ANALYSIS OF TSUNAMI TRAVEL TIME MAPS FOR DAMAGING HISTORICAL TSUNAMIS IN THE WORLD OCEAN


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Abstract. The report prepared by the WAPMERR Tsunami Research Group for the IOC/UNESCO describes the results of analysis of the Tsunami Travel Time (TTT) maps for regional and trans-oceanic damageable tsunamigenic events occurred in the main tsunamigenic regions of the World Ocean. It is based on the latest version of the Global Historical Tsunami Database (GTDB) that covers the period from 1628 B.C. till present and contains nearly 2250 historical events with 1206 of them occurred in the Pacific, 263 in the Atlantic, 125 in the Indian Ocean and 545 in the Mediterranean region. Out these 2250 historical events, only 223 (10%) tsunamis resulted in any fatalities, all others were weak local events observable only in some particular areas of the nearest coast. In total, they are responsible for 694,000 lives lost in tsunami waves during all the historical period of available observations. From these 223 deadly tsunamis, 212 (95%) fall into the category of local and regional events with most of damage and all fatalities limited to one-hour propagation time. These regional events are responsible for 322,000 (47% of the total) fatalities. The 11 trans-oceanic tsunamis that occurred in the World Ocean during the last 250 years resulted in 372,000 (53% of the total) fatalities. The detailed analysis of spatial distribution of fatalities for these most destructive tsunamis shows that although their damaging impact can last up to 23-24 hours, over 84% of all their fatalities occur within the first hour of propagation time. Another 12% of fatalities happen within the second hour, and the rest of 4% occur during the remaining time (greater than two hours). The overwhelming majority of other tsunamis (that is 99.5% of all historical cases and 95% of all damaging events) are the local and regional events whose major damage and all fatalities are limited to a near-source area within one-hour of propagation time. Among them, more than a half (60%) had their sources within 30-min travel time limit. The above conclusions, obtained by the analysis of the most complete historical dataset, currently available in digital domain, are important and should be taken into account in design and implementation of any regional or basin-wide tsunami warning system.
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1. Introduction

Tsunamis are a series of 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 Ocean. The tsunami phenomenon includes three overlapping but quite distinct physical stages: generation by any external force that disturbs a water column, propagation with a high speed in the open ocean and, finally, the run-up in the shallow coastal water and inundation of the dry land. Most tsunamis occur in the Pacific, but they are known in all other areas of the World Ocean like the Atlantic and the Indian oceans, the Mediterranean and many marginal seas. Tsunami-like phenomena sometimes happen in lakes, large man-made water reservoirs and even in big rivers.

Most of destructive tsunamis can roughly 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 propagation time that is from one to four hundred kilometers depending on bottom topography and configuration of the coastline. In all tsunamigenic regions of the World Ocean, most of damage and casualties come from local tsunamis. Far less frequent but potentially much more hazardous are trans-oceanic tsunamis capable of a widespread distribution. Formally, this category includes the events with run-up exceeding five meters at a distance of more than 5000 km. Historically, almost all trans-oceanic tsunamis are known in the Pacific with only two exceptions - the 1755 Lisbon tsunami in the Atlantic that hit the Caribbean with 5-7m waves, and 2004 tsunami in the Indian Ocean that reached the east coast of Africa still having height of 6-9 meters.

In all but largest seismically induced tsunamis, their damage is limited to an area within one hour propagation time (200-400 km). A typical distribution of tsunami run-up heights along the coast is shown in Fig.1. This is a modification of the figure from (Chubarov, Gusiakov, 1985) obtained as a result of calculation of tsunami generation 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 a double 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 is a result of the three main factors: (1) initial directivity of energy radiation by a seismic source, (2) ellipticity of a source, (3) wave refraction on the inclined bottom. Among these factors, the most important is the third one – refraction on the continental slope and the inclined shelf.

