Physics of Tsunamis

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Preface

Till the very end of the twentieth century tsunami waves (or ‘waves in a harbour’, translated from Japanese) were considered an extremely rare and exotic natural phenomenon, originating in the ocean and unexpectedly falling upon the seaside as gigantic waves. The 26th of December 2004, when tsunami waves wiped out, in a single day, more than 250,000 human lives, mourned in many countries, turned out to be a tragic date for all mankind.

The authors of this book, who have studied tsunami waves for many years, intended it to be a systematic exposition of modern ideas concerning

- The mechanisms of tsunami wave generation
- The peculiarities of tsunami wave propagation in the open ocean and of how waves run-up beaches
- Methods for tsunami wave registration and the operation of a tsunami warning system
- The mechanisms of other catastrophic processes in the ocean related to the seismic activity of our planet

The authors considered their main goal to be the creation of book presenting modern knowledge of tsunami waves and of other catastrophes in the ocean to scientific researchers and specialists in geophysics, oceanography, seismology, hydroacoustics, geology, geomorphology, civil and seaside engineering, postgraduate students and students of relevant professions. At present, it has become clear that the demand for the information and scientific results presented in the book may be significantly broader and that they may be of interest to a large part of the population. Politicians, administrators, mass media, insurance companies, owners of seaside resorts and hotels, the civil fleet and the navy, oil-extracting companies, security services, space agencies, publishing houses, public education systems, etc., is a short list of possible users interested today in assimilating and spreading knowledge of the nature and manifestations of tsunami waves.

Waves that regularly devastate the coasts of oceanic islands and are called tsunami in Japan have been known for several centuries. The European civilization first encountered such catastrophic waves in 1755, when an exceptionally strong earthquake took place in the Atlantic Ocean near the coast of Portugal and gave rise to a tsunami wave that immediately killed over 50,000 people in the blooming city of Lisbon, which was about a quarter of the city's population. In the USSR, the Kamchatka tsunami of 1952 (2,336 victims) resulted in creation of a State tsunami warning system. During the past 10 years (not counting the tragedy caused by the Indonesian tsunami in 2004) tsunami waves in the Pacific Ocean took the lives of more than 10,000 people.

According to UNESCO information, by the year 2010 residents of the coasts of oceans and seas will represent about 70% of the total population of our planet. One should add persons visiting numerous seaside resorts, those who like to celebrate the New Year on exotic oceanic islands and, also, individuals seeking maritime adventures. All these people may happen to be within the reach of one of the oceanic catastrophes, of which tsunami waves are the most dangerous.

Today, many states of the Pacific region, Russia, Japan, the USA, and Chile, operate tsunami warning systems. The Russian system includes two tsunami Centers, situated in Yuzhno-Sakhalinsk and Petropavlovsk-Kamchatskii that are managed by the respective Board of the State Committee (Goskomitet) for hydrometeorology of Russia. The tsunami centres receive online information from seismic stations that carry out round-the-clock observation within the framework of the Geophysical Service of the Russian Academy of Sciences (RAS). In former times there were six such specialized seismic stations functioning along the Far East coast of the USSR. At present only three stations (Yuzhno-Sakhalinsk, Petropavlovsk-Kamchatskii, Severo-Kuril'sk) are in operation, and they all long need to be modernized and re-equipped.

The International Tsunami Information Center, the Pacific Tsunami Warning Center, and the Alaska Tsunami Warning Center function successfully within the framework of the USA National Oceanic and Atmospheric Administration with participation of the UNESCO Intergovernmental Oceanic Commission (IOC/UNESCO). In Japan, the duties of tsunami warning are performed by several hundred seismic and sea-level stations united in a common information system managed by national agencies (JMA, JAMSTEC).

All national Tsunami warning services exchange online information via the Internet, electronic mail and the specialized Tsunami Board Bulletin. Scientific studies of tsunami waves are coordinated by the International Tsunami Commission within the International Union for Geodesy and Geophysics (IUGG). During the period between 1977 and 1979 this commission was led by Academician S. L. Soloviev, who founded the Soviet Tsunami School. Another Russian scientist, Dr. V. K. Gusyakov (Novosibirsk) occupied this position from 1995 up to 2003. In 2003, Professor K. Satake (Japan) was elected Chairman of the Commission. The Tsunami Commission and the International Group of the UNESCO Intergovernmental Oceanographic Commission (IOC/UNESCO) organize regular international scientific and practical conferences, devoted to the problem of tsunami waves, in situ inspections of coasts that were victims of tsunami waves; they publish reviews, information bulletins, national reports, general-education literature; and support the creation of databases.

In 1996, The European Geophysical Society (EGS) established the Sergei Soloviev medal to mark the recognition of S. L. Soloviev's scientific achievements. This medal is presented to scientists who have made essential contributions to the investigation of natural catastrophes.

The Russian school of tsunami researchers organized and led for many years by Academician S. L. Soloviev is still considered a leading team in this scientific sector. A large contribution to the development of tsunami studies has been made by RAS Corresponding members S. S. Lappo and L. N. Rykunov; the Doctors of Sciences, who grew up in the Russian Tsunami School, A. V. Nekrasov, A. A. Dorfman (Leningrad), B. W. Levin, M. A. Nosov, A. B. Rabinovich, E. A. Kulikov, L. I. Lobkovsky (Moscow), E. N. Pelinovsky, V. E. Friedman, T. K. Talipova (Nizhny Novgorod), V. K. Gusyakov, L. B. Chubarov, An. G. Marchuk (Novosibirsk), P. D. Kovalev, V. V. Ivanov (Yuzhno-Sakhalinsk), and their pupils have done much for successful development of the science of tsunami waves. Specialized tsunami laboratories and several scientific groups work in the M. V. Lomonosov Moscow State University (MSU) and in various RAS institutes: the Institute of Oceanology (Moscow), the Institute of Applied Physics (Nizhny Novgorod), the Institute of Computational Mathematics and Mathematical Geophysics of the RAS Siberian Branch (RAS SB) (Novosibirsk), the Institute of Marine Geology and Geophysics of the RAS Far-East Branch (RAS FEB) (Yuzhno-Sakhalinsk), the Institute of Vulcanology and Seismology of RAS FEB (Petropavlovsk-Kamchatskii).

Many Russian specialists in tsunami waves, including the authors and the editor of this book, have acquired significant teaching experience not only in the universities of Russia (MSU, MSGU, NSU, NNSU, NSTU, SakhSU), but also in universities of the USA, France, Guadelupa, Australia, and Columbia. Recently, owing to the development of new computer technologies and software, original models have appeared of rare phenomena in the ocean, that were hitherto beyond the reach of scientific analysis. The experience of elaborating original ideas accumulated by Russian scientists in the research of seaquakes, killer waves, temperature anomalies above underwater earthquakes, the formation of cavitation zones, plumes and surges of water require detailed exposition and physical analysis. The experience of collaboration with foreign colleagues, regular participation in international meetings, as well as experience in organizing international conferences in Russia (the Tsunami conferences of 1996, 2000, 2002) have revealed an increased demand in tsunami wave specialists and in systematization of the knowledge accumulated in this field.

At present, no proof is needed of the fact that the influence of tsunami waves on the coasts of continents and islands is of a global nature. This catastrophic phenomenon cares nothing about the borders of states and of the nationalities of individuals, who happen to be in the zone within the reach of the catastrophe. In the nearest future the politicians of civilized countries will be compelled to start resolving the issue of creating a global tsunami warning system, something similar to the World Meteorological Organization. This task will require scientists from all countries to make enormous efforts for systematization of the knowledge on tsunami waves, for the preparation of national experts, specialists and teachers in the problem of tsunami waves, for developing new methods and means of monitoring, for publishing series of textbooks, scientific and general-education literature.

