Chapter 14

Tsunami as a Destructive Aftermath of Oceanic Impacts

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14.1 Introduction

Tsunamis belong to the long-period oceanic waves generated by underwater earthquakes, submarine or subaerial landslides or volcanic eruptions. They are among the most dangerous and complex natural phenomena, being responsible for great losses of life and extensive destruction of property in many coastal areas of the World's ocean. The tsunami phenomenon includes three overlapping but quite distinct physical stages: the generation by any external force that disturbs a water column, the propagation with a high speed in the open ocean and, finally, the run-up in the shallow coastal water and inundation of dry land (Gonzalez, 1999). Most tsunamis occur in the Pacific, but they are known in all other areas of the World including the Atlantic and the Indian oceans, the Mediterranean and many marginal seas. Tsunami-like phenomena can occur even in lakes, large man-made water reservoirs and large rivers.

In terms of total damage and loss of lives, tsunamis are not the first among other natural hazards. Actually, they rank fifth after earthquakes, floods, typhoons and volcanic eruptions. However, because of their high destructive potential, tsunamis have an extremely adverse impact on the socioeconomic infrastructure of society, which is further strengthened by their suddenness, terrifying rapidity, heavy destruction of property and high percentage of fatalities among the population exposed. The feature that differs tsunamis from other natural disasters is their ability to produce a destructive impact far away from the area of their origin (up to 10 000 km). In the ocean where the bottom is flat, their far-field amplitude decreases as $1/\sqrt{r}$ because of cylindrical divergence that is a minimum possible attenuation allowed by the energy conservation law. One of the largest Pacific tsunamis historically known was generated by a strong (magnitude 8.6) earthquake which occurred on May 22, 1960 near Chiloe Island (southern Chile), and some 22 hours later reached Japan still generating waves 6–7 meters high, producing extensive damage (nearly 10 000 houses were destroyed) and claiming some 229 lives (Fig. 14.1).

In the open ocean, tsunamis travel at a speed ranging from 400 to 700 km per hour depending on the water depth. The velocity is controlled by the ocean depth as described by the formula

$$v = \sqrt{gH}$$

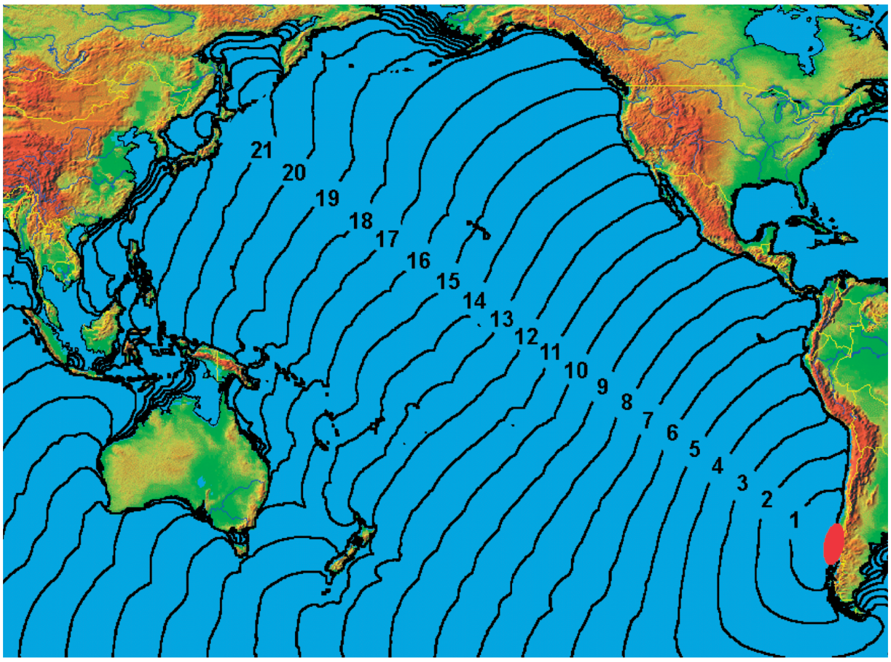

Fig. 14.1. Tsunami travel-time chart for the 1960 Chilean tsunami. *Digits* near the isochrones – propagation time in hours. The *solid ellipse* shows the position of the earthquake source

where g is acceleration due to gravity, and H is depth of water. The typical periods of oscillations in these waves cover the range from 5–6 minutes to 1 hour. Due to their great wavelength, reaching 500–700 km in the deep ocean and 50–100 km on the continental shelf, tsunamis rarely approach the coast as breaking waves, rather, they appear as a quick succession of floods and ebbs producing strong, up to 10 m s^{-1}, currents.

Destruction from tsunamis results from the three main factors: inundation of salt water, dynamic impact of water current and erosion. Considerable damage is also caused by floating debris that enhance the destructive force of the water flood. Flotation and drag force can destroy frame buildings, overturn railroad cars and move large ships far in-land. Ships in harbours and port facilities can be damaged by the strong current and surge caused by even a weak tsunami.

A typical height of tsunami, generated by an earthquake with magnitude of 7.0 to 8.0 (the range where most of tsunamigenic earthquakes occur) is from 5 to 10 meters at the nearest coast where run-ups are typically observed along 100 to 300 km of the coastline. This height is still within the range of the largest possible storm surges for many coastal locations. However, having a longer wavelength, tsunami can penetrate in-land to much greater distances reaching in many places several hundreds of meters and sometimes several kilometers. The highest run-up of tectonically induced tsunamis can reach 20–30 meters (1952 Kamchatka, 1960 Chile, 1964 Alaska tsunamis). Even a higher water splash (up to 50–70 meters) can be produced by submarine or coastal landslides when compared to those triggered by earthquakes. Such strong tsunamis have an enormous destructive power and sweep everything on land lying in their way, removing soil, vegetation and all traces of existing settlements.