The present report is prepared by the WAPMERR Tsunami Research Group for the IOC/UNESCO in connection with the WAPMERR’s involvement in the development of the new regional Tsunami Warning Systems in the Indian Ocean and other tsunami-prone areas of the World Ocean and in the assessment of the long-term tsunami risk (coastal tsunami zoning) of particular coastal areas.
2. Geographical and temporal distribution of tsunamis

The world-wide catalog 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 B.C. till present and currently contains nearly 2250 historical events with 1206 of them occurred in the Pacific, 263 in the Atlantic, 125 in the Indian ocean and 545 in the Mediterranean region. The geographical distribution of tsunami is shown in Fig.2 as a map of seismic, volcanic and landslide sources of historical tsunamigenic events. When analyzing this map, one should take into account the fact 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 the 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 the central parts of the marginal seas, except several cases of small tsunamis originated along the mid-ocean ridges and some major transform faults.

Since more than three quarters of all tsunamigenic events were caused by the seismic origin, the spatial distribution of tsunamigenic events reflects first of all the spatial distribution of large submarine earthquakes, most of them occurred in subduction zones located near the active continental margins in the Pacific, Atlantic and Indian ocean. That is why sources of most of tsunamigenic events, especially the largest ones, responsible for the major damage and a great number of fatalities, are located so close to the coastline. A typical distance from the center of a tsunamigenic source to the nearest coast is only 80-100 km that corresponds to 20-25 min of the leading wave propagation time. In fact, such a close proximity of tsunamigenic sources to the coast creates the main problem in design and operation of any Tsunami Warning System (TWS), because in most cases the decision on issuing a warning should be taken within the first 15-20 min after an event occurrence.
Fig. 2. Geographical distribution of tsunami sources in the World Ocean. The 1963 historical events for the period from 1628 BC to 2005 are shown. The size of circles is proportional to the earthquake magnitude, color represents the tsunami intensity on the Soloviev-Imamura scale.

The temporal distribution of historical tsunamis is highly non-uniform in time with three quarters of all the events reported within the last two hundred years. Although the total duration of the historical catalog exceeds 3,500 years, its median date, dividing the data into two equal parts, lies around 1910. The most complete data are available for the XX century, when the instrumental measurements of weak tsunamis became available. In all the regions (except, possibly, Japan) there are obvious gaps in reporting even large destructive events for the period preceding the XIX century (Fig. 3).

Fig. 3. Tsunami occurrence versus time for the last 1000 years. Events are shown as circles with a color corresponding to the tsunami intensity and the size proportional to the earthquake magnitude.
In 1901-2000, a total of 943 tsunamis were observed in the World Ocean, which makes about ten events per year. Most of these events were weak, observable only in mareograph records. About 260 tsunamis were “perceptible”, having a run-up height exceeding one meter. Among them, in 33 cases the run-up greater than one meter was observed at a distance of more than 1000 km from the source. During this period, five trans-oceanic tsunamis, all in the Pacific, occurred (1946 Aleutians, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska). In 2004, a trans-oceanic tsunami in the Indian ocean was generated by the Ms9.0 Great Sumatra-Andaman earthquake of December 26, 2004.

Of all 2250 tsunamigenic events historically known, only 223 (about 10%) resulted in human fatalities. Geographical distribution of these events is shown in Fig.4. Less than a quarter of all the events had the number of fatalities exceeding 1000, and only in 132 cases the death toll exceeded 10,000. In all but 11 events, listed in Table 1, the resulted damage and all fatalities were limited to a nearby area within one hour propagation time. Those 11 events are the so called trans-oceanic tsunamis and they were able to transfer their energy well outside the area of origin. However, a detailed analysis given in Section 4 shows that even in trans-oceanic tsunamis a major damage and over 90% of all fatalities occur in the nearby area within one hour propagation time.

Рис.4. Geographical distribution of 223 tsunamigenic events in the World Ocean that resulted in human fatalities. The size of circles is proportional to the earthquake magnitude. Sources that generated the trans-oceanic tsunamis are shown in red.
Table 1. The list of historically known trans-oceanic tsunamis occurred in the World Ocean during the last 250 years.