The authors hope that this book will contribute to the formation of a general collection of knowledge on tsunami waves. The necessity of such a book has ultimately become evident.

Many of our colleagues have taken part in completing the book and preparing it for publication. Section 6.1 was in part prepared by the Director of the SakhUSMS Tsunami Center T. N. Ivelskaya (Yuzhno-Sakhalinsk), Sect. 6.2 was written by Dr. T. K. Pinegina (Petropavlovsk-Kamchatskii), a well-known specialist in palaeotsunami. The illustrations, used in the book and based on computer graphics, were prepared by the leading scientific researcher of the RAS Institute of Oceanology Dr. E. V. Sasorova (Moscow). The image of the word 'tsunami' in the form of Japanese hieroglyphs was prepared for the book by Dr. H. Matsumoto (Japan, Tokyo). Certain material, put at our disposal by Dr. E. A. Kulikov (Moscow), Dr. V. K. Gusyakov (Novosibirsk), Dr. V. V. Titov (Seattle, USA) and other colleagues of ours, has been included in the book. The authors express their sincere gratitude to all of them.

We are grateful to our teachers S. L. Soloviev and L. N. Rykunov for the good school, and we revere their memory. We are grateful to our pupils and colleagues, whose friendly participation and help promoted the appearance of this book. We wish to express particular gratitude to Professor E. N. Pelinovsky, referee of the Russian issue of this book. The support of the Russian Foundation for Basic Research and of the Russian Academy of Sciences was an enormous stimulus for the preparation of this book. The authors are especially grateful to G. Pontecorvo, who translated the original Russian text into English and to V. E. Rokolyan, who prepared the text of the book for typesetting.

B. W. Levin
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Contents

Chapter 1

General Information on Tsunami Waves, Seaquakes and Other Catastrophic Phenomena in the Ocean

Abstract Fundamental information on the physics and geography of tsunami waves is presented. Examples are given of known historical events, illustrating the character of tsunami manifestation on coasts. Quantitative characteristics are introduced that describe tsunami strength: magnitude and intensity. Physical principles of the operation of tsunami warning systems are described. Information is provided on tsunami catalogues and electronic databases. The seaquake phenomenon is defined, and a synthesized description is given. Information is presented on the main hydroacoustic effects, related to underwater earthquakes: the T-phase, low-frequency elastic oscillations, and cavitation. Basic information on killer waves is given.

Keywords Tsunami · seaquake · surface gravitational waves · long waves · run-up · sudden inundation · impact of waves · erosion · damage · fires · environment pollution · epidemics · human casualties · local tsunami · regional tsunami · teletsunami · tsunami catalogue · historical tsunami database · tsunami magnitude · tsunami intensity · tsunami warning · hydroacoustic signals · T-phase · cavitation · freak waves

Catastrophic oceanic waves, termed ‘tsunami’ back in the 1960s, were considered a mysterious and inexplicable phenomenon of the life of the ocean. The sudden onslaught on the coast by a rabid giant wave would take the lives of tens of thousands of people and leave memories engraved for a long time on the minds of those who remained alive. Scientists of many countries have united their efforts to understand the secret of this awe-inspiring phenomenon and to bring nearer resolution of the problem of tsunami waves. At present, scientists have at their disposal the information on 1,500 events in oceans and seas that have given rise to tsunami waves.

The Pacific is considered the most tsunami-dangerous region, in which approximately 1,300 events are known [Soloviev et al. (1974), (1975), (1986)]. About 300 tsunami events are known to have taken place in the Mediterranean Sea. There exists information on tsunamis in the Atlantic Ocean and the Caribbean sea, in the Black and Caspian Seas [Nikonov(1997), Dotsenko et al. (2000), Lander et al. (2002)]. Insignificant tsunamis also occurred on lake Baikal [Soloviev, Ferchev (1961)]. Europe was exposed to the action of the catastrophic tsunami of 1755, during

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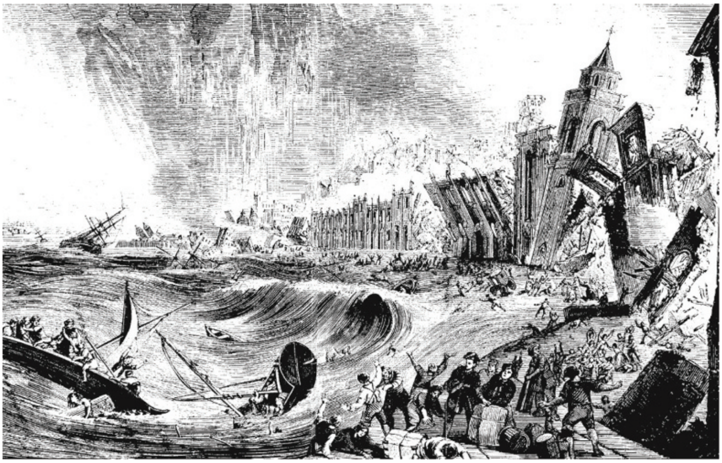

Fig. 1.1 The 1775 Lisbon earthquake and tsunami. Old engraving by unknown author

which the city of Lisbon was destroyed. This event was reflected in an old engraving (Fig. 1.1). At present, researchers are paying particular attention to the Indian Ocean, although in the past, also, its coasts were repeatedly attacked by catastrophic tsunami waves.

The seaquake phenomenon caused by seismic oscillations of the sea-floor is only known to specialists and to experienced seafarers. Even the edition of the Grand Soviet Encyclopedia had no place for this term, although the amount of registered natural events of this type already exceeded 250. Other transitory, but violent, phenomena in the ocean (killer waves, temperature anomalies and acoustic effects) have only recently attracted the interest of scientists owing to the rapid development of methods for remote observation, the improvement of methods of data handling and the accessibility of electronic databases and catalogues. Investigation of the entire complex of mentioned phenomena in the Ocean sheds light on the interaction mechanisms of various media in the communicating and interpenetrative lithosphere–hydrosphere–atmosphere system.

1.1 Tsunami: Definition of Concepts

The word tsunami originates from a combination of two Japanese hierogliphs (Fig. 1.2), translated together as a ‘wave in the harbour’. This term has already been conventionally adopted in scientific literature, although in mass media one may still encounter terms that prevailed some time ago, such as ‘high-tide wave’, and ‘seismic sea wave’ and ‘seaquake’. Sometimes the antique European terms ‘zeebeben’ and ‘maremoto’ are also used.

Usually, tsunami waves are understood to be surface gravitational waves exhibiting periods within the range of $T \sim 10^2$–10^4 s. Tsunamis pertain to long waves;

津波

Fig. 1.2 Japanese hierogliphs, pronounced as ‘tsu-nami’ and literally translated as a ‘wave in the harbour’

therefore not only the subsurface layer, but also the entire thickness of water becomes involved in the motion. Here, the term ‘surface’ signifies that the presence of a free surface is a necessary condition for this kind of waves to exist.

The formation of tsunamis is primarily considered to be related to seismic motions of the sea-floor, slides and collapses (underwater, also) and underwater volcanic eruptions. Waves exhibiting similar characteristics may be due to sharp changes in the atmospheric pressure (meteotsunami) and to powerful underwater explosions. Recently, the issue has been actively discussed of tsunami originating as the result of falling meteorites. One must bear in mind the possibility of combinations of various causes. Thus, for example, underwater slides, provocated by earthquakes, may provide an additional contribution to the energy of the tsunami waves, formed by displacements of the sea-floor. We stress that the main cause of destructive tsunami consists in sharp vertical displacements of parts of the sea-floor due to strong underwater earthquakes. Considering all the causes together, it may be asserted that any coast of a large water reservoir is potentially dangerous from the point of view of tsunamis.