All destructive tsunamis can be divided into two categories: *local* or *regional* and *trans-oceanic*. For local tsunamis, the destructive effect is confined to the nearest coast located within one hour of the propagation time (from 100 to 500 km). In all tsunamigenic regions of the World oceans, most of damage and casualties come from local tsunamis. Far less frequent but potentially much more hazardous are trans-oceanic tsunamis capable of widespread distribution. Formally, this category includes the events that have run-ups higher than 5 meters at a distance of more than 5000 km. Historically, all trans-oceanic tsunamis are known in the Pacific with only one case recorded in the Atlantic (the 1755 Lisbon tsunami, that reached the Caribbean with 5–7 m waves).

The overall physical size of a tsunami is measured on several scales. Among most common is the *Soloviev-Imamura* scale denoted by I. This is an intensity scale, first proposed by A. Imamura (Imamura, 1942) and then slightly modified by S. Soloviev (Soloviev, 1978). It is based on the average run-up height of waves h_{av} along the nearest coast according to the formula

$$I = \frac{1}{2} + \log_2 h_{av}$$

In this scale, the largest trans-Pacific tsunamis have an intensity of 4–5, destructive regional tsunamis – an intensity of 2–3, not damaging but still visually observable and finally local tsunamis – an intensity of 0–1. Tsunamis detectable only on instrumental records have a negative intensity (from –1 to –4).

14.2 Geographical and Temporal Distribution of Tsunamis

The world-wide catalogue and database on tsunamis and tsunami-like events that is being developed under the GTDB (Global Tsunami DataBase) Project (Gusiakov, 2003), covers the period from 1628 BC to the present and currently contains nearly 2250 historical events with 1206 of these for the Pacific, 263 for the Atlantic, 125 from the Indian ocean and 545 from the Mediterranean region. The geographical distribution of tsunami is shown in Fig. 14.2 as a map of seismic, volcanic and landslide sources of historical tsunamigenic events. When analyzing this map, one should take into account that it reflects not only the level of tsunami activity, but also the regional historical and cultural conditions that strongly influence the availability of the historical data. From geographical distribution of tsunamigenic sources, we can see that most of tsunamis were generated along subduction zones and the major plate boundaries in the Pacific, the Atlantic and the Mediterranean regions. Very few historical events occurred in the Deep Ocean and central parts of the marginal seas, except several cases of small tsunamis that originated along the middle-ocean ridges and some major transform faults.

The temporal distribution of historical tsunamis is shown in Fig. 14.3 for the last 1000 years. From this graph we can see that the historical data have a highly non-uniform distribution in time with three quarters of all events reported within the last two hundred years. The most complete data exist for the 20th century, when the instrumental measurements of weak tsunamis became available. In all tsunamigenic regions (except possibly Japan) there are obvious gaps in reporting even large destructive events for the period preceding the 20th century. Thus, any estimates of tsunami recurrence should be considered with this fact (data incompleteness) in mind.

In 1901–2000, a total of 943 tsunamis were observed in the World Ocean that results in about ten events per year. Most of these events were weak, observable only on tide

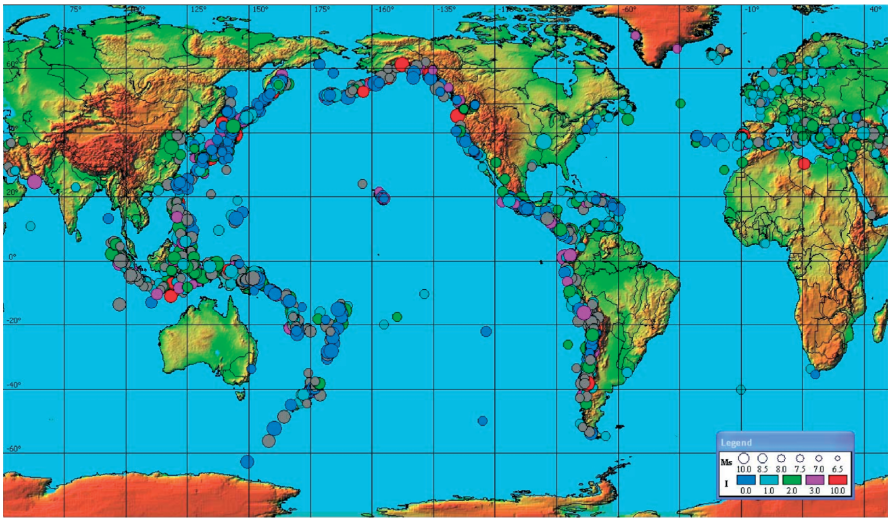

Fig. 14.2. Geographical distribution of tsunami sources in the World Ocean. The size of *circles* is proportional to the earthquake magnitude, density of *gray tone* – to the tsunami intensity on the Soloviev-Imamura scale

