TSUNAMIS: CAUSES, CONSEQUENCES, PREDICTION AND RESPONSE

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Contents

Summary

Tsunami waves rank the fifth among the world's natural hazards in terms of the number of casualties. This article presents the essentials of a tsunami event which may be induced by a bottom earthquake, a submarine landslide, underwater volcano eruption, atmospheric disturbance, cosmic body fall or the decomposition of a gas hydrate at the shelf. These gravity waves at the water surface occur in the sea as the result of a large-scale fast-acting disturbance on the water basin. The typical length of a tsunami wave is from 1 to 1000 km, the event`s duration may run between 5 and 100 minutes, the propagation velocity is from 1 to 200 m s^{-1}, and the wave height may reach up to 10 - 30 m above the coastline. The peculiarities of tsunamis, seaquakes and unusual seism-generated kindred phenomena in the open ocean are presented in this article. What one should know about tsunami prediction and means of warning and salvaging are described in the article. Recent development of tsunami warning systems in the USA, Japan, Russia, France, and other countries are also discussed.

1. Introduction

If you are planning to visit a country of volcanoes and earthquakes - Japan, the Kuril Islands or Kamchatka - you will be surely ready for a surprise at any time. And when you have set up a camp at the coast of the bluest warm sea for fine days of relaxation with your friend (or for an expedition survey) you hardly expect an invasion of water in the form of a deadly tsunami wave. The ocean is the forefather of humankind, and continues to be its strict teacher.

Often a tsunami wave warns of its arrival with roaring and rumbling from the ocean, but sometimes a rising wall of water approaches silently and imperceptibly. A flowering and crowded sea-coast may be transformed into devastated ruins in a matter of minutes (Paramushir, USSR, 1952; Okushiri, Japan, 1993; Papua New Guinea, 1998; Izmit, Turkey, 1999). The consequences of the giant earthquake and tsunami in Lisbon in 1755 are imaged in the ancient etching (Figure 1).

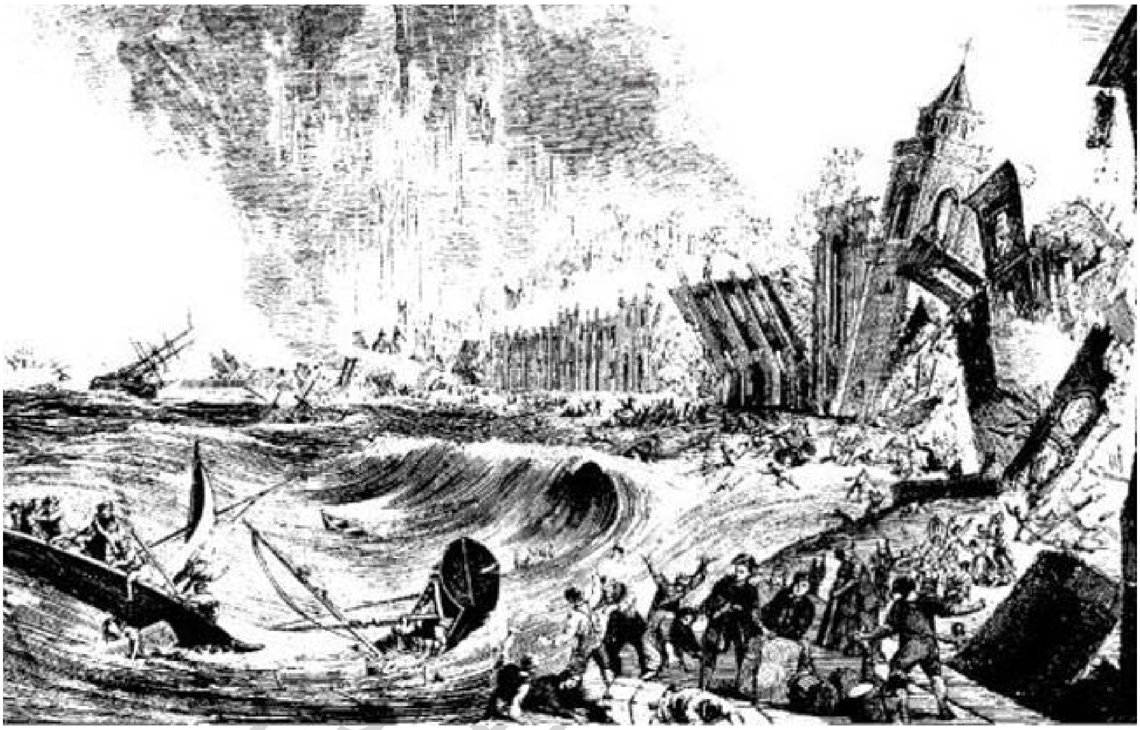

Figure 1. Computer copy of etching "Earthquake at Lisbon in 1755," Mary Evans Picture Library, London, England.