Modern ideas of the sources of tsunami waves are not unambiguous. Usually, the source of tsunami waves is characterized by its horizontal dimension $L \sim 100\,\text{km}$, which significantly exceeds the typical depth of the World Ocean, $H \sim 4\,\text{km}$. A certain quite rapid transient process results in gravitational waves originating at the source with a wavelength $\lambda \sim L$. From the point of view of hydrodynamics these waves are long $(\lambda \gg H)$. The propagation velocity of long waves in a reservoir of depth H is determined by the formula $c = \sqrt{gH}$, where g is the free-fall acceleration of gravity. In the case of a depth $H \sim 4\,\text{km}$ the tsunami wave propagates with a velocity of the order of magnitude of 200 m/s, or about 720 km/h, which is comparable to the velocity of a modern jet aircraft. From the tsunami wavelength and its propagation velocity one can readily estimate the tsunami wave period $T = \lambda/c \approx 500\,\text{s}$ (actually, it varies within the limits of 10^2–$10^4\,\text{s}$). The tsunami wave amplitude in the open ocean, even in the case of catastrophic events, is usually limited to tens of centimeters and, most likely, rarely exceeds 1 m. Nevertheless, the displacement amplitude of the water surface at the tsunami source may amount to 10 m and more. But in this case, also, it is essentially inferior to the depth of the ocean.

The small amplitude together with the large period renders the tsunami wave in open ocean practically imperceptible for an observer on board a ship. The catastrophic tsunami wave that took 28,000 lives in Japan (June 15, 1896), destroyed the port of Sanriku and all the settlements along the 275 km coastline was known not to have even been noticed by fishermen, who were only 40 km from the coast.

Dependence of the tsunami wave propagation velocity on the depth renders these waves sensitive to the shape of the sea-floor. Effects peculiar to tsunamis include the capture of wave energy both by underwater ridges and by the shelf, focusing and defocusing exhibited when waves propagate above underwater elevations and depressions. Irregularities of the sea-floor lead to the scattering of tsunami waves.

Actually, the propagation velocity of gravitational waves does not depend only on the depth, but on the wavelength, also. The formula presented above for the velocity of long waves is the limit case (for $\lambda \gg H$) of the more general expression $c = \sqrt{g \tanh(kH)/k}$, where $k = 2\pi/\lambda$. Wave dispersion results in transformation of the initial perturbation into a wave packet, with the most rapid long waves leading. Note that this effect is manifested in the case of tsunami wave propagation over quite extended routes (1,000 km or more). Dispersion, resonance properties of the coastal relief, phenomena such as reverberation (i.e. when the wave perturbation reaches a certain coastal site via different routes) and the peculiarities of wave formation at the source, all these, as a rule, result in a tsunami being manifested not as a solitary wave, but as a series of waves with a period amounting to tens of minutes. In this case, the first wave is often not the strongest. The absence of knowledge of precisely this property of tsunami waves often leads to human casualties, which could have been avoided.

The tsunami wave amplitude increases as it approaches the coast—which to a great extent is what determines the danger of these waves, is also related to the relief of the sea-floor. A decrease in the water depth leads to a decrease in the wave propagation velocity and, consequently, to compression of the wave packet in space and an increase of its amplitude. In the case of catastrophic tsunamis the run-up height reaches 10–30 m, while the wave is capable of inland inundation (runin) of 3–5 km from the coastline. A scheme of the tsunami onshore run-up, explaining the main parameters of this process, is shown in Fig. 1.3. Note that the maximal wave height can be achieved at the shoreline, at the inundation boundary or at any point in between them.

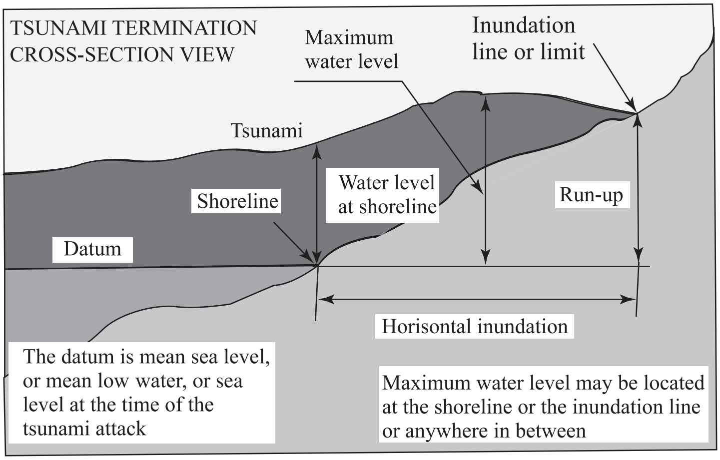

Fig. 1.3 Scheme of tsunami onshore run-up. Adapted from [UNESCO-IOC. Tsunami Glossary (2006)]

The danger carried by tsunami waves is primarily related to the following three factors: the sudden inundation of part of the land, the impact of waves upon buildings and erosion. Strong flows of water, reaching velocities of tens of meters per second, are capable of breaking up houses and of displacing them, washing out substructures of buildings, destroying bridges and buildings in ports. The flows of water often carry pieces broken off buildings and other structures, trees, small and large vessels, which leaves people, picked up by the fast-moving water, no chance of survival. The damage caused by tsunamis may, also, be due to fires, pollution of the environment and epidemics resulting from devastation of the coastal infrastructure.

Depending on the scale of the area, in which the destructive force of tsunamis is manifested, one conventionally distinguishes local, regional and remote (teletsunami) events. The latter are sometimes termed transoceanic tsunamis. Local tsunamis include events, the destructive effect of which is concentrated within distances not exceeding 100 km from the source. If destruction occurs at distances up to 1,000 km from the source, then such an event is classified as regional; when above 1,000 km, as a teletsunami. Most catastrophic events pertain precisely to local or regional tsunamis. At least 18 such events were recorded in the Pacific during the period between 1975 and 1998. The occurrence of transoceanic tsunamis is much less frequent, but they are, naturally, much more dangerous. After having caused significant destruction in the immediate vicinity of the source, these waves are capable of travelling many thousands of kilometers from the source and to continue carrying with them death and devastation. In the past 200 years at least 17 such events took place in the Pacific Ocean.

1.2 Manifestations of Tsunami Waves on Coasts

There exist numerous descriptions of the effect of tsunamis on a coast that are due to eyewitnesses or scientists investigating the consequences of these events. Detailed information on tsunami manifestations can be found in tsunami catalogues and historical databases, e.g. [Soloviev et al. (1974), (1975), (1997)], http://tsun.sscc.ru/, http://www.ngdc.noaa.gov/.

We shall present brief descriptions of some of the outstanding events.

The 1868 tsunami near the city of Arica (Chile) was caused by an underwater earthquake of magnitude $M = 8.8$. In the evening, after it became dark, an enormous 'wall' of phosphorescent foamy water mixed up with sand arrived from the ocean with a thunderous noise. The height of the waves amounted to 15–18 m. Upon hitting the coast with an enormous force, the wave then carried the large US warship 'Wateree' from the harbour 2 miles inland and gently put it down at the rocky foot of the Andes. This event permitted Gabriel Garcia Marquez to depict the fantastic scene of an encounter with a three-mast sailboat amongst trees in the remote jungles (selva) of South America.

The tsunami reduced the site, where the city of Arica with about 5,000 inhabitants had been, to a smooth sandy valley without any signs of buildings. Only individual structures remained here and there on the mountain slopes.

The catastrophic 1908 Messina tsunami was caused by an earthquake of magnitude 7, the source of which was located under the bottom of the Messina Strait (in between continental Italy and Sicily). The tsunami started nearly immediately after the shaking stopped with a withdrawal of the sea water. Part of the sea-floor, adjacent to the coast, happened to be drained, in some places the sea-floor opened up for nearly 200 m. Then, all of a sudden, waves started to advance, the first three being the strongest. The tsunami was preceded by a strong noise, similar to the noise of a tempest or of waves hitting rocks with force. The maximum run-up height on the coast of Sicily amounted to 11.7 m, on the Calabrian coast to 10.6 m. Noticeable waves reached the coasts of Libya and Egypt. Of the mareographs that were not damaged, the one closest to the tsunami source was located on the Malta island. It recorded a tsunami of amplitude 0.9 m.