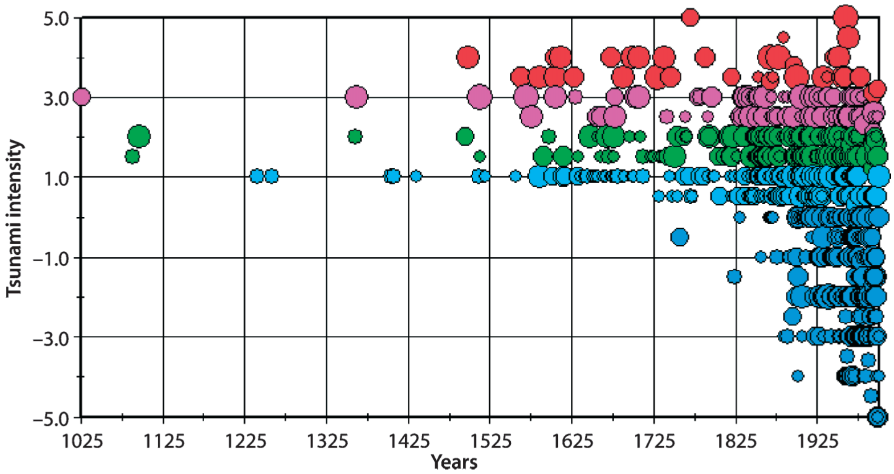

Fig. 14.3. Tsunami occurrence versus time for the last 1000 years. Events are shown as *circles* with the color depending on tsunami intensity and the size proportional to the earthquake magnitude

gauge records. About 260 tsunamis were "perceptible", having a run-up height exceeding one meter. Among these, in 33 cases the run-up was greater than one meter and it was observed at a distance of more than 1000 km from the source. During the last 100 years, five destructive trans-oceanic tsunamis, all in the Pacific are known to have occurred (1946 Aleutians, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska).

14.3
Basic Types of Tsunami Sources

Most of oceanic tsunamis (up to 75% of all historical cases) reported in historical catalogues are generated by shallow-focus earthquakes capable of transferring sufficient energy to the overlying water column. The rest are divided between landslide (7%), volcanic (5%), meteorological (3%) tsunamis and water waves from explosions (less than 1%). Up to 10% of all the reported coastal run-ups still have unidentified sources.

Seismotectonic tsunamis. Tectonic tsunamis are generated by submarine earthquakes due to the large-scale co-seismic deformation of the ocean bottom and the dynamic impulse transferred to a water column by compression waves. Tsunamigenic earthquakes occur along subduction zones, middle ocean ridges and main transform faults, i.e. within the areas with a large vertical variation of the bottom relief. The size of tsunami generated by an earthquake relates to the energy released (earthquake magnitude), source mechanism, hypocentral depth and the water depth at the epicenter.

Concerning the spatial distribution of tsunami damage, the rule of thumb is that in all but largest seismically induced tsunamis, their damage is limited to an area within one hour of the propagation time. The typical distribution of tsunami run-up heights along the coast is shown in Fig. 14.4. This is a modification of the figure from (Chubarov and Gusiakov 1985) obtained as a result of calculations of tsunami genera-

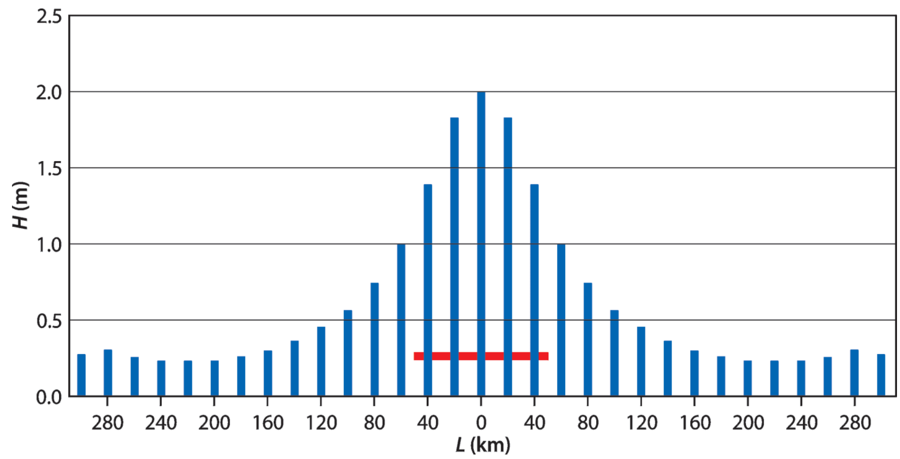

Fig. 14.4. Typical distribution of tsunami run-up heights along the coast calculated for a model source equivalent to a magnitude 7.5 submarine earthquake. Section of the *solid line* shows the position and size of the seismic source

tion by a model source having some basic features of a real earthquake with moment-magnitude 7.5 and wave propagation over the inclined bottom modeling the continental slope and shallow-water shelf. One can see that the area of the dominating heights is roughly limited to twice the size of the earthquake source (100–200 km for an earthquake of magnitude 7.0–7.5). Outside of this area, the run-up heights rapidly decrease. Such a strong directivity results from three main factors: (*1*) initial directivity of energy radiation by a seismic source, (*2*) ellipticity of a source, and (*3*) wave refraction on the inclined bottom. Among these factors, the most important is the third – refraction on the inclined bottom – and this effect dominates in the coastal run-up distribution in all regional tsunamis, having their sources on the continental slope and shelf.

Note, that initial wave height in the source area as derived from the co-seismic displacement produced by an earthquake source is about 0.7 m, thus giving the magnification factor (ratio of the maximum coastal height to the wave height in the deep water) of about 3. Further wave amplification during run-up on to dry land can give another factor of 2, thus resulting in total magnification from 5 to 6, that is significantly less than 10 to 40 as postulated in (Morrison et al. 1994). Such great amplification is possible just under very specific combination of the near-shore bathymetry, configuration of the coastline and the coastal relief. Indeed, the 30.8 m run-up measured after the 1993 Okushiri tsunami in the Japan Sea, was a rare feature above the average 8–10 m run-up along the rest of the Okushiri coast.

