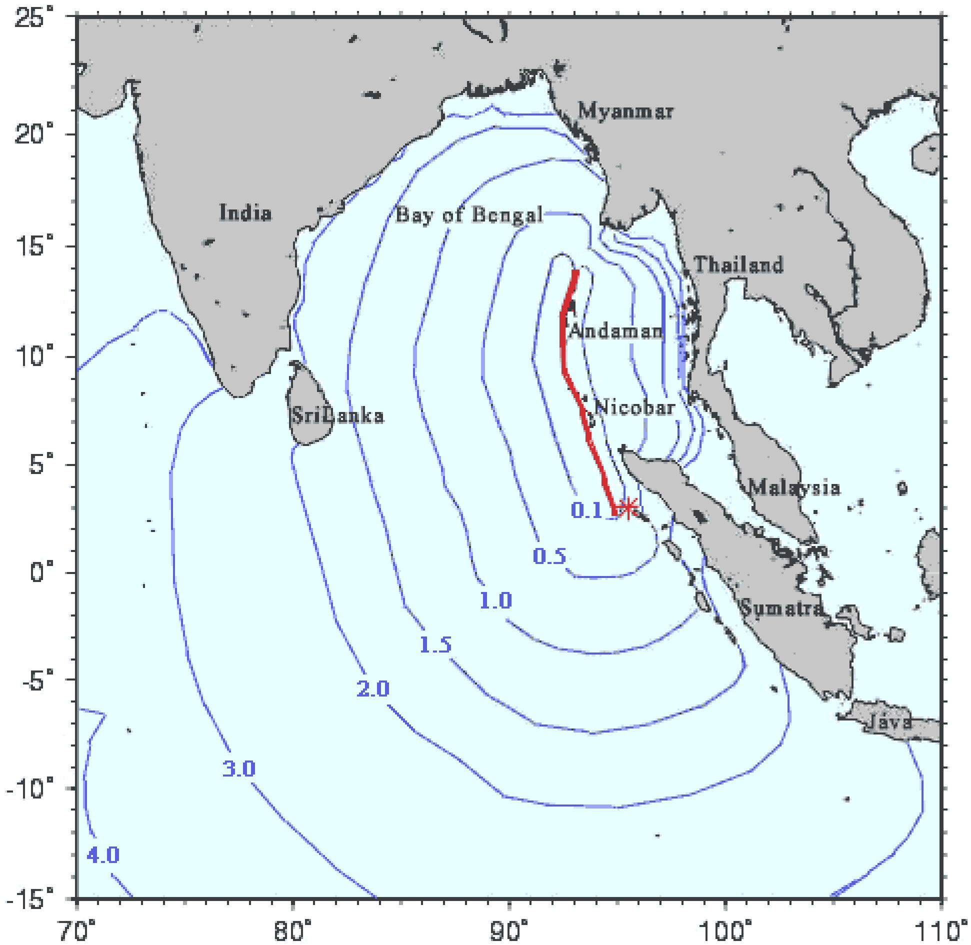

Figure 14: Travel-times in hours (dark blue curves) of the tsunami generated by the magnitude 9.0, Southeast Asia earthquake of 2004. The red star shows the location of the epicenter. The red line represents the extent of the fault break that triggered the tsunami (Modified from a map produced by the National Institute of Advanced Industrial Science and Technology).

This tsunami was one of the largest ever in terms of casualties because it hit heavily populated low-lying coastal areas that were not well prepared. The lack of a warning system meant that most people were caught by surprise, and it had been a long time since there had been a tsunami in this region. People reported seeing the ocean pull back, exposing the sea floor and then returning as a swift rise in the sea level, like an extremely high tide, inundating villages near the coast. The wave then pulled back, sucking houses, trees, people and everything in its path out to sea. These waves had a long period, so other waves returned after several minutes and continued to pound the same areas over and over until all the energy dissipated.

The waves struck tourist resorts from Phuket in Thailand to Bentota in Sri Lanka at the peak of the tourist and holiday season. The tsunami, reported as 15-20 feet high waves in open water, fanned out over the Indian Ocean at high speed causing severe and sudden flooding to the coastal areas of many countries. Whole fishing villages were washed away along the coastlines. Affected were Indonesia (Sumatra, over 166,000 dead), Thailand (over 2,500 dead), Malaysia, the Andaman and Nicobar Islands, Myanmar, Bangladesh, Sri Lanka (over 30,000 dead), India (over 7,000 dead). The Maldives and countries as far away as Somalia, Tanzania and Kenya, along the East Coast of Africa, were also affected. In the entire region casualties have been very high, with over 220,000 deaths, mostly from the tsunami generated by the earthquake and up to five million people have been left homeless.

Presented below are two aerial photographs of a portion of the coastline of Banda Aceh, the capital city of the province of Aceh, located at the northern tip of Sumatra, just before and just after the disaster hit the island. These photographs, which were published in the popular press, help the reader visualize the real extent of the damage.