<table>
<thead>
<tr>
<th>Date and place</th>
<th>Magnitude</th>
<th>Max run-up near the source, m</th>
<th>Max run-up in the far-field, m</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 1, 1755 Lisbon</td>
<td>8.5</td>
<td>18</td>
<td>7.0</td>
<td>40000</td>
</tr>
<tr>
<td>November 7, 1837 Chile</td>
<td>8.5</td>
<td>8</td>
<td>6.0</td>
<td>many</td>
</tr>
<tr>
<td>August 13, 1868 Chile</td>
<td>9.1</td>
<td>18</td>
<td>10</td>
<td>3000</td>
</tr>
<tr>
<td>August 27, 1883 Krakatau</td>
<td>9.1</td>
<td>36</td>
<td>1.5</td>
<td>36000</td>
</tr>
<tr>
<td>February 3, 1923 Kamchatka</td>
<td>8.3</td>
<td>8</td>
<td>6.1</td>
<td>some</td>
</tr>
<tr>
<td>April 1, 1946 Aleutians</td>
<td>7.4</td>
<td>42</td>
<td>9.1</td>
<td>&gt;10000</td>
</tr>
<tr>
<td>November 4, 1952 Kamchatka</td>
<td>9.0</td>
<td>18</td>
<td>18</td>
<td>165</td>
</tr>
<tr>
<td>March 9, 1957 Aleutians</td>
<td>9.1</td>
<td>15</td>
<td>10</td>
<td>none</td>
</tr>
<tr>
<td>May 22, 1960 Chile</td>
<td>9.5</td>
<td>18</td>
<td>12</td>
<td>1180</td>
</tr>
<tr>
<td>March 28, 1964, Alaska</td>
<td>9.2</td>
<td>68</td>
<td>6.0</td>
<td>123</td>
</tr>
<tr>
<td>December 26, 2005 Sumatra</td>
<td>9.3</td>
<td>34</td>
<td>9.1</td>
<td>280000</td>
</tr>
</tbody>
</table>

3. Numerical algorithm for the TTT calculation

There are several possible ways for numerical calculation of the tsunami travel time charts. The ray method is based on a short wavelength approximation and its application requires that parameters of propagation media (ocean bathymetry) is changed smoothly within a wavelength. The main advantage of the ray method is that it requires much less computational time. However, its application for areas with complicated bathymetry (sharp changes of bottom relief) and topology (islands and narrow passages) presents a number of problems. It is invalid near caustics (areas of ray concentration) and cannot give the estimates in shadow zones where rays can not penetrate. As a result, its numerical implementation requires some special measures to ensure the continuous coverage the area with complicated bathymetry by the resulting TTT chart. However, in operational applications the ray method can be used for the fast preliminary estimation of tsunami travel times where the estimated TTT should be obtained within few minutes after the position of a tsunami source is determined.

Method of TTT calculation used in the present study is based on Huigens-Fresnel principle. According to this principle, any point that was reached by a tsunami wave can be considered as a point source of secondary radiation. This allows us to divide the continuous process of the wave propagation on a number of elementary steps. During one step the wave front can move on the distance of the order of one grid step, that allows us to consider that the wave propagates along the straight line between the neighboring grid points and therefore easily to calculate the increment in the propagation time.

At the initial moment t=0 we assign t(i,j)=-1 for all grid points except the points located within the source area where t=0. Numerical implementation of Huigens-Fresnel algorithm is based on the iterative procedure that on every time step checks all points of the calculation grid to determine whether within their neighboring pattern there are points where the tsunami travel times are already determined. Suppose, there are k points (k=1,...,16) where the TTT values t(k,l) are known. For each point we can calculate the time interval dt(k) that is equal to the tsunami propagation time between the points (i,j) and (k,l). dt(k) is calculated on the based on the linear approximation of bathymetry between these points. For each calculated value we compare the calculated propagation value dt(k) with the time step dt. If dt(k) < dt, we assume t(i,j)=t(k,l)+dt(k), if dt(k)>dt we continue to keep t=-1 for the point (i,j).

In this study, 16-ray pattern is used in the iterative procedure for the TTT calculation. For flat bottom, the calculated wave fronts reflect the 16-ray grid pattern used for TTT calculation.
However, this effect of numerical algorithm is quickly smoothed in the process of propagation over the real bottom with variable bathymetry.