The number of tsunami waves observed varied from place to place from 3 to 9, and the period of the waves from 5 to 15 min. The waves washed out the structures destroyed by the earthquake and destroyed many buildings that had survived. Of the buildings and structures only the foundations, sliced off at land level, remained.

Many vessels, having been damaged, either sank or were stranded inland. The tsunami stirred up sea-floor sediments; bubbles of gas came up from the sea-floor to the surface of the strait; sea animals and fish, including deep-water inhabitants, unknown to fishermen, were thrown up onto the beach. Sailors on vessels moored several miles from the coast felt a strong seaquake, but couldn't understand why all the lights had gone out in the towns along the coast.

After the tsunami all the strait was full of broken and overturned boats, other vessels, floating debris, bodies of human beings and animals, washed off the coasts of Messina and Calabria.

The 1952 tsunami that occurred near the eastern coasts of Kamchatka and of the Island of Paramushir is considered one of the most destructive tsunamis of the twentieth century. We shall present the description of this event given in the article by S. Soloviev [Soloviev (1968)]. In the night between November 4 and 5 the inhabitants of Severo-Kurilsk were woken up by an earthquake: stoves were destroyed, chimneys and household utensils fell down. Forty minutes after the earthquake stopped a rumble was heard from the ocean, and a water bore moving with a high velocity fell upon the city. In several minutes the water retreated, carrying away what it had destroyed, and the ocean bottom opened up for several hundred meters. In 15–20 min a wall of water 10 m high once again advanced upon the city. It practically washed away everything in its way, at the most leaving only concrete foundations of various structures. Old pillboxes were wrenched out of the ground and thrown around, in the harbour the walls of a bucket were turned upside down, and launches that happened to be there were stranded hundreds of meters inland.

Several minutes later, after this strongest wave, a third relatively weak wave ran up the devastated coast, leaving much debris after it.

The events of 1952 were totally unexpected for most of the population. Thus, for example, some of the vessels moored near the Island of Paramushir, transmitted messages that the island was sinking into the ocean waters.

A. E. Abaev, captain of a detachment of hydrographic vessels sent to Severo-Kurilsk immediately after the catastrophe, witnessed the strait between the islands of Shumshu and Paramushir to be completely crammed with floating wreckage of wooden houses, logs and barrels. The bodies of human beings were seen on the wreckage—it was practically impossible to survive in the ice-cold water.

Another witness of this tsunami, A. Shabanov, who lived in Severo-Kurilsk and at the time was 14 years old, told one of the authors of this book, that soon after the earthquake the water receded from the coast and left the ocean bottom open. When Shabanov's mother saw this sudden ebb tide she ran with her two sons towards the hills, which saved their lives. Their family was the only family, in which no one was killed. On their way they had difficulty in crossing a deep ditch across which the Japanese in former times had thrown several narrow wooden footbridges. By 1952, most of the footbridges had been used as firewood, since it was not clear to the people arriving from the continent what they were for.

The wave that in some parts of the coastline reached a height of 10–15 m ($H_{\max} = 18.6$ m) totally destroyed many buildings and port structures of Severo-Kurilsk (Island of Paramushir) and carried them out to sea, taking the lives of 2,336 people. The source of the tsunami wave generated by an underwater earthequake of magnitude $M_w = 9.0$ extended over 800 km and was about 100 km wide.

The fantastic event that gave rise to a tsunami wave of record height took place on July 9, 1958 in Lituya Bay (Alaska) [Soloviev et al. (1975)]. The bay exhibits a T-like shape. Its length amounts to 11 km, its width in the main external part up to 3 km, and its maximum depth about 200 m. The internal part of the bay is part of the Fairweather canyon. Here the bay resembles a fjord, and its steep walls rise up to heights between 650 and 1,800 m. During the earthquake a gigantic slide of snow-and-ice together with local rock of volume about 0.3 km^3 took place. The water ousted by the falling mass splashed out onto the opposite coast and reached the height of 524 m! The displacement of water was so rapid, that all the trees in the flooded wood were wrenched up and the bark and leaves of the trees were rubbed off. Besides this enormous splash, a wave formed that crossed the whole bay right up to the ocean, devastating the bay's shores. Three fishing-launches were caught by the wave in the bay; one of them sank together with two crewmen. The two other crews were lucky to escape. The fishermen spoke of a wave about 30 m high. Signs of the run-up and of trees broken by the wave remained on the slope during decades after the catastrophe. Note that the expedition led in 1786 by G.-F. La Perouse encountered a similar phenomenon in the French Harbour (presently known as Lituya Bay). An enormous wave carried the two-mast vessel of the expedition through the narrow strait and smashed it against the underwater rocks. Of all the 21 crewmen no one was left alive.

The Chilean tsunami of May 22, 1960 was caused by the strongest earthquake of the twentieth century ($M = 9.4$), the source of which was located in the southern part of central Chile [Soloviev et al. (1975)]. The maximum elevation of water amounted to 25 m in Chile, 10.5 m on the Hawaiian islands, 9 m in the Oceania, 6.5 m in Japan and the USSR and 3.5 m in the USA. About 1,000 persons lost their lives in Chile, 60 on the Hawaiian islands and 200 in Japan. It took approximately 15 h for the waves to cover 10,000 km and to reach the Hawaiian islands and nearly a day and night to reach Japan and the Far-East coast of the USSR. Naturally, the earthquake was felt neither on the Hawaiian islands, nor in Japan, nor in the USSR, so the wave turned out to be unexpected.

The 1994 tsunami caused by an earthquake of magnitude $M = 8.3$ near the Island Shikotan, resulted in the destruction of numerous coastal structures. Part of the island sank by 60 cm, which was recorded by the mareograph in the village of Malokurilsk. In the city of Yuzhno-Kurilsk, located at a distance of 120 km from Shikotan, the tsunami wave tore down a single-storeyed block of flats from its foundation and carried it 300 m inland. The wave's maximum run-up amounted to 10.4 m.

The 1998 tsunami that occurred in the region of Papua New Guinea gave rise to particular interest among specialists. A relatively small earthquake of magnitude $\mathrm{M_w} = 7.1$ resulted in an unexpectedly large wave of height amounting to 15 m. The tsunami attacked the coast with three waves about 18 min after the earthquake. The area influenced was limited to part of the coastline 30 km long, where several fishing villages were destroyed and about 3,000 people lost their lives. The formation of such a gigantic wave was mainly due to the underwater slide caused by the earthquake, rather than to the earthquake itself.

The catastrophic tsunami of December 26, 2004 that occurred in the Indian Ocean was caused by an exceptionally strong earthquake of magnitude $M_\mathrm{w} = 9.3$, the epicentre of which was near the northern extremity of Island Sumatra. Comparable magnitudes were exhibited during the past 100 years only by several seismic events [Aleutian Islands, 1946; Kamchatka, 1952; Aleutian Islands, 1957; Chile, 1960; Alaska, 1964]. The manifestation of the tsunami was of a global character. Besides the castastrophic consequences in the vicinity of the source (the coast of Sumatra), where the run-up amounted to 35 m, waves were registered all over the World Ocean. Tsuami waves of significant amplitudes were registered in remote parts both of the Pacific coast (Manzanillo, Mexico—0.5 m, New Zealand—0.5 m, Chile—0.5 m, Severo-Kurilsk, Russia—0.3 m, British Columbia, Canada—0.2 m, San Diego, California—0.2 m) and of the Atlantic coast (Halifax—0.4 m, Atlantic City—0.2 m, the Bermuda islands—0.1 m, San Juan, Puerto Rico—0.05 m). The worst hit were countries of the basin of the Indian Ocean: Indonesia, Thailand, India, Sri Lanka, Kenya, Somalia, South Africa and the Maldive Islands. The total number of victims exceeded 250,000 people, the damage was enormous and it still has to be estimated. The number of casualties makes this catastrophe the largest of all known catastrophes in the history of tsunamis.