Figure 15: Aerial view of a stretch of the Banda Aceh shoreline photographed on June 23, 2004, Well before the occurrence of the earthquake and tsunami of December 26, 2004 (Source: Digital Globe Aerial Photos).

Figure 16: Same aerial view of Banda Aceh shown on figure 15, photographed on December 28, 2004, two days after the disaster struck. The photo shows the missing shoreline that was wiped out by the tsunami (Source: Digital Globe Aerial Photos).

Eye Witness Account

Below is an eyewitness account of what happened to a survivor who was rescued adrift a few miles from shore two weeks after the disaster. This diary was abstracted from an Associated Press report published in the popular press at the time of the event.

“That morning, when the ground began to shake, I was on a scaffolding hammering nails into a plank, with a crew building a beach home in Aceh Jaya, a town about 150 miles from the Indonesian provincial capital Banda Aceh. Frightened, I moved with the crew away from the house and squatted in the sand, on the beach. Then the waves started coming. The first one, 3 feet high, ripped the scaffolding down. A minute later came the big wave, a bluish-white wall of water about 30 feet high. It produced a deep sound and destroyed the house. The wave hit all the other surrounding houses with a terribly loud sound and destroyed them too. At this point I felt that I was caught in a giant washing machine. I was tossed 1,500 feet inland and banged against a mango tree and grabbed a branch. I saw my friends also hanging on to trees. I thought the world was coming to an end.

As the tsunami receded, it pulled me under and sucked me out to sea. Swimming desperately, I could see the hills of Aceh receding fast. I swam and floated an hour before encountering a wooden plank about 5 feet long. I clambered onto the plank and noticed that I had cuts all over my body. Five bodies floated past. About 300 feet away two other men clung to debris. I could not even find my voice to call out for help. Eventually they all drifted away and I was all alone. I survived on coconuts that were drifting by, caught in a mass of debris swept out to sea by the tsunami.

The next day, a leaking and listing fishing boat drifted by. I swam to it and found no one on board. I was adrift for several days in a busy shipping lane near Sumatra. Many ships passed by my small boat, barely noticeable in the vast ocean. After five days, I began to loose hope. I had been drifting for seven days when I spotted a large unmanned raft with a hut on it. Abandoning the sinking fishing boat, I swam to the raft and found a gallon bottle of water to slake my thirst. Coconuts were still plentiful in the sea. Finally, on the 15th day I awoke to the sight of the bow of a container ship looming over me. It was too close to miss me. I pulled my shirt off and waved. I put my fingers in my mouth and whistled. The container ship eased passed my raft, leaving in its wake a foamy slurry of sea water. But the ship slowed down, came around and sounded its siren three times. I knew then that I was saved."

Tsunami Warning

In 1995 the US National Oceanic and Atmospheric Administration (NOAA) initiated the development and deployment of a prototype tsunami warning system in the Pacific to record and assess real time conditions in the deep ocean. The stations of this Deep Ocean Assessment and Reporting of Tsunamis (DART) warning system give detailed information about tsunamis as they begin to develop and while they are still far offshore. Each DART station consists of a seafloor bottom pressure recorder and a transceiver buoy floating at the surface of the ocean for real-time communication with the Tsunami Warning Centers (TWC). These two components of a DART station are shown during deployment on the following figure.

Figure 17: A bottom pressure recorder being lowered into the ocean (left) and a transceiver floating buoy being released at the surface of the ocean (right) (Source: National Oceanographic and Atmospheric Administration).

The two components of a DART station (bottom pressure recorder and surface buoy) are linked together in an operational configuration as shown below.