In the practical application of this algorithm, in the selection of time step \( dt \), we should select the \( dt \) value to be of an order of expected propagation time between two neighboring grid points located in the deepest part of the area under consideration. For the most part of Caribbean region, the \( dt=10 \) sec can be accepted as a realistic estimate for the time step.

The above algorithm is considered as one of the most stable and reliable methods of the tsunami travel time calculation and ensure the propagation of the tsunami wave even through very narrow passages and penetration into small bays.

4. Trans-oceanic tsunamis

Trans-oceanic tsunamis, capable to transmit their energy far away of the source area, are quite rare events as compared to local and regional events, however, they are responsible for a considerable part of damage and fatalities resulted from all tsunamis. In this section, we give a brief description and calculate the TTT maps for the trans-oceanic tsunamis occurred in the World Ocean during the last 300 years

**November 1, 1755 Lisbon, Portugal**

A violent earthquake of intensity XI on the MMI scale occurred in the morning of November 1, 1755, the All Saints Day Catholic holiday, near the Gorringe Bank off the Iberian Coast near Lisbon, Portugal. The earthquake generated a destructive tsunami that affected the coast of Portugal, Spain, North Africa, and the Caribbean. The tsunami wave reached Lisbon about 40 minutes after the first destructive shock and surged up to 18 meters in some places near Lisbon. At Azores the wave height was up to 15 meters (Fig.4). In 9.3 hours the tsunami arrived to Saba, Netherland Antilles having 6.4 m in height. The total number of fatalities in Portugal is estimated to be 60,000. It is difficult to resolve what part of them was due to tsunami, but we can assume that it is at least half of the total that gives the estimated 30,000 victims. The Moroccan Atlantic coast was struck by 15-m waves at a cost of 9,000 – 11,000 lives (O’Loughlin, Lander, 2003). There is no any quantitative data on tsunami victims in the Caribbean islands, but taking into account the reported run-up height (from 6 to 8 meters) there should be at least some.

![Fig.5. Tsunami travel time chart for the 1755 Lisbon tsunami. Solid ellipse marks position of the earthquake source. Red color shows the area within 1-hour propagation time. Digits near the isochrones - propagation time in hours. Digits in bold show the reported fatalities, digits in italic - maximum reported run-up within the particular TTT interval.](image)
November 7, 1837 Valdivia, Chile
A 8.5 Ms destructive earthquake hit the coast southern Chile on November 7, 1837 with epicenter near Valdivia, Coral and Ankud. The waves reached 8 meters at the nearest Chilean coast. 6-meter waves were observed in Hilo, Hawaii after almost 14 hours of propagation time (Walker, 1994). There is no quantitative data on the number of victims in Chile, but according to (Soloviev. Go, 1985) in Hawaii the 6-meter tsunami resulted in 58 fatalities.

August 13, 1868 Arica, Chile
A destructive 9.1 Mw earthquake with epicenter near Arica, northern Chile resulted in 18-m tsunami waves that in 20-30 min after the quake hit the nearest Peruvian and Chilean coast. Data on resulted fatalities are fragmentary, but one can guess that at the nearby coast the tsunami took several thousand victims. Outside the source area, the largest waves (up to 10 meter) were observed at the Chatham Islands at the distance almost 10,000 km (DeLange and Healy, 1986). Along the east coast of New Zealand waves were of 3 to 5 meter in high. These waves turned out to be the most severe far-field tsunami observed in New Zealand during the 160-year period of available observations. DeLange and Healy (1986) list this tsunami as caused loss of life in New Zealand, however, do not give any numbers for fatalities. Five-meter waves reached Hawaii and resulted there in 47 fatalities in Hawaii, where waves reached 5 meter in high (O’Loughlin, Lander, 2003).