Central Kuril Islands Tsunamis. An extremely strong earthquake of magnitude $M_\mathrm{w} = 8.3$ took place on November 15, 2006, in the Central-Kuril segment of the Kuril-Kamchatka seismofocal zone. The epicentre of the earthquake was located in the Pacific Ocean at about 85 km from the northern extremity of Simushur Island. Before this event, the Central-Kuril segment was considered a 'seismic gap' zone, an earthquake of such strength was registered here for the first time in the history of seismic observations. Nearly 2 months later, on January 13, 2007, another earthquake of practically the same strength, $M_{\mathrm{w}} = 8.1$, occurred in the same region. Both seismic events were accompanied by tsunami waves, noted over the entire area of the Pacific Ocean: Shikotan Isl., Malokurilsk—1.55(0.72) m, Kunashir Isl., Yuzhno-Kurilsk—0.55(0.11) m, Alaska, Shemya—0.93(0.69) m, Crescent City, California—1.77(0.51) m, Hawaii, Kahului—1.61(0.24) m, Peru, Callao—0.73(0.3) m, Chile, Talcahuano—0.96(0.23) m (the wave heights indicated in brackets correspond to the event of January 13, 2007). However, owing to the absence of mareographic stations and inhabitants on the Central Kuril Islands, no information on the wave heights in the immediate vicinity of the sources was available. During the period from July 1 to August 14, 2007, two seafaring expeditions were organized with one of their main tasks consisting in the investigation of the coasts of the islands so as to determine the tsunami run-up heights [Levin et al. (2008)]. The participants of the expedition were the first people to visit the islands after the tsunamis and to estimate the scale of the natural disaster. The time for the expedition depended on the complicated weather conditions in the area. Landing on the coasts of the islands earlier (before April–May) was practically impossible to realize. The highest tsunami run-ups (up to 20 m) were revealed on Matua Island. The tsunami strongly altered the morphology of the coast in the Ainu Bay (south-west of Matua Island) by washing away a section of the sea terrace 20–30 m wide. The maximum run-up height in Dushnaya Bay (north-east part of Simushir Island) amounted to 19 m; here the tsunami left numerous scours. Besides erosion on the coasts investigated, accumulation was also observed everywhere. Tsunami deposits consisted of marine sand, pebbles, boulders and floating debris shifted toward the land. The vegetation on steep slopes was partly destroyed, and the soil washed away. If waves of such strength were to hit a densely populated coast, casualties could certainly not be avoided. The only reason the tsunamis of November 15, 2006, and of January 13, 2007, did not become an awful tragedy was the total absence of population on the Central Kuril Islands. These two events can rightfully be considered the strongest tsunamis that were not accompanied by human casualties.

Table 1.1 presents several examples of recent catastrophic tsunamis.

Table 1.1 Recent catastrophic tsunamis

No	Date	M[a]	h[b]max (m)	Number of casualties	Location of event
1	12/12/1992	7.5	26	1,000[c]	Flores Is., Indonesia
2	12/07/1993	7.7	31	330[c]	Okushiri Is., Japan
3	02/06/1994	7.8	14	223	Java, Indonesia
4	04/10/1994	8.1	10	11[c]	Shikotan Is., Russia
5	09/10/1995	8.0	11	1	Manzanillo, Mexico
6	17/02/1996	8.1	7.7	110	Irian Jaya, Indonesia
7	17/07/1998	7.1	15	2,200	Papua New Guinea
8	23/06/2001	8.1	10	26	Peru
9	26/12/2004	9.3	36	250,000[c]	Indian Ocean, Sumatra
10	15/11/2006	8.3	20	0	Central Kuril Is., Russia

[a] Earthquake magnitude
[b] Maximum wave height
[c] May include earthquake victims

1.3 Tsunami Magnitude and Intensity

Estimation of the degree of tsunami danger for one or another coast (long-term tsunami forecast) is primarily based on the statistical analysis of events, that occurred in the past. Tsunamis evidently vary in strength within wide limits: from weak waves, that can be registered only with the aid of instruments, up to terrible catastrophic events devastating the coast along hundreds of kilometers. How can one estimate the strength of a tsunami? The point is that without the introduction of some quantitative characteristic of this strength it is not only impossible to perform any statistical analysis, but also to speak of estimating the degree of danger. The determination of such a quantitative characteristic is quite a non-trivial problem, the ultimate resolution of which has not yet been achieved. Similar difficulties are encountered by seismologists determining the strength of an earthquake. On the one hand, an earthquake is characterized by objective physical parameters showing the energy emitted by the source, or the released seismic moment. These parameters are measured quantitatively, and the scale of earthquake magnitudes is made to correspond to them. On the other hand, there exists a descriptive scale of earthquake intensities, which is related to the so-called macroseismic data, based on the results of in situ studies. Clearly, in practice, it is precisely the intensity scale that is important, but contrary to the magnitude scale it is not rigorous, from a physical standpoint.

Going back to tsunamis, we note that this phenomenon is also characterized, on the one hand, by objective and quantitatively measurable parameters (energy, amplitude, period, etc.), and on the other hand—by subjective descriptions, reflecting the scale and degree of the destructions caused by the wave or the character of its manifestations on the coast. Like in the case of earthquakes, for estimation of the tsunami danger precisely these subjective descriptions are more important than abstract physical parameters. The inhabitants of coastal regions are not interested in the energy of the approaching wave in joules, but they are interested in whether the wave is dangerous to their lives, what damage may be done and how it can be avoided. And, until further modelling is realized of the entire process starting from the actual formation of a wave up to its run-up onto the shore, such a situation will remain intact.

The first attempt at classification of tsunamis was made by Sieberg, who introduced a six-point scale of tsunami intensities by analogy with the scale of earthquake intensities [Sieberg (1927)]. This scale was not related to the measurement of physical parameters (wave heights, run-up lengths, etc.); it was based on the description of macroscopic effects, revealing the degree of destruction. Subsequently, the Sieberg scale was somewhat modified [Ambraseys (1962)].

The Sieberg–Ambraseys tsunami intensity scale

1. **Very light.** Waves can only be registered by special tide gauges (mareographs).
2. **Light.** Waves noticed by those living along the shore. On very flat shores waves are generally noticed.

3. **Rather strong.** Waves generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coasts. In estuaries reversal of the river flow some distance upstream.
4. **Strong.** Significant flooding of the shore. Buildings, embankments, dikes and cultivated ground near coast damaged. Small and average vessels carried either inland or out to sea. Coasts littered with debris.
5. **Very strong.** General significant flooding of the shore. Quay-walls and solid structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land. Littering of the coast with floating items, fish and sea animals thrown up on the shore. With the exception of big ships all other type of vessels carried inland or out to sea. Bores formed in estuaries of rivers. Harbour works damaged. People drowned. Wave accompanied by strong roar.
6. **Disastrous.** Partial or complete destruction of manmade structures for some distance from the shore. Strong flooding of coasts. Big ships severely damaged. Trees uprooted or broken. Many casualties.

Numerous attempts were made in Japan to introduce a quantitative characteristic of the tsunami strength. Imamura introduced, and Iida further improved, the concept of tsunami magnitude [Imamura (1942), (1949); Iida (1956), (1970)]. A proposal was made to estimate the magnitude by the formula

$$m = \log_2 H_{\max},$$

where $H_{\max}$ is the maximum wave height in metres, observed on the shore or measured by a mareograph. In practice, the Imamura–Iida scale is a six-point scale (from -1 up to 4).