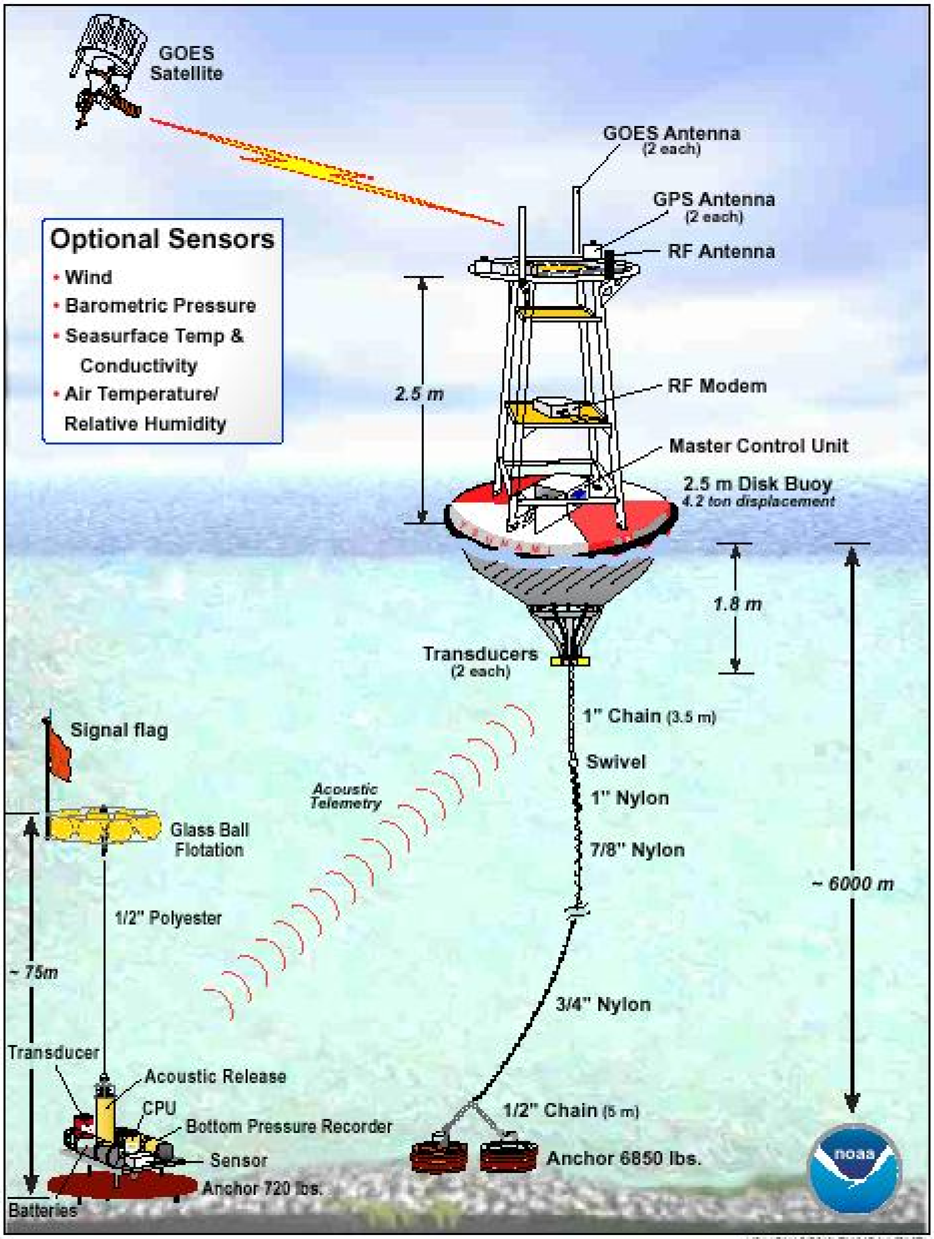

Figure 18: The sensitive bottom pressure recorder detects the passage of a tsunami and transmits the data to the surface buoy via an acoustic modem. The surface buoy then radios the information to the Tsunami Warning Center (TWC) via a Geo-stationary Operational Environmental Satellite (GOES).

Each DART station is capable of detecting tsunamis as small as 1 cm at the surface from a depth of 6,000 meters (21,000 ft). The bottom pressure recorder has a serviceable life of two years while the surface buoy is usually replaced every year.

By 2001, NOAA had deployed in the Pacific Ocean the first six stations of the Deep-ocean Assessment and Reporting of Tsunamis (DART) network. In 2005, as a result of the Great Southeast Asia Earthquake and Tsunami of December 2004, NOAA announced plans to add over 30 more DART stations to go online by mid-2007. The distribution of these stations is shown on the following figure.