August 27, 1883 Krakatau, Indonesia
The cataclysmic explosion of the Krakatau volcano in Indonesia in the morning of August 27, 1883 (the final one in a series of several gigantic explosions that started a day earlier) generated a 25-30 meter tsunami in the Sunda Strait with maximum reported run-up of 41 meter (Fig.7). These waves swept away many villages along the both coast of the strait and killed over 36,000 people. It also caused an atmospheric pressure wave that was globally registered by recording barographs. Atmospheric gravity waves caused disturbance of water surface that was widely recorded by the existing mareograph network at very remote locations France, England, Alaska, Hawaii. Among 38

Fig.6. Tsunami travel time chart for the 1868 Arica, Chile tsunami. Notations are the same as in Fig.5.

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available sea-level records, the largest wave (1.5 meter) was recorded by the tide-gauge in Galle (Ceylon). It is important to stress that despite the global manifestation of tsunami, most of damage and all the fatalities were confined to the close neighborhood of the source area and occurred within one hour propagation time.

Fig. 7. Tsunami travel time chart for the 1883 Krakatau tsunami. Notations are the same as in Fig. 5.

February 3, 1923 Kamchatka, Russia
A major 8.3 Mw earthquake off the east coast of Kamchatka, Russia generated an 8-meter tsunami that caused several fatalities and considerable damage in Kamchatka (Soloviev, 1978) and propagated all over the northern Pacific. Seven waves were observed in Hilo, Hawaii, the third wave was the largest with height up to 6.1 m (Walker, 1994). The waves caused at least 1 victim in Hawaii (O’Loughlin, Lander, 2003). The tsunami waves were observed in Japan and were recorded by tide-gauges at the Canada and US West Coast. It is worth to note that in Hawaii, at the distance over 5,000 km from the source area the waves (5-6 m) were almost as high as in Kamchatka, in the immediate proximity of the source (6-8 m).

April 1, 1946 Unimak Island, Aleutians
The April 1, 1946 Aleutians tsunami is unique among other trans-oceanic event in two aspects. First, this destructive tsunami was caused by an earthquake with very moderate magnitude (7.4 Ms) that led H. Kanamori to formulate his conception of a tsunami-earthquake (Kanamori, 1972). Second, it is the only example of transoceanic tsunami that caused more damage and fatalities in the far-field rather than in the source area. The maximum run-up of 42 meter was observed at the Scotch Cap Light House in the Unimak Island (Okal et al., 2003). Low number of fatalities (5 persons in Alaska) is, of course, the result of low population density of this area. In 5 hours up to 16-meter waves flooded all the coast of the Hawaiian Island and caused there 159 fatalities. One more fatalities was reported at the US West Coast (Fig. 8).
November 4, 1952 Kamchatka, Russia

The magnitude 9.0Mw earthquake on early morning November 4, 1952 to the east of southern Kamchatka generated 18-meter waves at the nearest coast of the Paramushir Island (North Kuriles). In six hours the waves struck the Hawaiian Islands still having 6-8 meters in height (maximum wave of 9.1 meter was observed near Kaena Point of easternmost tip of Oahu Island). Property damage from these waves in Hawaii was estimated from $800,000 to $1,000,000, but, fortunately, no lives were lost. Locally, the city of Severo-Kurilsk on the Paramushir Island was completely destroyed. Most of its inhabitants were newcomers, who arrived to the Kuriles just after the Second World War, they were not aware such disaster as tsunami and most of them died in the tsunami waves. All the fatalities resulted from this tsunami occurred at the nearest coast of the Paramushir Island and at the south-eastern coast of Kamchatka. The exact number is not known but in some recent studies the death toll is estimated to be as high as 10,000. No fatalities were reported from the far-field areas affected by this tsunami.
March 9, 1957 Aleutians Island, Alaska
The magnitude 9.1 Mw earthquake on March 9, 1957 south of the Andreanoff Island, Central Aleutians, generated a tsunami that did a severe damage on the Adak Island. However, the maximum run-up on Aleutians (15 meters) was observed at Scotch Cap on the Unimak Island located almost 2500 km away of the source area. Possibly, this large wave was generated by the local landslide. In 4.5 hours tsunami reached Hawaii and hit the coast with up to 10-meter waves. Estimated damage turned out to be nearly $5,000,000. Fortunately, no fatalities resulted from this tsunami locally and at distant coast. There were two indirect fatalities in Hawaii, a reporter and a pilot, and injury to a photographer when their small chartered plane crashed in the ocean near Oahu.