Tsunami (translated from Japanese for "a big wave in a harbor") is a sequence of long gravity water waves, propagating with high velocity from a tsunami source in the ocean (a large-scale zone of short-lived disturbances on the water surface) to the coastline. Local rising or sinking of the water-level in the ocean may be rather small, about 10 meters. At the same time, the large horizontal size of the geophysical disturbance, which is in the order of 100 km above the bottom earthquake, may give rise to a gravity wave about 100 km in length. The wave propagates from the source with a velocity of long gravity water waves in accordance with the equation

$$C_G = (g H)^{1/2}, \quad (1)$$

where g is the acceleration due to gravity, and H is the depth of the basin. Because the average depth of the world ocean is 4 km, the typical velocity of tsunami in the ocean is 200 m s^{-1} or 720 km h^{-1}.

Such a wave, propagating with the velocity of an airplane, may traverse the Pacific ocean in 10-12 hours and bring down a wall of water 10 m high with a velocity of more than 70 km h^{-1} upon a calm ocean beach. The wave velocity is decreased near the coastline because of shallower water and the slowing of the wave by the roughness of the bottom. The steepness of the wave is increasing because the crest of the wave moves faster than the trough of the wave, whose motion is delayed by the bottom impact.

2.Causes of tsunamis

2.1.Generation of a tsunami by earthquake

Many large underwater earthquakes, whose epicenters are dislocated at the bottom of ocean or sea, are able to generate tsunami waves. These events, so-called tsunamigenic earthquakes (i.e. tsunami-making), are characterized by high energy, and the magnitude on the Richter scale are M>7.0. The horizontal size of the zone of the strongest bottom oscillations for such an event may be as great as 100 km or more.

The oscillating motions of the bottom during the tsunamigenic event are noted for the following parameters: vertical oscillation amplitude ~ 1 - 100 cm, particular velocity ~ 10 - 100 cm s^{-1}, acceleration due to gravity is around 0.5 g. Such a velocity on the bottom of U=1 m s^{-1} leads to the occurrence of an acoustic wave with a pressure amplitude equal to P=15 atmospheres ($P = \rho cU = 10^3$ kg $m^{-3} \times 1{,}5\ 10^3$ m $s^{-1} \times 1$ m s^{-1} = $1{,}5\ 10^6$ Pa =15 atmosphere; here ρ is the density of water, c - sound velocity).