Slide-generated tsunamis. Not as frequent as tectonic generation, but still very common world-wide, slide-generated tsunamis result from rock and ice falling into the water, or sudden submarine landslides. Typically, they produce an extremely high water splash (up to 50–70 m, with the highest historical record of 525 m noted in Lituya Bay, Alaska in 1958) but not widely extended along the coast. In general, the energy of landslide tsunamis rapidly dissipates as they travel away from the source, but in some cases (e.g., if the landslide covers a large depth range), a long duration of slide movement can focus the tsunami energy along a narrower beam than the equivalent seismic source (Iwasaki, 1997). One of the most recent cases where the involvement of slide mechanism in tsunami generation was definitely confirmed is the 1998 Papua New Guinea tsunami when 15-m waves were observed after the Mw 7.0 earthquake (Okal and Synolakis 2001; Synolakis et al. 2002; Tappin et al. 2002). The slide-generated water waves occur not only in the oceans and seas, but pose a clearly recognised hazard to reservoirs, harbours, lakes and even large rivers where they may endanger lives, overtop dams, or destroy the waterside property.

In the case of large earthquakes, the accompanying landslides, locally triggered by strong shaking, can produce waves greatly exceeding the height of the main tectonic tsunami. They are particularly dangerous as they arrive within a few minutes after the earthquake, leaving no time for a warning. One of the primary causes of death in the 1964 Alaska earthquake was the secondary tsunami generated by slides from the fronts of the numerous deltas at the Alaska coast (Lander 1996). These locally-triggered landslide tsunami can be an important factor even for a land impact especially in the case where it happens within a coastal area particularly vulnerable to landslides given the existence of numerous fiords, narrow bays and steep submarine canyons having large potential for slumping (e.g. Norway, Kamchatka, Alaska, west coast of Canada and US) (Rabinovich et al. 2003).

Volcanic tsunamis. Although relatively infrequent, explosive volcanic eruptions on small islands can generate extremely destructive water waves in the immediate source area. The 1883 Krakatau eruption with 150–200 MT of TNT equivalent and 18–20 km^3 of the estimated volume of the eruptive material resulted in 25-meter tsunami that flooded the coast of the Sunda Strait and killed 36 000 people (Yokoyama 1981). The catastrophic tsunami that devastated the northern coast of the island of Crete, was generated by an explosion of the Santorini volcano in 1628 BC with the estimated volume of eruptive material 50–60 km^3 (McCoy and Heiken 2000; Minoura et al. 2000). Smaller eruptions can generate a significant tsunami if they are accompanied by a volcanic slope failure (e.g. 1792 Unzen volcano collapse in Japan) or a large lahar or a pyroclastic flow (e.g. 1902 Mount Pele eruption in Martinique). As compared to tectonically-induced tsunamis, volcanic tsunamis can be extremely destructive locally, but rarely transport their energy far from the area of origin. It is widely known that the 1883 Krakatau tsunami was globally observed and recorded by 35 remote tide stations including several in the northern Atlantic, but it is rarely recognised that most of the damage and all deaths actually occurred in the very limited area along the coast of the Sunda Strait within the distance of 300 km from the site of explosion.

Meteorological tsunamis. Tsunami-like waves can be generated by a rapidly moving atmospheric pressure front moving over a shallow sea at approximately the same speed as a tsunami could allow them to couple. The resulting run-up can be increased by the hydrostatic water rise due to the low pressure zone in the cyclone center and the dynamic surge resulting from a strong wind pressure. In fact, after the 1883 Krakatau eruption at some remote tide stations the recorded sea level disturbance was a result of the water response to the air pressure waves traveling in the atmosphere from the site of explosion (Ewing and Press 1955; Press and Harkrider 1966).

Explosion-generated tsunamis. The world-wide historical tsunami catalogue contains several cases of tsunamis generated by large explosions. In December of 1917, large waves were generated by the greatest man-made explosion before the nuclear era – this happened in the Halifax Harbour (Nova Scotia, Canada) after a collision of the munitions ship *Mont Blanc*, having 3 000 tons of TNT on board, with the relief ship *Imo*. At the coast near to the explosion site, the waves were over 10 meters high, but their amplitude diminished greatly with distance (Murty 2003). An extensive study of water waves generated by submarine nuclear explosions, both on and under the sea surface and up to 10 MT yield, and also on a series of smaller-scale tests carried out in Mono Lake (California) was made by W. Van Dorn (Van Dorn 1968) for the US Navy. The main conclusions from his study were that tsunamis from explosions have a shorter wavelength as compared to the size of the resulting cavity (a few km in diameter), in near-field the tsunami height can be very large, but rapidly decays as the waves travel outside the source area. He also indicated (however, without any proof and details presented) to the effect of breaking of short-length waves when they cross the continental shelf, generating large-scale turbulence, but leaving the coast without damageable run-up (Morrison 2003).