In attempts at improving the Imamura–Iida scale S. L. Soloviev introduced the following tsunami intensity:

$$I = \frac{1}{2} + \log_2 H,$$

where H is the average tsunami height on the coast closest to the source. At present such a definition of the tsunami intensity is widespread, and the corresponding scale is conventionally termed the ‘Soloviev–Imamura tsunami intensity scale’.

Note that the Imamura–Iida definition of magnitude is, generally speaking, unambiguous. It only requires knowledge of the maximum wave amplitude. The Solviev–Imamura definition of intensity is not mathematically rigorous and, consequently, provides for much ‘freedom’ in calculating the average height of tsunami waves. At any rate, both scales are not very sensitive to small errors in the determination of wave heights, since it is the logarithms of these quantities that count. It is also important to note that in the case of numerous historical events and, more so, of prehistoric events (paleotsunamis) the only available information comprises estimates of wave heights at a single point or at several points along the coast. Thus, both scales are quite convenient and will still be applied in practice for a long time. Anyhow, as a base characteristic to be measured in calculating the magnitude or intensity one may consider the flooded area, instead of the wave height. This characteristic may turn out to be a successful and promising alternative to the wave heights on the coast. A clear advantage of the flooded area consists not only in that it can be conveniently measured by remote means (from satellites, airplanes, etc.), but also in that this characteristic automatically reflects the scale of the catastrophe that took place.

Abe and Hatori proposed to modify the magnitude scale so as to take into account the weakening of waves, as the distance from the source increases [Abe (1979), (1981), (1985), (1989); Hatori (1986)],

$$M_t = a \log h + b \log \Delta + D,$$

where h is the maximum wave amplitude on the coast measured from the foot up to the crest in meters, Δ is the distance from the earthquake epicentre to the point of measurement in kilometers, a, b and D are constants. Such a definition resembles the definition of magnitude in seismology.

An essentially different approach to the definition of tsunami magnitude was put forward in [Murty and Loomis (1980)]. Here, the calculation of magnitude is based on estimation of the tsunami's potential energy E (in ergs),

$$\mathrm{ML} = 2\,(\log E - 19).$$

The definition of magnitude based on the wave energy is, naturally, the most adequate definition, from a physical point of view. However, it is not always possible to calculate the wave energy. At any rate, at the present-day stage calculations can be based on the potential energy of the initial elevation of the water surface, considering it to be identical to the residual displacements of the sea-floor. These displacements are calculated from the earthquake parameters by the Okada formulas [Okada (1985)].

It must be noted that the Imamura–Iida magnitude or the Soloviev–Imamura intensity gives an idea of the wave height on the coast and, consequently, permit to judge the scale of destructions. But, although the Murty–Loomis tsunami magnitude ML is a physically correct quantity, it cannot be unambiguously related to the manifestation of a tsunami on the coast.

Recently, a new detailed 12-point descriptive tsunami intensity scale was proposed in [Papadopoulos, Imamura (2001)]. Its elaboration was based on the more than 100-years-long experience, accumulated by seismologists in drawing up earthquake intensity scales. This scale is not related to any quantitative physical parameters (wave amplitudes, energy and so on), it is organized in accordance with the following three features:

(A) Its influence upon people
(B) Its impact on natural and artificial objects, including boats of different sizes
(C) The damage caused to buildings

Therefore, a tsunami of large amplitude that hits a weakly inhabitated coast may be assigned a low intensity in accordance with the Papadopoulos–Imamura scale.

And, contrariwise, a tsunami of moderate amplitude that hits a densely populated coast may be characterized by quite a high intensity.

It is useful to present the Papadopoulos–Imamura intensity scale here completely. A consistent and systematic description of tsunami manifestations on the coast provides quite a full picture of the phenomenon.

The Papadopoulos–Imamura tsunami intensity scale

I. Not felt[1]

(a) Not felt even in most favourable circumstances
(b) No effect
(c) No damage

II. Scarcely felt

(a) Felt by some people in light boats. Not observed on the shore
(b) No effect
(c) No damage

III. Weak

(a) Felt by most people in light boats; observed by some people on the shore
(b) No effect
(c) No damage

IV. Largely observed

(a) Felt by all people in light boats and some on large vessels; observed by most people on shore
(b) Some light boats are slightly carried onto the shore
(c) No damage

V. Strong

(a) Felt by all people on large vessels; observed by all people on shore; some people are frightened and runup elevations.
(b) Many light vessels are carried inland over significant distances, some of them collide with each other or are overturned. The wave leaves layers of sand in places with favourable conditions. Limited flooding of cultivated land along the coast.
(c) Limited flooding of coastal structures, buildings and territories (gardens etc.) near residential houses.

VI. Slightly damaging

(a) Many people are frightened and run up elevations.
(b) Most light vessels are carried inland over significant distances, undergo strong collisions with each other or are overturned.

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[1] Registered only by special instruments.

(c) Some wooden structures are destroyed and flooded. Most brick buildings have survived.

VII. Damaging

(a) Most people are frightened and try to run away onto elevations.
(b) Most light vessels are damaged. Some large vessels undergo significant vibrations. Objects of varying dimensions and stability (strength) are overturned and shifted from their positions. The wave leaves layers of sand and accumulates pebbles. Some floating structures are washed away to sea.
(c) Many wooden structures are damaged, some are totally wiped away or carried out to sea by the wave. Destructions of first degree and flooding of some brick buildings.

VIII. Heavily damaging

(a) All people run up elevations, some are carried out to sea by the wave.
(b) Most light vessels are damaged, many are carried away by the wave. Some large vessels are carried upshore and undergo collisions with each other. Large objects are washed away. Also Erosion and littering of the coast, widespread flooding and insignificant damage in antitsunami plantations of trees. Many floating structures are carried away by the wave, some are partially damaged.
(c) Most wooden structures are carried away by the wave or completely wiped of the earth's surface. Destructions of second degree in some brick buildings. Most concrete buildings are not damaged, some have undergone destruction of first degree and flooding.

IX. Destructive

(a) Many people are carried away by the wave.
(b) Most light vessels are destroyed and carried away by the wave. Many large vessels are carried inland over large distances, and some are destroyed. There is also Broad erosion and littering of the coast, local subsidence of the ground and partial destruction of antitsunami plantations of trees. Most floating structures are carried away, and many are partially damaged.
(c) Destructions of third degree in many brick buildings. Some concrete buildings have undergone destructions of second degree.

X. Very destructive

(a) General panic. Most people are carried away by the wave.
(b) Most large vessels are carried inland over large distances, many are destroyed or have undergone collisions with buildings. Small rocks (pebbles, stones) have been carried onshore from the sea-floor. Vehicles are overturned and displaced. Petroleum is spilt, there are fires and widespread subsidence of ground.
(c) Destructions of fourth degree in many brick houses, some concrete buildings have undergone destructions of third degree. Artificial dams (embankments) are destroyed and harbour wavebreakers damaged.

XI. Devastating

(b) Vital communications are destroyed. There are widespread fires. Reversed flows of water wash away to sea vehicles and other objects. Large rocks of different kinds are carried onshore from the sea-floor;
(c) Destructions of fifth degree in many brick buildings. Some concrete buildings suffer damage of fourth degree, and many of third degree.

XII. Completely devastating

(c) Practically all brick buildings are wiped out. Most concrete buildings have suffered destructions of degrees not lower than third.

1.4 Tsunami Warning Service: Principles and Methods

The extremely long and sad experience of Japan's population with many thousands of lives lost to tsunamis and earthquakes is expressed in the short inscription on the stone stellae often found near the coastline. The hieroglyphs on the stellae say the following:

Don't forget about earthquakes. If you feel an earthquake, don't forget about tsunamis. If you see a tsunami, run up a high slope.