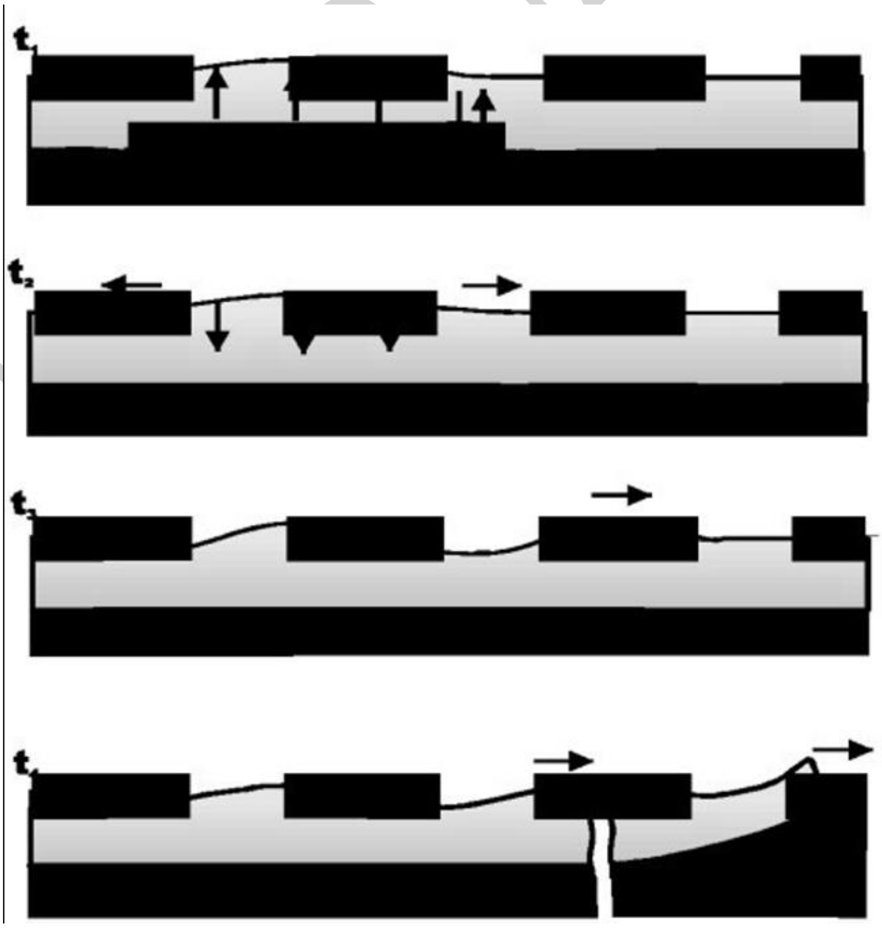

Figure 2. Schematic drawing of the tsunami generation by the bottom oscillating motion

In some instances, the earthquake may initiate faults and fractures in bottom rock. The blocks of crust are displaced up/down relative to each other and along the direction of the fault plane horizontal. The dimension of vertical displacement may reach 5 meters, and horizontal displacement may reach 20 meters or more. Finite displacement of the crust blocks, combined with bottom oscillating motion, often leads to generation of submarine landslides, revival of active faults, intensive emission of fluids transporting matter out of the Earth`s interior.

As the intensive oscillating motion of the bottom takes place in an area whose size is much greater than the thickness of the water layer, in certain situations, a rise or elevation is formed at the water surface (Figure 2).

The rise continues for the whole oscillation period, which is approximately 100 seconds for a large earthquake. When the bottom trembling stops, the sea surface elevation that was induced by seismic energy begins to spread over the surface with the release of gravity water waves from the source.

The directional diagram of generated waves depends on the form of the source and the relief of the bottom. The length of the wave comprises about 50-100 km in the open ocean, the period of wave is close to 10-20 minutes, and the maximum trough-to crest wave height is ~ 10 meters. Such a wave characterized by steepness of less than 1/1000 (ratio of amplitude to the length of the wave) will be practically unnoticed in the open ocean.

In the case of finite displacement of the ocean crust blocks due to earthquake, water elevation may occur over a large part of the ocean surface (at the overfault of bottom rocks) as well as the trough at the standard level of the ocean (after the strike-slip fault). After discontinuance of bottom motion, the generated disturbance of the water level (Figure 3) spreads over the surface in accordance with hydrodynamics laws radiating the gravity waves, much like the previous scheme (see Figure 2).

When a tsunami wave propagates in the ocean and arrives at the coastline, it is transformed due to non-linear and dispersion effects. Thus, the same wave may reach one section of the coast as a crest but reach another as a leading trough.

In reality, the tsunami usually arrives at the coastline as a wave train whose parameters depend on many factors. Sometimes the reflux appears as the first event before a tsunami wave, and the ocean bottom is uncovered far from the coastline (up to 1 km!). After some time, the reflux is converted into a distant wave that occupies the whole horizon and moves to the coast with a deafening roar. When the first wave of a tsunami passes into shallow water, the wave front becomes very steep (nearly vertical) due to slowing of the bottom water layer. The velocity of the tsunami run-up becomes close to 70 km h^{-1}, and its height may reach more than 10-15 meters. After the first wave, a second wave and following waves may come to the coastline. The period between arrivals of following waves may be of the order of 20 minutes.