14.4 Tsunamigenic Potential of Oceanic Impacts

Since evidence for asteroid impact on Earth exists, we have to conclude that there is a four-to-one chance that they hit oceans, seas or even large internal water reservoirs and therefore tsunami or tsunami-like water waves can be generated by an extra-terrestrial impact. There has been a general concern that the tsunami from a deep-water impact of a 1-km asteroid could contribute substantially to its overall hazard for the people living near coasts and would wash out all coastal cities of the entire ocean (Chapman 2003; Morrison 2003). However, a 1-km asteroid is quite close to the global disaster threshold (impact of a 2–3 km object) and tsunami could therefore contribute somewhat to other hazardous aftermaths of this natural catastrophe that would have a large enough potential to end our modern civilisation era. Fortunately for humankind, it is indeed a very rare event, available estimates of its return period vary in the range of 100 000 to 1 000 000 years. Much more frequent are the Tunguska-class impacts (the size of an object being 100 m or less) with the return period being more relevant to the human time scale and spanning from several hundred to one thousand years. Unless the small asteroid is made of solid metal (iron or nickel), it would likely explode in the upper atmosphere with a TNT equivalent in the first tens of megatons. Available estimates, based mainly on nuclear tests results, show that tsunami from such an airblast should be from several tens of centimeters to one meter (Glasstone and Doland 1977), so the water impact of such a small, once-per-century asteroid could be in general less hazardous than an equivalent explosion above land.

A practical concern related to impact tsunamis is that the risk they impose can be significant for asteroids with a diameter between 200 m and 1 km (Hills et al. 1994). Possible effects of tsunamis are mentioned in numerous publications devoted to the estimation of impact aftermaths (Hills et al. 1994; Hills and Mader 1997; Hills and Goda 1998; Mader 1998; Ward and Asphaug 2000, 2003). The resulting deep-water wave height and expected run-up distribution along the coast depends on many factors – the size of an impactor and its composition, velocity and angle of collision, finally, the particular site of an impact. Even for a concrete set of these parameters, researchers are very uncertain about the expected height of an impact generated tsunami. The main reason for that is, of course, that the problem of modeling of the generation stage and, especially, the first initial 10 seconds of the impact process is extremely complicated. The full-scale modeling of this high-speed process requires the solution of 3D equations describing the non-linear dynamics of compressible multi-substance fluid (model of the ocean) overlying the layered elastic half-space (model of the Earth's crust) and allowing for hyper-velocity shock waves and large deformations. This is still a very challenging task for the modern hydrodynamics and computational mathematics required and the application sophisticated numerical algorithms, like LPIC (Lagrangian Particles In Cell) method, and supercomputing.

One of the most fascinating examples of this kind of computations was made by D. Crawford of Sandia National Laboratory (Crawford, 1998) during the initial testing of the Intel Teraflop supercomputer and with additional purpose of generating unclassified data to test innovative visualisation techniques. The CTH Shock Physics Hydrocode was used to model the impact of a 1 km diameter comet (with 300 GT

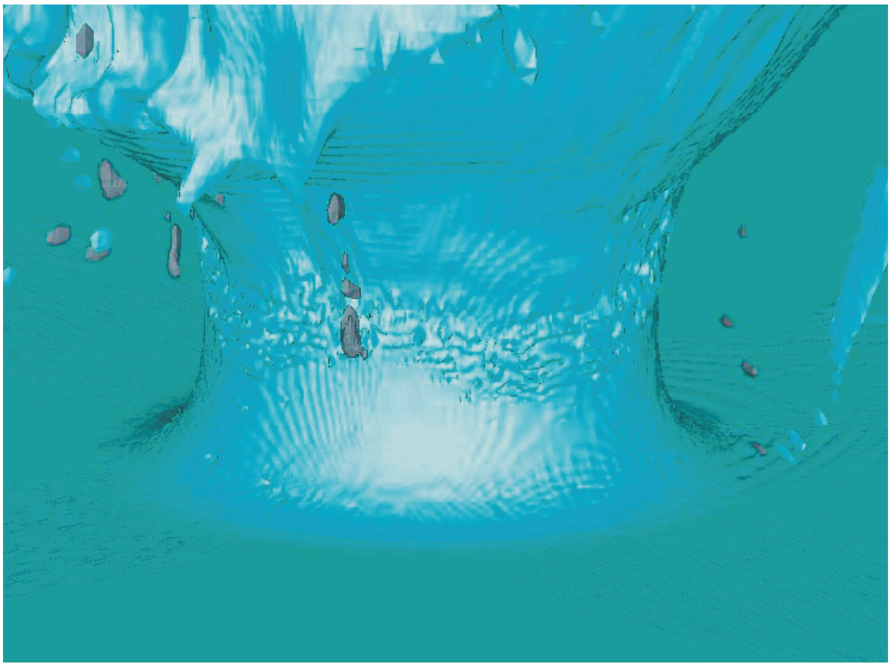

Fig. 14.5. Snapshot of the Crawford's numerical model of 1-km ice comet into the ocean. The comet and large quantities of ocean water are vaporised and ejected onto suborbital ballistic trajectories. Picture is downloadable from *http://sherpa.sandia.gov/planet-impact/comet/*

TNT equivalent) into a 4-km depth ocean. A large tsunami initially several kilometers high was generated and radiated from the point of impact (Fig. 14.5). However, it rapidly decayed having just 50–100 m high crests in the open ocean at the distance of 1000 km from the impact site.

In this paper, I refer to the estimates of possible wave heights from the water impacts of a solid asteroid as function of its basic parameters (diameter, density and velocity) that were obtained by V. Petrenko (Petrenko, 2000), based on the available experimental data on underwater nuclear explosions (Glasstone and Dolan 1977), the rules of similarity for hydrodynamic processes and application of models developed for simulation of dynamics of compressible multi-substance fluids with large deformations (Petrenko, 1970). These estimates are shown in Table 14.1 for the "deep water" case (the size of the resultant cavity being smaller than the average water depth) and in Table 14.2 for a "shallow water" case (the size of the resultant cavity being comparable to or larger than the average water depth).