May 22, 1960 Chile
On May 22,1960 a magnitude 9.5 Mw earthquake, the largest earthquake ever instrumentally recorded, occurred in the southern Chile (Fig.10). The earthquake ravaged the vast area along nearly 1000-km of the Chilean coast. The main shock generated a destructive tsunami that hit the nearest coast with 8-10 meter waves. The maximum waves, reaching 15 meter in high, were observed along the 350-km section of the coast between Corral in the south and Concepcion in the north. Number of reported fatalities varies in different sources from 490 to 5,700. In the present study, 1000 fatalities was accepted as a reasonable assumption of the tsunami death toll in Chile. In 15 hours, 8-10 meter waves reached Hawaii (reported maximum was 12.1-m wave observed at Ahukini Point on the Kauai Island) and caused 61 fatalities in Hilo, despite the advance warning was given and warning sirens sounded more than 3 hours before the first wave arrived. However, several first waves were small, and many people returned to their homes only to be caught by the largest wave that had in Hilo up to 6 meter in high. In 22 hours, the waves reached east coast of Japan, still having 5-6 meter in high. More than 10,000 house were destroyed and 122 people died.
March 28, 1964 Alaska
The magnitude 9.2 Mw Prince William Sound earthquake, second largest during the instrumental period of seismological observations, hit a large part of southern Alaska and neighboring areas of Yukon territory and British Columbia and resulted in large destruction of property and $84 million of damage. The main tectonic tsunami had a height of 10-15 meters along the nearest coast, however, in many places local tsunamis were triggered by submarine landslides having height up to 68 meters (Lander, 1996). 106 tsunami-related fatalities were reported in Alaska, and 17 in the US West coast. The damage in western Canada was about $10 millions and on the West Coast of US was nearly $12 million. In 5 hours tsunami reached Hawaii with 3-4 meter waves (the maximum 4.9-m wave was reported in Waimea Bay in the north of Oahu). In Hawaii, this tsunami caused only minor damage and, fortunately, no fatalities.
Figure 11. Tsunami travel time chart for the 1964 Alaska tsunami. Notations are the same as in Fig. 5.

December 26, 2005 Sumatra, Indonesia

A devastating mega-thrust earthquake occurred on the morning of December 26, 2004 at 250 km south-west of Banda Aceh, northern Sumatra. With its Ms=9.3 value, it is the fourth-largest earthquake instrumentally recorded and the first one of that scale occurred in the Indian ocean region (Fig. 11). The estimated rupture fault size is 1300 km by 100 km with average slip amount up to 15 m. The earthquake generated a destructive tsunami that made a severe damage at coast of 11 countries and took almost 280,000 lives - the largest mortality toll for a single tsunamigenic event historically known. The worst hit country in terms of fatalities was Indonesia where over 228,948 are listed as dead or missing. The remaining fatalities occurred in Sri Lanka (36,081), India (16,423), and Thailand (8,567). In addition to these four most affected countries, there were 300 reported fatalities in Somalia, 82 in the Maldives, 68 in Malaysia, 61 in Myanmar, 11 in Tanzania, 2 in Seychelles, 2 Bangladesh and 1 in Kenya. The Pacific Tsunami Warning Center (PTWC) in Ewa Beach, Hawaii has timely determined the earthquake with operational magnitude as high as 8.0 (soon upgraded to 8.5) but since its source was located well outside of the PTWC area of responsibility, the warning was not issued for the affected areas. The tsunami wave heights varied from 15 to 20 m along the large part of the nearest coast (north-western Sumatra), with the absolute run-up maximum of 34.5 m reached near Lhonga village, some 15 km east-west of Banda Aceh. In the far-field, the largest run-up (9.3 meter) was measured at the coast of Somalia.
5. Regional tsunamis