The following legend is told by the inhabitants of the city of Wakayama, situated not far from Kyoto, the former capital of Japan and a most beautiful city. The major of Wakayama once felt an earthquake. He understood he had no time to warn the people on the shore of the tsunami danger, so he run-up the slope to the rice fields, where the rice had been harvested, and set the granaries on fire. People, seeing the burning supplies of rice, hurried up to put the fire out and, thus, they happily evaded the lethal strike of the tsunami wave against the coast. The grateful inhabitants of the city erected a monument to the wise ruler.

By the 1960s many countries of the Pacific region had organized national tsunami warning systems. The tsunami service organizations include a whole network of seismic and hydrometeorological stations, special systems for operative alert transmission, administrative organs for adopting resolutions and regional organizations for implementing evacuation plans of the population.

In past years the work of a tsunami warning service (TWS) was based on routine and/or urgent dispatches from operators on duty at seismic stations with round-the-clock tsunami services. If a nearby strong earthquake (of magnitude $M > 7$) is registered, the operator had, within 10 min, to determine the distance to its epicentre, the earthquake's magnitude and the approximate region of its location. The operator had, then, to transmit the signal 'TSUNAMI warning' to the administrative organ, to the tsunami headquarters and to the meteostation. The oceanology on duty at the meteostation applied additional information to decide whether to announce the warning or not. The all-clear signal was announced by the tsunami headquarters upon agreement with specialists.

In modern TWS this technology is automized. However, the main physical principles of operative tsunami forecasting remain the same. The possibility itself of warning is based on the propagation velocity of seismic waves being many times larger than the velocity of a tsunami wave. A warning is announced, when registration occurs of an underwater earthquake of magnitude exceeding a threshold value.

In Russia, the Far East tsunami service is implemented by seismic stations of the Geophysical service of the Russian Academy of Sciences and by meteostations of the Administrations of Hydrometeorological Services (AHMS) subordinate to the Committee for Hydrometeorology of the Russian Federation. The tsunami service relies on seismostations of Petropavlovsk-Kamchatskyi and Ust-Kamchatsk (Kamchatka), Yuzhno-Sakhalinsk (isl. Sakhalin), Severo-Kurilsk (isl. Paramushir), Kurilsk (isl. Iturup) and Yuzhno-Kurilsk (isl. Kunahsir). The meteostations of the Kamchatka AHMS and the Sakhalin AHMS, as well as the tsunami centres of these Administrations are on round-the-clock duty for implementation of operative tsunami warning service and preparation of routine and/or urgent dispatches and reports.

A well-developed Tsunami Warning System has been organized in the USA within the National Oceanic and Atmospheric Administration (NOAA). It includes several hundreds of seismic and mareographic stations. All these stations, as well as several large oceanic buoys and sea-floor sensors reporting the ocean level transmit the information obtained in a real-time mode to the common servers of two centres: ATWC in Palmer, Alaska and PTWC in Honolulu, Hawaii. The information is freely available to all Internet users. The tsunami service in Japan, created significantly earlier than the others, is subordinate to the Japanese Meteorological Agency (JMA) and is noted for its very high level of organization.

An important success, achieved in operative tsunami prognosis, consists in the possibility of rapid (real-time) calculation, with a precision and reliability sufficient for practical purposes, of the arrival time of a wave at a given (protected) point of the coast. Such a calculation can be performed by applying simple ray theory. To this end it is only necessary to know the location of the tsunami source and the distribution of depths in the basin considered. We recall that the tsunami propagation velocity depends on the ocean depth, $c = \sqrt{gH}$. Data on the bathymetry of the World Ocean are free for a grid with steps of 1×1 angular minutes, and for many regions even with a significantly improved spatial resolution.

The situation concerning calculation of a tsunami run-up height at a given point of the coast is much worse. The calculation precision and speed required for practical purposes in resolving this problem have not been achieved yet. On the one hand, this is due to the enormous volume of calculations to be performed in estimating the evolution of a wave starting from its rise at the source up to its run-up to the shore. On the other hand, in the real-time mode it is impossible to calculate what has happened at the tsunami source with necessary precision. The time required for the reliable determination of sea-floor deformations, due to an earthquake, essentially exceeds minutes or even hours available for operative forecasting. In those cases, when underwater landslides participate in the tsunami generation, operative resolution of the problem turns out to be practically impossible.

There exist several promising ways for resolving the problem. One of them is realized in the Japanese system of operative tsunami prognosis [Tatehata(1998); Handbook for Tsunami Forecast (2001)]. The method is based on tsunami sources exhibiting the property of recurrence. Therefore the problem, requiring long-time calculations, has been resolved beforehand. The results of calculations are presented in a special database. When a real underwater earthquake takes place, then in accordance with its magnitude and epicentre location necessary data are extracted from the database and used for calculating the possible run-up heights applying the interpolation method.

The second way consists in making use of deep-water sensors of tsunamis established far from the coast (for instance, DART, JAMSTEC). The actual idea and its first realization are related to the name of S. L. Soloviev. There exist various possibilities for using such systems. One of them is based on the fact that timely registration of a wave permits to measure its characteristic (amplitude) with precision and to correct inaccuracies in the calculation of the wave generation at the source.

The catastrophic tsunami that occurred in December 2004 in the Indian Ocean was registered by a radio-altimeter established on the satellite JASON-1. Thus, the good prospects became evident of methods involving satellite monitoring of tsunamis.

Regretfully, the modern tsunami service is mainly based on regional principles. Analysis of the actions taken by national services on December 26, 2004, revealed their ‘zones of responsibility’ to be limited only to the sectors of the coast under their control. Taking into account the restricted capabilities of certain developing countries to provide operative tsunami warning at a modern level and, also, the scale of such catastrophes, it seems expedient to create a global monitoring system of the ocean’s surface to function under international control. The authors of this book fully support the International Tsunami Information Center (ITIC, NOAA USA) in its efforts aimed at the rapid as possible creation of a worldwide tsunami warning system.

1.5 Databases and Tsunami Statistics

There exist several different informational resources containing the main information on tsunamis. One of the most effective and in greatest demand is the historical database for tsunamis in the Pacific Ocean, which was created in the Tsunami laboratory of the Institute of Computational Mathematics and Mathematical Geophysics, SB RAS (Novosibirsk) with support of UNESCO and the Russian Foundation for Basic Research [Gusiakov (2001)]. The Internet version of the database is available at http://tsun/sscc.ru/htdbpac.

The database contains information on approximately 1,500 tsunamigenic events that occurred in the Pacific region (within the geographical boundaries 60° S–60° N, 80° E–100° W) during the entire historical period of observations (starting from the year 47 BC up to now). This database includes a large volume of coastal observations of tsunamis (about 9,000 records) as well as various auxiliary information on regional bathymetry, seismicity, tectonics, vulcanism and on settlements in coastal regions, and, also, about the regional network of mareographic observations.

An important advantage of this informational resource is a specialized graphical shell, the construction of which is based on the technological principles of state informational networks and which provides convenient means for users to select, visualize and process data, and, also, to analyse the quality and completeness of historical catalogues. The cartographic shell includes means for working with raster images of the earth's surface and of the sea-floor, which permits the user to create digital maps of the area of interest and to subsequently superimpose observational data on them.

For application of the shell in tsunami warning services it has a special option—the 'New event' mode, permitting to realize selection of historical data within a circular vicinity of the event, undergoing operative processing. The built-in subsystem for estimation of the tsunami hazard permits to obtain estimates of the long-term tsunami hazard for coastal areas of the Pacific aquatorium, for which there exist sufficient observations of tsunami heights. The fields in which the created database is applied comprise scientific research and developments in the field of marine geophysics, seismology and oceanology, related to studies of natural catastrophes, the seismicity of the World Ocean and seismoproof building projects in coastal regions.