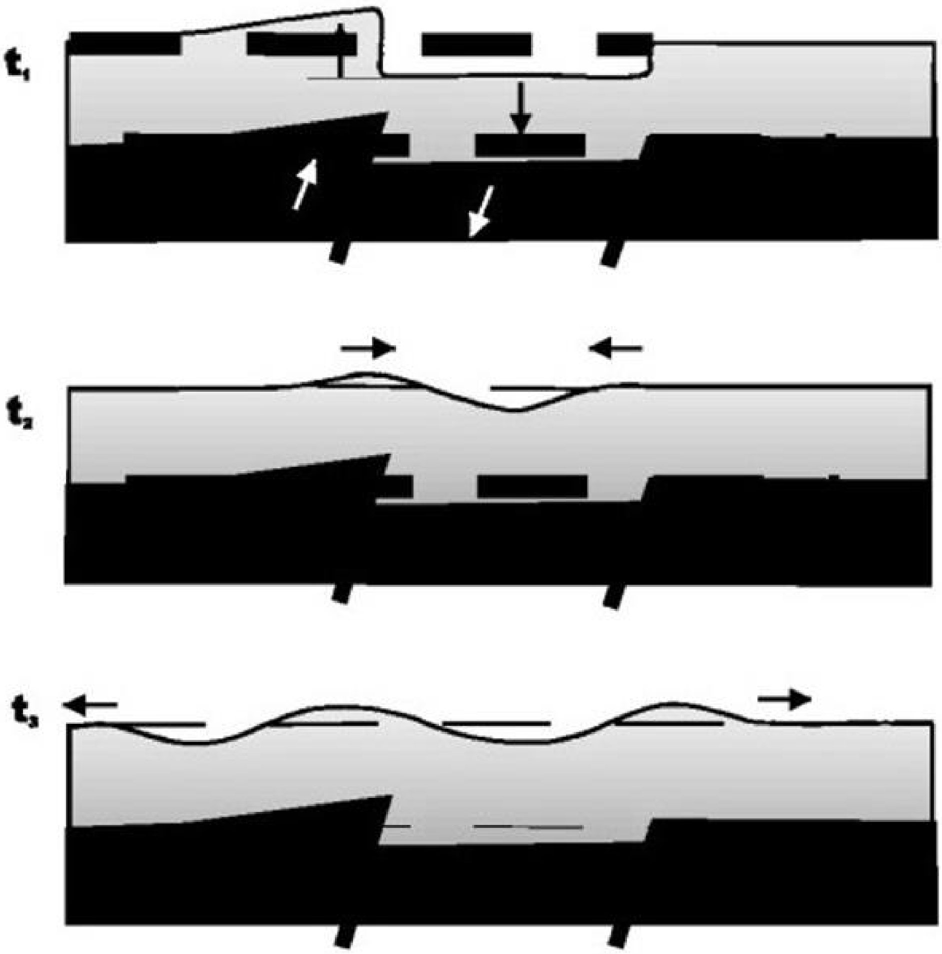

Figure 3. Schematic drawing of the tsunami generation by the bottom block displacement.

2.2.Tsunamis induced by submarine landslide and landfall.

A landslide-created tsunami, as a rule, has a local character. However, in the case of an extensive landslide involving the bottom sediments of the continental shelf or at the fall of a marine glacier into sea, the tsunami source may reach a size of several kilometers. These tsunami waves have a huge height and present a real hazard to the coastal population. The large landslide containing a mixture of rock debris and ice blocks with a volume of 30×10^6 m^3 that occurred in the Lituya Bay, Alaska because of the earthquake in Alaska on July 9, 1958 generated a tsunami wave with maximum trough-to-crest wave heights of ~ 60 meters. And believe it or not, an enormous run-up of the mega-tsunami washed out trees to a maximum altitude of 525 meters at the entrance of Gilbert Inlet! Much of the rest of the shoreline of the Lituya Bay was denuded by the tsunami from 30 to 200 meters altitude.

An landfall of caving coast, a break-away and the sliding of rock/ice blocks into the sea, occurrence of the bottom landslide and turbid flows, snow avalanches, or failure of harbor constructions may be responsible for tsunami generation. Quite a number of tsunamis generated by landslides and/or landfalls have been observed on the shelf off the south-eastern Alaska coast, near the coast of Canada, as well as in Norway, France, Italy.

A landslide motion process is usually caused by long-term accumulation of sediments at some ocean bottom areas, submarine slopes of basins, into the river deltas. The accumulated sediments are subjected to streams, storms, wind waves, tides, hurricanes, tectonic processes, and after this the landslide body comes into non-equilibrium. In this case, any weak perturbation action (micro-earthquake, meteorological disturbance, tide, etc.) plays a leading role as a trigger mechanism for failure of the unstable slide body. It is known that long-term rain, snow fall, and river inundation may provoke a landslide motion. The displacement of the landslide downwards leads to the local rise of the sea level above the landslide (Figure 4).