As an example of the TTT calculation for a regional tsunami, in Fig.13 a TTT chart for the June 15, 1896 Sanriku tsunami is shown. This was one of the largest tsunami whenever occurred in Japan. The maximum run-up height at the nearest coast reached 38.3 m. These destructive waves killed 27,122 people and 9247 were injured, 10617 houses were washed away. Despite the tsunami was observed all along the eastern coast of Japan as well as in Hawaii and the US West Coast, the main impact fell within just 200-km part of the eastern coast of the Iwate and Miyako Prefectures where all of 27122 fatalities occurred. From the TTT map in Fig.12 one can see that this part of the coast is located within just 40-min travel time zone. On this coast, a tsunami began after 20 min of a seismic shock. The largest was the second wave that caused most of the damage and almost all fatalities.

One of the most devastating recent tsunami was generated by a large Ms7.6 earthquake in the Moro Gulf in the Philippines on 16 August 1976 (Fig.15). A large tsunami with run-up height up to 5-6 meter generated by the earthquake resulted in the death of thousands of people in coastal communities in the Sulu Islands, North and South Zamboanga, North and South Lanao, North Cotabato, Maguindanao, and Sultan Kudarat, on the island of Mindanao (Pararas-Carayannis, 1976). Available estimates of the death toll for this tsunami vary from 3,700 (PHIVOLCS Webpage, 2006) to over 10,000 (Pararas-Carayannis Tsunami Web-page, 2006) people. (This particular example shows how uncertain can be the data on fatalities even for the recent tsunamis.) Since the source of this earthquake was located very close to the heavily populated coast most of these people died during the first 30 min after the quake. The Pacific Tsunami Warning System and its center in Eva Beach, Hawaii has registered this earthquake, but did not have a chance to warn timely all these people, since their operational procedures required at that time more than one hour for data collection and processing.
Fig. 13. A tsunami travel time chart for the 1896 Sanriku tsunami that resulted in 27,122 fatalities in the Sanriku coast of Japan (north-eastern Honshu). Solid ellipse marks the estimated position of the tsunami source, red color shows the area within 10-min travel time. Digits near the isochrones - travel time (in minutes).

Fig. 14. A tsunami travel time chart for the 1976 Mindanao tsunami that resulted in over 4,000 fatalities in the nearby coast of the Moro Gulf, Philippines. Solid ellipse marks the estimated position of the tsunami source, red color shows the area within 10-min travel time. Digits near the isochrones – tsunami travel time (in minutes).
The most recent example of the deadly regional tsunami that was not timely predicted by the newly established Tsunami Warning System in the Indian Ocean is the Mw7.7 Pangandaran earthquake of July 17, 2006. The earthquake occurred south of Java coast at the outer edge of subduction zone, that is the source of major tsunamigenic earthquakes in this area. The first wave came to the nearest coast in 25-30 min after the quake (Fig.15) having 3-4 meter in height and resulted in more than 300 fatalities.

The earthquake occurred at 08:19 UTC. The 1st Official Tsunami Bulletin, issued by the PTWC at 08:36 UTC, based on the preliminary determined magnitude Ms=7.2 declared that “TSUNAMI WATCH IS IN EFFECT FOR AUSTRALIA / INDONESIA. A DESTRUCTIVE WIDESPREAD TSUNAMI THREAT DOES NOT EXIST BASED ON HISTORICAL EARTHQUAKE AND TSUNAMI DATA. HOWEVER - THERE IS THE POSSIBILITY OF A LOCAL TSUNAMI THAT COULD AFFECT COASTS LOCATED USUALLY NO MORE THAN A HUNDRED KILOMETERS FROM THE EARTHQUAKE EPICENTER” (actually, the nearest coast, that was most severe hit by the wave, was at 170 km from the epicenter).

The 1st Official Tsunami Bulletin, issued by the JMA at 08:46 UTC, based on the same Ms7.2 value said that “THERE IS A POSSIBILITY OF A DESTRUCTIVE LOCAL TSUNAMI IN THE INDIAN OCEAN”.

Despite all these messages were quickly delivered to the Indonesian authorities responsible for tsunami warning, more than 300 people died from tsunami waves in the Pangandaran area at the southern Java coast.