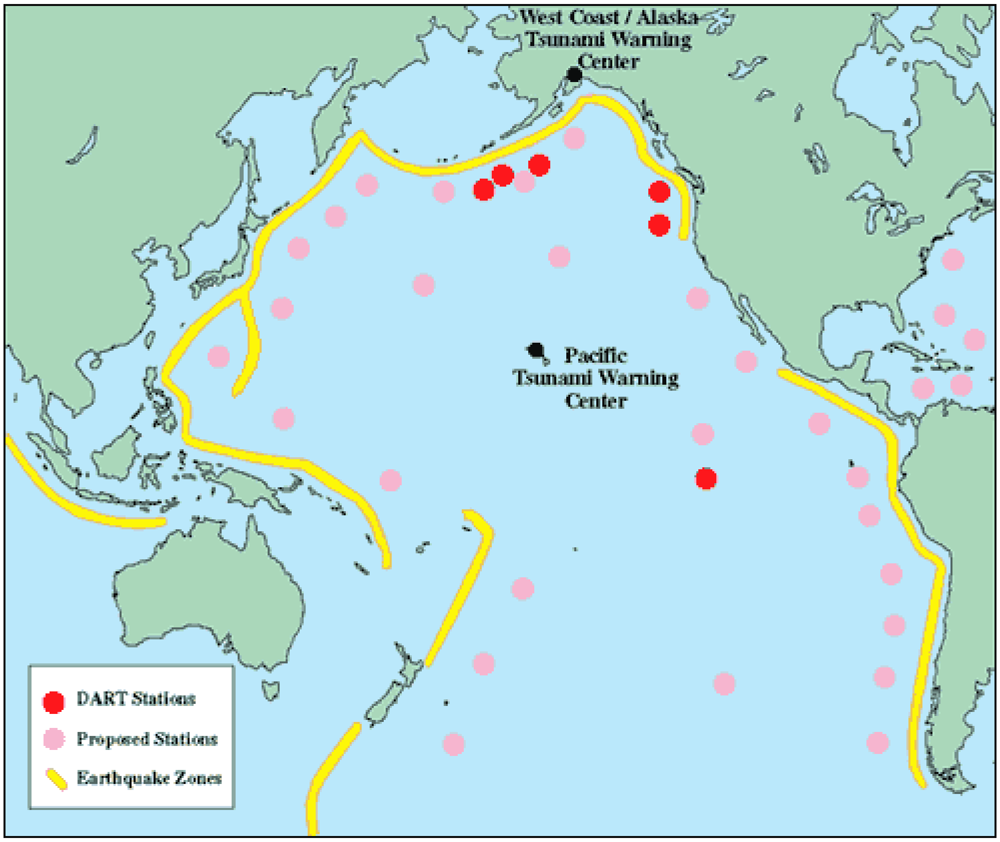

Figure 19: Map showing the distribution of DART stations. Earthquake zones capable of generating tsunamis are shown as yellow bands.

As shown on Figure 19, there are two Tsunami Warning Centers: 1) the Pacific Tsunami Warning Center (PTWC) and 2) the West Coast/Alaska Tsunami Warning Center (WC/ATWC). The areas of tsunami monitoring responsibility of each center are shown on the following map of the world.

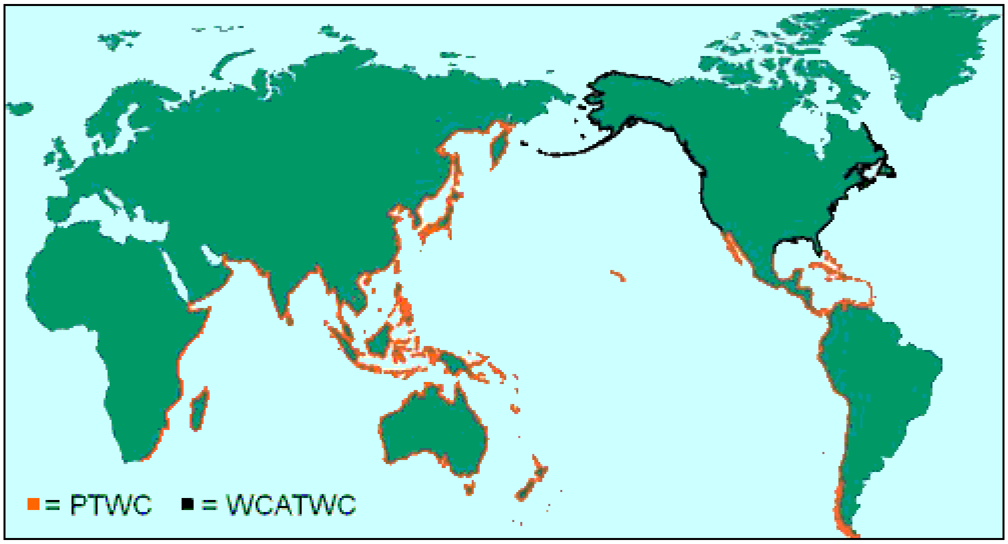

Figure 20: Map of the world showing the areas of tsunami monitoring responsibility for each of the two Tsunami Warning Centers (Source: National Oceanographic and Atmospheric Administration).

The Tsunami Warning Centers use seismic data as the starting point, but then take into account oceanographic data from the DART stations, when calculating possible threats. Tide gauges in the area of the earthquake are also checked to establish if a tsunami has formed. The appropriate center then forecasts the future course of the tsunami, issuing warnings to “at-risk” areas as needed. There can be no false alarms. If one of the centers issues a tsunami warning for a particular area, this means that the wave is already on its way and will hit as predicted by the travel time calculations. Also, since it takes a long time for a tsunami to travel Trans-oceanic distances, the Warning Center can take the necessary time it needs to ensure that its distant tsunami forecast is correct.

The detection and prediction of tsunamis is only the first step in a process that should lead without delay in the dissemination of the relevant information to the affected communities. Therefore, of equal importance to the detection and prediction of tsunamis is the ability to warn the populations of the areas that will be affected. The tsunami warning centers are equipped with dedicated multiple lines of communication (such as phones, cell-phones, computers with e-mail capabilities, fax and radios) enabling urgent messages to be sent to the government officials and emergency services of the affected communities. Local emergency broadcasts and alerting systems, such as sirens, are also used to notify the population to flee to higher ground for safety.