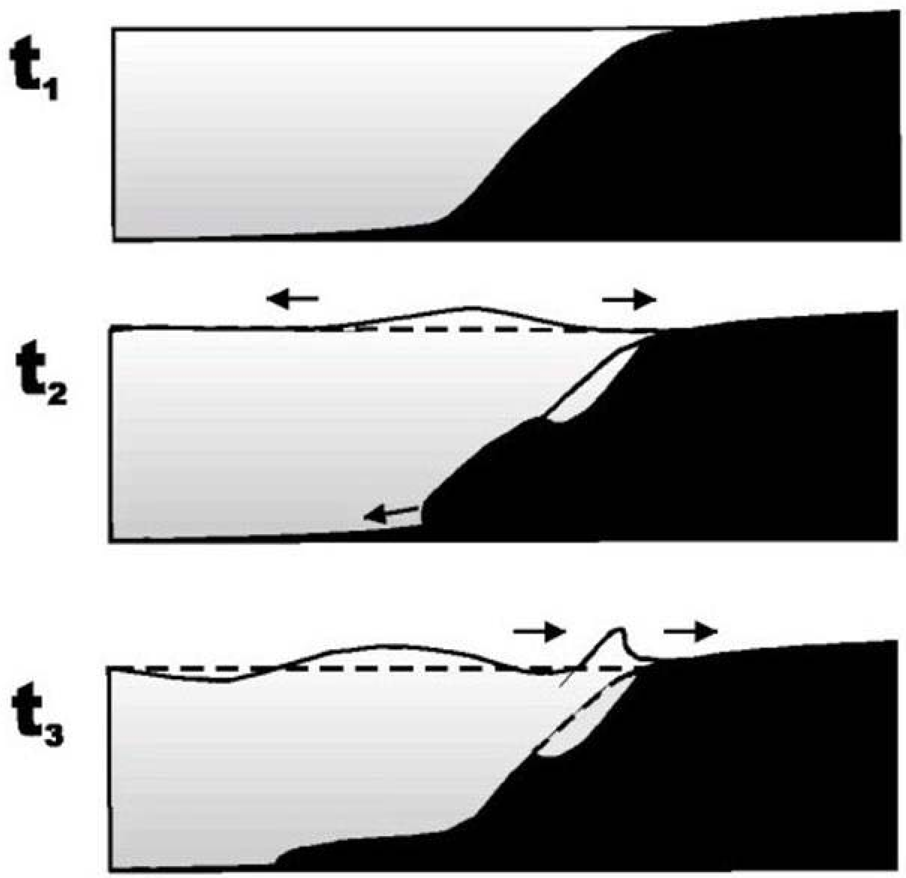

Figure 4. Schematic picture of the tsunami generation by the landslide motion.

When the landslide moves at a velocity equal to the velocity of a long gravity wave in this basin, then synchronism occurs. This specific situation creates a resonance condition for transmission of energy from the landslide to the surface water wave, and the height of the wave crest increases considerably.

In the last few years, landslide tsunamis induced by the failure of coastal constructions has assumed great importance. So, the tsunami in the harbor of Nice, France on October 16, 1979 generated by the sliding and failure of the sea-wall initiated waves several meters in height and caused fatalities. The submarine landslide associated with the dock failure in Skagway Harbor, Alaska on November 3, 1994 gave rise to a series of large-amplitude tsunami waves with maximum wave heights of 9-11 meters at the shoreline. The tsunami killed one person and destroyed many harbor structures.

As shown in the recent studies, the influence of landslides in some catastrophic tsunamis induced by earthquakes is much greater than was believed before. In specific cases, a landslide induced by an earthquake may amplify action of the tsunami wave. For this reason, the July 17, 1998 tsunami near Papua New Guinea (wave height: 10 meters, fatalities: 2182) proved to be more damaging than could be expected from an earthquake with a magnitude of M = 7.1. This paradox was explained by amplification of the tsunami due to a submarine landslide just after the earthquake.

A connection has recently been revealed between submarine landslides and the tide. The majority of landslide tsunamis occur at a time of extreme low tide.

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Levin Boris Wulfovich was born in Moscow, Russia in1937. Diplomaed Mining Engineer, Moscow, 1959; PhD, Skochinsky Institute of Mining, 1970; Diplomaed Senior Researcher, Russian Academy of Science, Moscow, 1980; Doctor of Science in physics and mathematics, Institute of Geosystems, Moscow, 1990; Diplomaed Professor of physics, Russian Ministry of Education, 2000.

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