From the data in the tables, we can see that in the "deep water" case, a 200-meter stone asteroid (density 3 g cm^{-3}) falling into the water at 20 km s^{-1} speed is capable of generating 5-meter waves at a distance of 1000 km. Similar waves are generated in the "shallow water" case. However, for a 500-meter asteroid the resulting wave height in the "deep water" case is almost double the size compared to the "shallow-water" case (21.9 m and 10.1 m, respectively).

Table 14.1. The estimated wave height *h* (m) and the impact kinetic energy *W* (GT TNT) in *deep water* at a distance of 1 000 km from the impact site as function of impactor diameter for iron-nickel ($\rho = 8.0$ g cm^{-3}) and stony ($\rho = 3.0$ g cm^{-3}) asteroids and ice comet ($\rho = 0.5$ g cm^{-3}) falling into water with the velocity 20 km s^{-1}

Diameter (m)	Density (g cm^{-3})					
	8.0		3.0		0.5	
	W (GT)	*h* (m)	*W* (GT)	*h* (m)	*W* (GT)	*h* (m)
200	1.60	8.4	0.60	5.0	0.10	1.9
300	5.39	16.2	2.02	9.6	0.34	3.6
400	12.77	25.9	4.79	15.2	0.80	5.8
500	24.93	37.1	9.35	21.9	1.56	8.3
1 000	199.47	114.1	74.80	67.2	12.47	25.5

Table 14.2. The estimated wave height *h* (m) and the impact kinetic energy *W* (GT TNT) in *shallow water* at a distance of 1 000 km from the impact site as function of impactor diameter for iron-nickel ($\rho = 8.0$ g cm^{-3}) and stony ($\rho = 3.0$ g cm^{-3}) asteroids and ice comet ($\rho = 0.5$ g cm^{-3}) falling into water with the velocity 20 km s^{-1}

Diameter (m)	Density (g cm^{-3})					
	8.0		3.0		0.5	
	W (GT)	*h* (m)	*W* (GT)	*h* (m)	*W* (GT)	*h* (m)
200	1.60	6.5	0.60	5.1	0.10	3.3
300	5.39	8.8	2.02	6.9	0.34	4.4
400	12.77	11.0	4.79	8.6	0.80	5.5
500	24.93	13.0	9.35	10.1	1.56	6.5
1 000	199.47	21.8	74.80	17.1	12.47	10.9

The further evolution of the initial water displacement strongly depends on the particular site conditions – whether it is a deep ocean, a marginal sea, an island archipelago or shallow-water coastal areas. Scattering in the final run-up and run-in distribution along the coast can be well above the factor of 10, thus making any scenario estimates of potential damage or human loss due to an oceanic asteroid tsunami very doubtful or even misleading. My personal feeling, based on long-term involvement in the study of historical and contemporary tsunamis and the analysis of available scenarios is that the total risk of asteroid tsunamis is somewhat overestimated in the literature, in particular, in the papers published in the 1990s (see for instance, Hills et al. 1994; Morrison et al. 1994). Under no conditions will 1% of the total population (that is more than 60 million people) be killed by tsunami from a single oceanic impact if it is below the global threshold.

14.5
Operational Tsunami Warning

The tectonically generated tsunamis can be predicted shortly before their arrival to the coast based on seismic observations and deep-water measurements. This is the task of the international Tsunami Warning System (TWS) that is in operation in the Pacific since the beginning of 60s (Master Plan 2000). The main operational center of this system is located in Ewa Beach, Hawaii, and provides 26 Pacific countries with operational warnings in about half to one hour after occurrence of an earthquake with magnitude above the threshold value (7.8 for most of the Pacific). Unfortunately, due to complexity and statistical nature of the tsunami generation process, these warnings quite often turn out to be false and, at the same time, several dangerous events in the last decade were not provided with timely warnings (1992 Nicaragua, 1994 Mindoro, Philippines, 1995 Jalisco, Mexico, and 1998 Papua New Guinea).

The International Co-ordination Group for the Tsunami Warning System in the Pacific (ICG/ITSU) was established by the Intergovernmental Oceanographic Commission (IOC) of UNESCO in 1965 for promoting the international cooperation and coordination of tsunami mitigation activities. It consists of national representatives from 26 Member States in the Pacific region and conducts biannual meetings to review progress and to coordinate the activity in improvement of the Tsunami Warning System. The IOC/UNESCO also supports the International Tsunami Information Center (ITIC) in Honolulu, Hawaii, whose mandate is to collect and distribute the data and information on tsunamis, to monitor and recommend improvements to the TWS, to assist in establishing national and regional TWSs in the Pacific and other tsunamigenic regions.

As mentioned above, on Earth the probability of an asteroid impact into a water basin is essentially higher that onto the land. Whereas available quantitative estimates of resulted run-up heights vary greatly, it is clear that a sub-kilometer asteroid can generate the significant tsunami that can be devastating locally or regionally. Such an impact will also produce a seismic waves that will be almost immediately detected by the global seismic network and, after routine processing, will be identified as a submarine earthquake with the very shallow focus depth. Even for a 10 MT impact, the estimated equivalent Richter magnitude is about 5.1, that is still well below the threshold (Ms = 6.5) for in-depth investigation adopted in the Pacific TWS, and such an event will be routinely placed on the list of current earthquakes. However, tsunami from the oceanic impact can be considerably higher (at least, locally) as compared to a submarine earthquake with the equivalent seismic magnitude.