While there remains the potential for sudden devastation from a tsunami, especially for the shoreline communities that are within a short distance from a very large submarine earthquake, the warning system can still be effective for distant areas. For example, if a very large earthquake occurs in the Eastern Pacific, people in the Western Pacific, for example, would have 10 to 15 hours of lead time before any tsunami arrives (see for example Figures 10 and 13). The local population should then have sufficient time to evacuate the low-lying areas that are likely to be affected.

Generation of Tsunamis by other Mechanisms

As explained in this course, a tsunami can be generated by any disturbance that displaces a large water mass from its equilibrium. In the case of earthquake-generated tsunamis, the uplift or subsidence of the sea floor, especially in the deep parts of the ocean, disturbs the entire water column above the source of the earthquake. Major earthquakes of magnitude 9.0 or greater may reactivate fault traces that are over 1,000 km in length generating in the process a very long and cohesive initial wave that propagates at high speed across an open ocean. However, other triggering mechanisms can also generate massive waves as explained below.

Landslides and Volcanic Explosions

Other mechanisms that could also trigger tsunamis include massive submarine landslides (often triggered by large earthquakes) as well as the collapse of marine volcanoes. Such events can disturb the entire water column as sediment and rocks crashing downward are redistributed across the ocean floor. Similarly, a violent marine volcanic eruption and the sudden collapse of the flank of an oceanic volcano, for example, can also create an impulsive force that disturbs the water column above the collapsed portion of the volcano resulting in the generation of a tsunami. The following figure is a diagrammatic representation of a tsunami triggered by the explosion and collapse of the flank of an oceanic volcano.

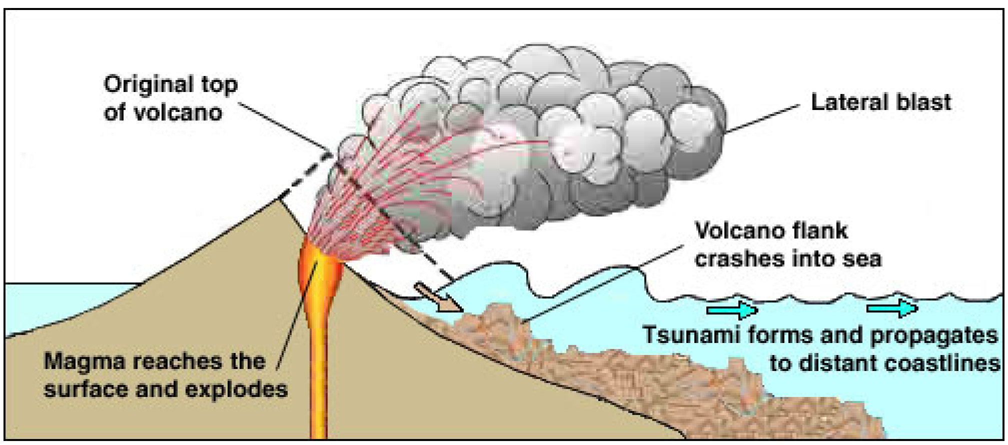

Figure 21: Diagram showing the formation and propagation (blue arrows) of a tsunami resulting from the collapse of the flank of a volcano.

In the case of submarine landslides and marine volcanic eruptions, the resulting tsunamis can be as strong and devastating as those generated by major earthquakes, but their effects are likely to be more localized. In addition, these types of tsunamis tend to attenuate faster because the total length of the initial wave is much smaller. For example, on April 21, 2007, at 1:53:45PM local time, a magnitude 6.2 earthquake occurred in Aisen, southern Chile. This earthquake did not trigger a tsunami, but shook free several landslides from neighboring hills sending an avalanche of rocks smashing into the sea at the bottom of a narrow fjord. These landslides generated massive 25-foot waves that swept away 10 beach goers into the ocean. Three bodies were recovered and rescuers searching the cold Pacific were unable to locate the other seven missing people.

Asteroid and Meteorite Impacts

Although there have been no detected large meteorite or asteroid impacts into an ocean during historical times, it is possible that such events could trigger tsunamis. Researchers have used computer simulations to model the effects of these types of impacts. For a given location on the Earth's surface, the risk of a "direct" hit by a large meteorite or asteroid is slight. However, researchers have long realized that an impact in the ocean has the potential to be much more destructive because of the possible generation of a tsunami. Because of this realization, some advanced computer simulations have been conducted to estimate the effects of large meteorite or asteroid impacts into deep oceans.

When an asteroid hits the ocean, at speeds on the order of 70,000km/h, there is a gigantic explosion. The asteroid and the water it contacts vaporize and leave a huge crater.