An example of graphical presentation of material is given in Fig. 1.4 by the distribution of sources of tsunamigenic earthquakes in the Pacific region that occurred during the period from 47 BC up to 2004.

An idea of the tsunami recurrence frequency can be obtained from Fig. 1.5, in which it is shown how the number of tsunamis (per decade) varied between 1800 and 2005. All the events are divided into two categories: the grey lines indicate significant tsunamis of intensities (the Soloviev-Imamura scale) $I \geqslant 1$, the dark lines

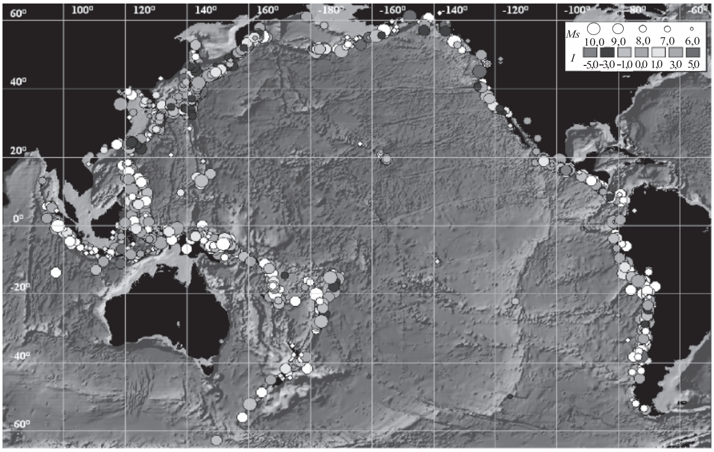

Fig. 1.4 Distribution of tsunami sources in the Pacific region within the period from 47 BC up to 2004. The sizes of the circles correspond to earthquake magnitudes and their colours to the tsunami intensities (see also Plate 1 in the Colour Plate Section on page 309)

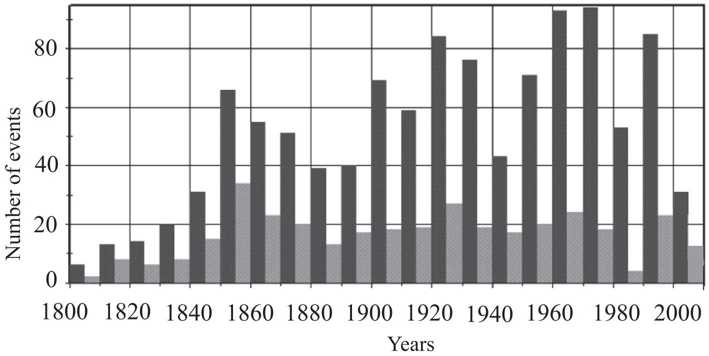

Fig. 1.5 Recurrence of tsunamis (number of events per decade) in the Pacific region between 1800 and 2005. The dark colour shows all the known tsunamis, the grey colour indicates tsunamis of intensity $I \geqslant 1$ according to the Soloviev-Imamura scale

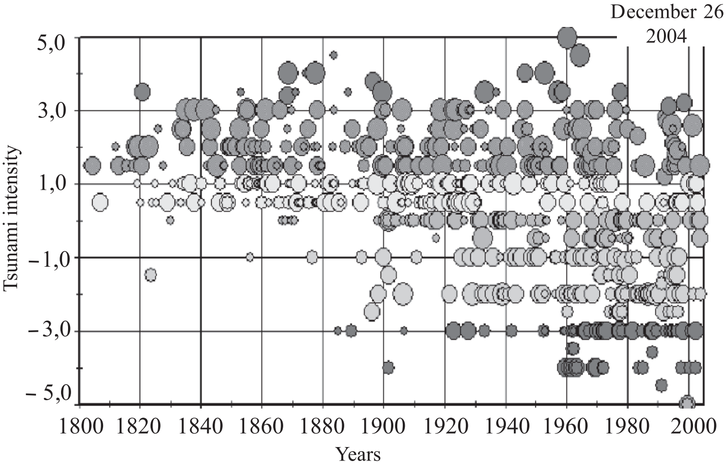

Fig. 1.6 Tsunamis of the Pacific region in the 'intensity–time' plane (see also Plate 2 in the Colour Plate Section on page 310)

show all known tsunamis. It can be seen that the recurrence of significant tsunamis remains approximately at the same level (about two events per year). The total number of tsunamis, here, shows a tendency of increasing, which is related to the progress in registering weak waves. Similar comments can also be addressed to Fig. 1.6, in which the tsunami intensity is plotted as a function of time. It must be stressed, here, that it would be wrong to conclude, on the basis of the presented data, that the tsunami recurrence frequency has increased during past centuries. The recurrence frequency of tsunamis can vary noticeably only over geological times.

The database can be applied for resolving a broad class of problems. Thus, for example, analysis of measurements of run-up heights of tsunami waves making use of approaches pertaining to dimensionality theory [Zav'yalov et al. (2005)] has permitted to reveal hidden information on the symmetry of a tsunami source and on peculiarities of the emission and damping of wave energy. It has been established that in the case of a large number of registered events, as the distance from the source increases, the weakening of waves follow a power law $r^{-\alpha}$, where the exponent α varies within the limits from 0.5 to 0.66. This corresponds to values of the source's symmetry parameter between 1 and 2, i.e. the source is an elongated ellipse. Similar estimates can be found in the book by Pelinovsky [Pelinovsky (1982)]. Note that precisely such a shape is attributed to the source of a tsunami in many publications dealing with the resolution of inverse hydrodynamic problems. In the case of continental earthquakes, the region of maximum shakings reconstructed in problems of macroseismics also exhibits a strongly elongated oval shape.

Statistical treatment of the material in the tsunami database has recently revealed an interesting periodicity in the appearance of tsunami sources [Levin, Sasorova (2002)]. The time sequence of events generated alternately in the Earth's northern and southern hemispheres is characterized by a 6-year period. Strong perturbations on Earth, caused by astronomical processes and the mutual arrangement of bodies in the Earth–Moon–Sun system arise with approximately the same periodicity. Further development of databases and of computational methods will permit future revelation of new laws in the processes of tsunami and underwater earthquake generation.

1.6 Seaquakes: General Ideas

Every year approximately 10,000 earthquakes are registered on Earth, of which about 4,000 events are perceptible earthquakes, for which the velocity of motion of particles in the wave or the mass velocity amounts to over 0.1 m/s. Of this amount the largest part are underwater earthquakes. Strong earthquakes result in the appearance near the coasts of gigantic devastating tsunami waves, while in the region of the earthquake epicentre unusual hydrodynamic phenomena are observed that are known to seafarers by the term seaquakes. In certain cases, the terms tide race and wave crowd are also used.

The transverse dimension of the perturbated region of the sea surface during a seaquake usually exceeds 50–100 km, while the duration of a strong seaquake may amount to 10 min. During a seaquake sets of very steep standing waves form on the surface of the aquatorium, individual vertical columns of water and solitary water formations arise and strong acoustic effects are noted. Spray sultans may be observed, as well as cavitational layers of water separating from each other and flying apart. A ship that happens to be in the zone of influence of a seaquake turns out to be surrounded by giant standing waves filling up the entire visible space. Terrible thunderous rumbling and howling are enhanced by sharp blows to the bottom, the most strong shaking of the vessel and the destruction of deck structures that had in the past endured more than a few storms.

We shall present the average quantitative characteristics of the phenomenon:

- Height of waves and of surges of water—over 10 m
- Velocity of surface motion up to 10 m/s
- The acceleration of water particles may amount to $10\,\mathrm{m/s^2}$