Because of relative slowness of tsunami propagation on the continental slope and shelf, there will be a limited time interval, spanning from tens of minutes to several hours, to warn the population of coastal areas at risk and to implement the Tsunami Response and Mitigation Plan existing in many countries faced with the threat of tectonic tsunamis. However, being exceptionally oriented to seismically-induced tsunamis, the Pacific TWS may not recognize the signature of an asteroid impact if it occurred in an unusual place (i.e. in abyssal oceanic plate or aseismic marginal sea) and may not timely implement the standard tsunami evaluation procedure based on the analysis of telemetric tide gauge records and start the warning dissemination as prescribed by the TWS Communication Plan. As a result, the essential part of a possible warning time may be lost before non-standard warning situation is resolved and a potentially dangerous asteroid tsunami is identified and evaluated.

14.6 Detection of Impact Tsunamis by Tide Gauge Network

For the last one hundred years, we are sure that we did not miss any damageable impact-generated tsunami if it happened to occur in the World oceans. All the considerable coastal run-ups were associated with identified seismic, volcanic or landslide sources. However, we cannot be so confident in relation to numerous weak events that are identified only on tide gauge records.

Instrumentally, tsunamis are recorded by the world-wide network of tide gauge stations that has almost a 200-year history starting from the first tide gauge installed in Brest, France in 1807. In 1883 a distant tsunami resulting from the catastrophic Krakatau eruption was recorded by 35 instruments situated along the coast of the Pacific, the Atlantic and the Indian oceans (Simons 1888). By the beginning of the 20th century, there were nearly 100 tide stations in operation. Presently, the sea level recording system includes almost 1500 instruments installed all over the world (Fig. 14.6), some of them having real-time or near real-time telemetry to the data processing centers.

Normally the search for instrumental records starts from a report about the "event occurrence" (that usually comes from seismologists) or from a local account about unusual wave activity or coastal run-up. After that, the examination of records of the nearest tide stations is made in the time windows corresponding to the expected arrival times of tsunami, and the parts of records, containing the tsunami signal, stored

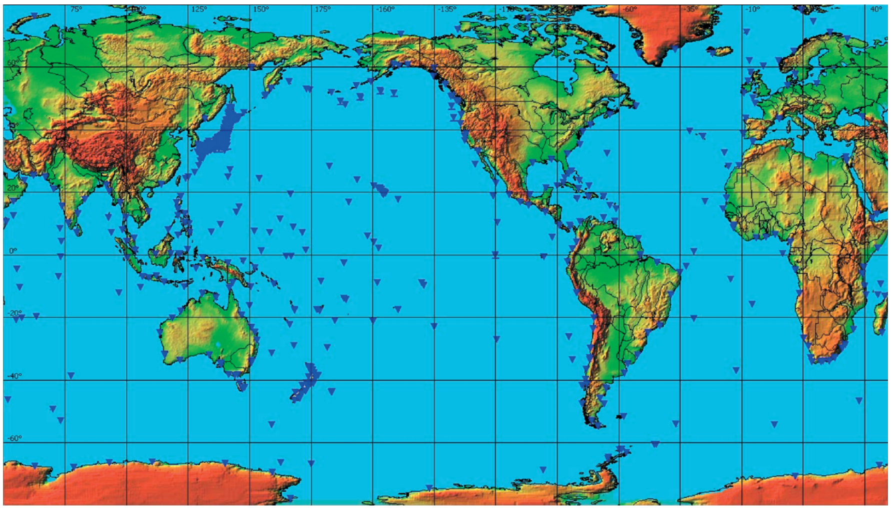

Fig. 14.6. Geographical distribution of the world-wide tide gauge network. The stations are shown as *blue triangles*

in the local archives. Agencies, that are responsible for operation of tide gauges, are interested in recording of long-term sea level changes, tides and storm surges and usually ignore small-amplitude impulsive signals appearing on tide gauge records. Thus, the signature of a small, "non-seismic" tsunami has little chance to be discovered and reported.

As distinct from seismologists, tsunami researchers do not have a routine system for systematic examination of tide gauge records with the purpose of identification of a "signal onset" on the tide records, their association between different stations and search for a possible source. The only exception is the work of S. Wigen (Wigen 1983) who systematically studied records from Tofino tide station (Canada) from 1906 to 1980 in order to identify potential tsunami arrivals and locate their sources. There is no doubt that a wealth of data on non-identified tsunami-like signals exists and these data are lying dormant in archives of tide gauge stations. Being found and reported, most of them would be later identified as records of small tsunamis from weak earthquakes, submarine slides or underwater eruptions. However, all such events originate in well-defined zones of seismic, volcanic or slumping activity. Discovering the signals with an estimated source outside of the well-known tsunamigenic areas would be a strong indication to a possible trace of oceanic impact. The absence of known reports of such an impact into the ocean doesn't mean that these events did not actually occur during the last one hundred years. It is worth noting that the 1908 Tunguska explosion remained almost unknown for scientists and general public for another 20 years (the first expedition to the area of explosion was conducted only in 1927).