Figure 22: Illustration of a collision between a large asteroid and the earth at an oceanic point near a continental mass.

Computer simulations have shown that a crater thus formed is typically 20 times the diameter of the asteroid (that is, a 1km asteroid will create a 20-kilometer diameter crater). Following the impact, the water rushes back into the center of the crater, overshoots and creates a bulge of water. The center of the "crater" oscillates up and down several times and a series of waves (tsunami) radiate out. The following figure is a diagrammatic representation of this phenomenon.

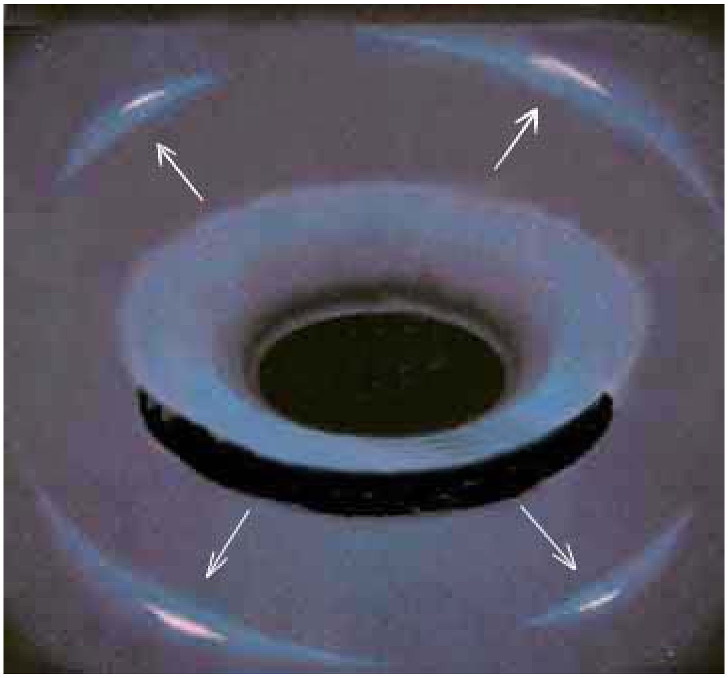

Figure 23: Crater formed by the impact of an asteroid in the ocean resulting in the formation and radial propagation (white arrows) of a tsunami.

At this time, there are substantial differences in asteroid-generated tsunami predictions between various researchers. The main items of contention are:

- The initial size of the wave (based on analysis of the size and shape of the "crater" and the manner in which it collapses), and
- The rate at which a tsunami from an asteroid impact dissipates as it travels.

Researchers agree that for an impact to produce a coherently propagating wave (one that does not dissipate substantial energy when it travels over great distances) the crater must be 3 to 5 times broader than the depth of the ocean at the point of impact. Using the results derived from these simulations, for a typical ocean depth of 4km the impacting asteroid must be at least 1 km in diameter to produce a coherent wave. On this basis, for asteroids that are smaller than about 1km, the wave (tsunami) that forms will dissipate considerably as it travels over thousands of kilometers of ocean.

Records of Some Notable Tsunamis

1883 Krakatoa Tsunami

As explained in the section on the generation of tsunamis by other mechanisms, and as shown on Figure 21, this is exactly what happened following the August 1883 eruption of the Krakatoa volcano. This volcano is located in the Sunda Strait that separates the Islands of Java and Sumatra. The crashing of the flanks of the volcano into the ocean formed the initial tsunami. The last and strongest tsunami formed following the final explosion and collapse of the entire volcanic edifice below sea level. The waves that were initiated at the Island of Krakatoa battered the coastlines of Southern Sumatra and

Western and Northern Java. The waves generated by these events traveled across the Indian Ocean, but with rapidly diminishing heights. By the time they reached India, they were only fourteen inches high in Madras, six to ten inches high in Calcutta, a foot high in Karachi, and about six inches in Aden, along the southern coast of Arabia. The waves spread southwestward as well towards the African coast. By the time they reached the Atlantic Ocean, they were barely perceptible.

1755 Lisbon, Portugal, Tsunami

Tens of thousands of Portuguese who survived the great November 1, 1755 Lisbon earthquake were killed by a tsunami which followed the earthquake about a half-hour later. Following the earthquake, many townspeople fled to the waterfront believing the harbor area safe from fires, from falling debris, and from aftershocks. In a classic fashion, before the great wall of water hit the harbor, waters retreated, revealing lost cargo and forgotten shipwrecks that drew the attention of the curious population who were then drowned by the crashing of the tsunami.

The earthquake, tsunami, and subsequent fires killed more than 60,000 people. In the wake of this disaster priceless historical records of explorations of early navigators were lost, and countless buildings were destroyed. Europeans of the 18th century struggled to understand the disaster within their religious and rational belief systems with no avail, because the causes of earthquakes and tsunamis were not understood at the time. The notable philosophers Voltaire and Immanuel Kant wrote about this event. For the first time in history, however, we have detailed descriptive information of what happened because all the parish priests were asked by their bishops to document their observations in as much detail as they could. The role this earthquake played in the development of our present day understanding of the earthquake cycle is explained in the course titled: “Earthquakes: Basic Principles” (course G175).

Pre 1,500 BC Tsunami

For historical interest, and to emphasize that tsunamis are one of the recurring geologic hazards of our planet, the disappearance of the Minoan civilization, of Northern Crete, is attributed to the explosion of a volcano that triggered a devastating tsunami. At some time between 1650 BC and 1600 BC, the Greek volcanic island of Santorini erupted and most of the volcanic edifice blew-up and collapsed into the Mediterranean. The ensuing tsunami that formed is believed to have generated 100 to 150 m run-ups along the northern coast of Crete, which is located 70 km (45 miles) away. It is also interesting to note that Santorini is also regarded as the most likely source for Plato's literary legend of Atlantis.

65 million years old Tsunami

A meteor impact created the Chicxulub Crater about 65 million years ago which is now buried underneath the Yucatán Peninsula, Mexico. The center of the crater is located approximately underneath the town of Chicxulub, but much of the crater lies under the ocean and all of it is buried under 300 to 1,000 meters (1,000 to 3,000 ft.) of limestone sediments.

The meteorite's estimated size was about 10- to 15-km in diameter and created a crater about 180 to 300 kilometers (110 to 180 miles) wide. The impact caused a giant tsunami that disturbed and transported sediments over huge distances and hit the Caribbean Island of Cuba especially hard. The emission of dust and particles caused extreme environmental changes and the surface of the Earth was totally covered by a cloud of dust for several years. The timing of this event is in good agreement with the theory of a meteorite impact postulated by the physicist Luis Alvarez and his son Walter, a geologist, whom they speculated, caused the extinction of the dinosaurs.

The location of the crater rim, discovered over a decade ago by seismic exploration methods and drilling, is delineated on an assembled satellite image of the northern portion of the Yucatan Peninsula and is shown on the following figure.

Figure 24: Satellite image of the northern portion of the Yucatan Peninsula showing the approximate location of the land portion of the Chicxulub crater rim (white band) (Modified from a figure published by the Jet Propulsion Laboratory of the National Aeronautic and Space Administration).

On land, a ring of ground water springs coincides with the interpreted location of the crater rim. These springs form the only visible features on the surface that indicates the presence of a buried crater at depth.

Course Summary

In this course you have learned that large earthquakes that affect the ocean floor are capable of generating immense sea waves called "tsunamis", a Japanese word that means "harbor wave". You now also understand why this is an appropriate term for the description of this phenomenon.

You have also learned that the crust of the earth is divided into a number of rigid plates that move and interact with one another along their boundaries. It is this continuous movement and interaction between plates that cause the seismic activity along their boundaries. When these disturbances occur in the ocean, they can trigger tsunamis.

In the open ocean tsunamis have relatively low wave heights, but are of enormous cohesive dimensions. As they approach the coast, these waves undergo significant transformations that determine the ensuing wave run-up above coastal mean sea level. Tsunamis can travel at great speed for very large distances such as across the entire widths of oceans, inflicting significant damage to far away coastal towns.

You have also been introduced to the historical record of the most devastating tsunamis that have occurred since 1900, namely:

1) The Great Chilean Earthquake and Tsunami of 1960,
2) The Great Alaskan Earthquake and Tsunami of 1964. And
3) The Great Southeast Asia Earthquake and Tsunami of 2004

You also read an eyewitness account of a survivor that experienced first hand the effect of being swept to the ocean by a tsunami. That person was lucky enough to survive his ordeal and live to recount his incredible adventure. You also learned how tsunamis can be detected, their course tracked, and how warnings are issued before these monstrous waves strike the vulnerable coastal areas.

You now understand that tsunamis can also be generated by other mechanisms, such as massive submarine landslides, the collapse of marine volcanoes, and even by the impact of large meteorites or asteroids. The fact that tsunamis have occurred periodically throughout the geologic record indicates that these events represent one of the most potent recurring natural hazards of our planet.

Finally, if you want to explore this topic further on your own you can find additional fascinating and informative information about tsunamis on the United States Geological Survey (USGS) and the National Oceanic and atmospheric Administration (NOAA) web sites at www.usgs.gov and www.noaa.gov. Use the word "tsunami" to search through the extensive information contained on both sites. You can also reach a direct link maintained by NOAA on this topic at www.tsunami.gov

APPENDIX
Velocity of Ideal Waves in Open Water

The wave velocity (V) is the velocity of the wave form, not that of the water itself. A particle on the surface of the water moves in a vertical plane and describes in time (T) a circle with a diameter that is equal to the wave height (H). Although the generating forces for tsunamis and wind-generated waves are different, the restoring force for both is gravity.