14.7 Geological Traces of Tsunamis

The time coverage of historical tsunami catalogues that for many regions does not exceed 300–400 years can be greatly extended by application of geological methods of studying the paleotsunami traces preserved in coastal sediments or erosion features left by water impact on the coastal bedrocks. As was demonstrated by K. Minoura and S. Nakaya in Japan (Minoura, Nakaya, 1991) and later confirmed in numerous field studies in other countries, the invasion of a large volume of salt water onto land can produce a serious disturbance of the normal sedimentary process and leave unique deposits which could remain in the intertidal environment for a long time and, being investigated and interpreted in the correct manner, may represent a "geological chronicle" of a local tsunami history. In fact, tsunami deposits found in Texas was one of most essential evidences in favour of the reality of K/T boundary global catastrophe resulted from the Chicxulub impact (Bourgeois et al. 1988).

At present, paleotsunami studies are in progress in many countries providing a significant amount of new information about past tsunamis (Atwater 1987; Atwater et al. 1995; Bourgeois and Reinhardt 1989; Buckman et al. 1992; Darienzo and Peterson 1990; Dawson et al. 1988, 1991). At the Kamchatka Peninsula, the paleotsunamis studies made in 1993–1996 discovered up to 50 previously unknown pre-historical events that flooded the Kamchatka east coast during the last two thousand years (Pinegina and Bourgeois 2001). Thus, the historical catalogue, covering in Kamchatka only the last 250 years, was extended more than ten times.

The search and investigation of geological traces of paleotsunami can be one of the primary methods to confirm the occurrence of impact-generated tsunamis in the past. Since 1990 numerous geological evidence of destructive water wave impact have been found on south-east and north-west coasts of Australia suggesting a mega-tsunami impacts at these aseismic coastlines that have not been flooded any historically known considerable tsunami (Bryant 2001; Bryant and Young 1996; Bryant et al. 1996; Bryant and Nott 2001; Nott and Bryant 2003). Characteristics of these tsunami (vertical flooding of 30–40 meters covering more then 1500 km of coastline, maximum vertical run-up reaching 130 m, horizontal flooding up to 5 kilometers inland) so dramatically differentiate them from the largest tectonically-induced tsunamis that their cosmogenic origin becomes almost obvious. Recent discoveries of the Mahuika crater in the shallow water near the South Island of New Zealand along with numerous Aboriginal and Maori legends about comets, smog, dust, fire and flood gives complementary evidence for a mega-tsunami resulting from a comet or asteroid impact in the Tasman Sea around 1500 AD (E. Bryant, pers. comm. December 2004).

Geological evidence of mega-tsunami exists in other regions. R. Paskoff (Paskoff 1991) describes large boulders in the Herradura Bay scattered over the shelly beach deposits associated with an abrasion platform at an elevation of 30–40 m above the modern beach southwest of Coquimbo, Chile. Similar boulders exist in the Guanaquero Bay about 25 km southwest of the Herradura Bay. By his opinion, these boulders were displaced by powerful waves coming from the northwest. At that time of publication his paper, ideas about cosmogenic tsunami were rather unusual, perhaps it was the reason why R. Pascoff talked about "an earthquakes of exceptional magnitude that happens only once in Plio-Quaternary time, probably around 300 000 years ago". Now we cannot completely ruled out the hypothesis that those boulders were deposited by a tsunami resulted from an asteroid impact somewhere in the southeast Pacific.

14.8 Conclusions

1. Both distantly and locally generated tsunamis are a typical example of "low probability – high consequence" hazard. Having, as a rule, a long recurrence interval (from 10–20 to 100–150 years) for a particular coastal location, they produce an extremely adverse impact on the coastal communities resulting in heavy property damage, a high rate of fatalities, disruption of commerce and social life.
2. In most of historical tsunamis, the major damage is confined to the nearby coast, but in some cases, waves may cross the entire ocean and devastate distant shorelines. Locally highly destructive tsunamis are generated after earthquake-triggered subaerial or submarine landslides. The size of tsunami generated by an earthquake relates to the energy released (earthquake magnitude), source mechanism, hypocentral depth and the water depth at the epicenter. The size of tsunami generated by landslide relates mainly to its volume as well as to the angle of inclined bottom (that controls the maximum slide velocity), initial water depth (for submarine slides) or relative slide body height (for subaerial slides) and the type of material involved in mass movement.

3. The expected tsunami height from an oceanic impact of sub-kilometer asteroid remains highly controversial. Estimates available in the literature vary by more than factor of ten. In the near-field zone, impact tsunamis can be much higher than any tectonically induced tsunamis. However, they have essentially shorter wave length that results in a faster energy decay (as $1/r$ against $1//\sqrt{r}$ for tectonic tsunamis) as they travel across the ocean. Therefore, the total area of perceptible damage for asteroid tsunamis cannot be very large (e.g., essentially more than 1 000 km in radius) for all but the largest possible impacts approaching the threshold for a global catastrophe.
4. Being exceptionally oriented to seismically-induced tsunamis, the international Tsunami Warning System, established in the Pacific since 1965, might not recognize the signature of an asteroid impact and might not implement in a timely matter a standard tsunami evaluation procedure based on the analysis of tide gauge records available in real-time from many locations in the Pacific. As a result, an essential part of a possible warning time may be lost before an asteroid-induced tsunami can be identified.
5. The small tsunamis generated by Tunguska-class middle-oceanic impacts can hardly be visually observed even at the nearest coast. However, they can be recorded by the world-wide tide gauge network as small amplitude (from first centimeters to several tens of centimeters) short-period (from one to several minutes) impulsive wave trains. The careful search for "tsunami-like" signals of unknown origin on sea-level records available for the last one hundred years for many coastal locations can reveal the "signature" of oceanic impacts of extra-terrestrial bodies that otherwise could pass unnoticed.

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