The wave velocity is related to the square root of the wavelength (L) and water depth (D) as follows:

$$V = \sqrt{\frac{gL}{2\pi} \tanh \frac{(2\pi D)}{L}}$$

Figure 25: The Wave velocity equation

In this equation, g is the acceleration of gravity (9.81 meters/second^2).

Using the equation given in Figure 25, the following table presents the calculations of wave velocities for a hypothetical tsunami that has a wavelength of 100 kilometers. From a point in the ocean that has a water depth of 7,000 m to a continental shoreline location that has a water depth of 10 m, the waves will travel at the speeds shown on the following table. The results are presented in meters per second and between brackets in kilometers per hour:

Calculated Tsunami Velocities

V at Water Depth	**L=100,000m (100km)**
V at 7,000m	253.957m/s (914km/hr)
V at 5,000m	217.829m/s (784km/hr)
V at 2,000m	139.633m/s (503km/hr)
V at 1,000m	98.930m/s (356km/hr)
V at 500m	69.988m/s (252km/hr)
V at 100m	31.305m/s (113km/hr)
V at 10m	9.899m/s (36km/hr)

As mentioned in the text of the course, the depth of the ocean decreases, the height of the wave increases and the wavelength of the tsunami decreases. As a result, the front of the leading wave becomes significantly steeper because of the pile-up effect of the succeeding waves, an important factor that controls the ensuing wave run-up at the coast.

The limits on the hyperbolic tangent term (tanh) given in Figure 25 are:

Tanh X approaches X for small X, and
Tanh X approaches 1 for large X,

Consequently, in parts of the ocean where water depth (D) is say less than one twentieth of the wavelength (L), the equation reduces to:

$$V = \sqrt{g D}$$

Figure 26: Limit wave velocity equation in water depth that is less than about 1/20 of the wavelength

Alternatively, in parts of the ocean where water depth (D) is say greater than one half of the wavelength (L), the equation reduces to:

$$V = \sqrt{\frac{g L}{2 \pi}}$$

Figure 27: Limit wave velocity equation in water depth that is greater than ½ of the wavelength

Glossary of Terms and Acronyms used in this Course

Asteroid: A small celestial body that revolves around the sun. Asteroids have diameters between a few and several hundred kilometers and are chiefly located between Mars and Jupiter.

Epicenter: The point on the earth's surface that is directly above the focus, or point of origin of the earthquake.

Fault: A fracture that separates two blocks of the earth's crust that have slipped with respect to each other parallel to the fracture.

Fjord: A long and narrow winding inlet of the sea that is U-shaped, steep walled and usually several hundred meters deep.

Focus/Hypocenter: The initial rupture point of an earthquake at some depth within the earth.

GOES: Acronym for Geo-stationary Operational Environmental Satellite. This program is a key element in the US National Weather Service (NWS) operations. GOES provide a continuous and reliable stream of environmental information used to support weather forecasting, storm tracking, meteorological research and tsunami forecasting. GOES is designed to operate in geo-stationary orbit at 35,790 km (22,240 statute miles) above the earth, thereby remaining stationary (with respect to a point on the ground). The advanced GOES spacecraft continuously view the continental US, neighboring environs of the Pacific and Atlantic Oceans, and Central and South America.

Kinetic Energy: The energy possessed by a body because of its motion. It is equal to one half the mass of the body times the square of its speed

Meteorite: A stony or metallic mass of matter that has fallen to the earth's surface from outer space.

Period: The interval of time required for the completion of a cyclic motion, such as the time between two consecutive similar phases of a wave.

Potential Energy: The energy of a system derived from position, or condition, rather than motion. For example, a raised body has potential energy. Also, a charged battery has potential energy.

Plate (Tectonic): A rigid segment of the earth's crust that moves with respect to other adjoining plates. Seismic activity usually occurs along and marks the boundary between two such plates.

Strain: A change in the shape or volume of a body in response to the application of stress. This term is synonymous to deformation.

Strain (Elastic): The term elastic modifies the term strain to denote that the strain developed in a body is instantly and totally recoverable. This form of deformation is also independent of time.

Trench (Oceanic): A narrow and elongate deep depression in the ocean floor oriented parallel to an adjacent continental margin. A trench may be thousand of kilometers long and usually marks the boundary between two rigid plates of the earth's crust. It is along such boundaries that one plate descends into the interior of the earth underneath the other plate.

Tsunami: A gravitational sea wave produced by any large scale, short-duration disturbance of the ocean floor. Although caused primarily by shallow submarine earthquakes, large submarine earth movement or volcanic eruption may also cause it. It is characterized by great speed of propagation, long wavelength, long period, low wave height on the open sea, and may pile up to heights exceeding 50 feet on entering shallow water along an exposed coast.