Fig.15. A tsunami travel time chart for the July 17, 2006 Pangandaran tsunami that resulted in over 300 fatalities in the southern coast of Java. Solid ellipse marks the position of the tsunami source, estimated on the basis of aftershock distribution (red dots). Digits near the isochrones – tsunami travel time (in minutes). The first tsunami wave reached the nearest coast in 40 min after the earthquake occurrence.
6. Tsunami Travel Time Zones (TTTZ) for selected countries

As was mentioned in Section 2, the majority of all historically known tsunamis are local or regional events whose impact is limited to the nearest part of the coast. Their sources are located within the continental slope or the shelf at the average distance of 150-200 km of the coastline. The TTT software built-in the WinITDB graphic shell allows to calculate the TTT chart for any historical event, but also to construct the TTT zone map for any coastal area. It can be made on the basis of TTT calculation for the selected time intervals, e.g. 20, 30, 40, 60 and 90 min, for a set of point sources distributed along the coast (to construct so-called inverse isochrone map). Plotting the envelope around the selected isochrones gives the outer boundary of the particular TTT zone, that outlines the area where the travel time to any coastal point is less than the selected TTT value (e.g. 20 min).

An example of the calculated TTT zone map for Japan is shown in Fig. 16. In this figure, red and green dotted lines show the limits of 20-min and 40-min tsunami propagation time areas, respectively. Color circles show the position of tsunamigenic sources for 78 historical tsunamigenic events in this area resulted in human fatalities. One can see that about 40% of all deadly tsunamis in this region occur within 20 min of propagation time to the nearest coast, and ALL of them fall within 40-min time limit.

![Tsunami Travel Time Zones](image)

**Fig.16.** Map of Tsunami Travel Time zones in 20-min (red) and 40-min (green) intervals for the coast of Japan. Large circles show the sources of 78 deadly tsunamis that occurred from 684 to 2003 around Japan. Color represent the tsunami intensity on the Soloviev-Imamura scale, size of circles is proportional the earthquake magnitude.
Fig. 17 to 26 of this section show the TTTZ maps for several other countries in the Pacific and the Indian Ocean regions.

Fig. 17. Map of Tsunami Travel Time zones in 20-min (red) and 40-min (green) intervals for the west coast of South America. Large circles show the sources of 38 deadly tsunamis that occurred from 1575 to 2001 near South America coast. In South America, due to seismotectonic features of the region, the sources of ALL tsunamigenic events are located within the area with 20-min propagation time limit. For many South America tsunamis, their sources were located partly in-land, so the first wave arrived almost simultaneously or shortly after the end of seismic shaking caused by the fault rupture.
Fig. 18. Map of Tsunami Travel Time zones in 30-min (red), 60-min (green) and 90-min (yellow) intervals for the coast of Kenya. Red circles show the historical seismicity for this area. There are no historical tsunami observations for Kenya, except the December 26, 2004 Indian ocean tsunami that had a height up to 3 m and resulted in one fatality. Its territory has low level of seismicity, the largest known earthquake (1990) had magnitude 5.3. There is no subduction area or volcanic arc nearby the Kenyan coast, therefore the risk of local or regional tsunami is low, except possible landslides at the steep continental slope in the northern part of the coast.
Fig. 19. Map of Tsunami Travel Time zones in 30-min (red), 60-min (green) and 90-min (yellow) intervals for the coast of Somalia. Red circles show the historical seismicity for this area that is very low except north-western corner of the country. There are no historical tsunami observations for Somalia, except the December 26, 2004 Indian Ocean tsunami, that came here still having 5-6 m in high (with maximum measured height of 9.6 m). Reportedly, there were from 300 to 600 fatalities in Somalia resulted from the 2004 Indian Ocean tsunami.
Fig. 20. Map of Tsunami Travel Time zones in 20-min (red), 40-min (green) and 60-min (yellow) intervals for the coast of Oman. Red circles show the historical seismicity for this area that is associated mainly with middle-ocean ridge and southern coast of Iran. The Oman territory is almost aseismic, but just across the Gulf of Oman there is the area with high seismicity risk that imposes the immediate tsunami threat to the large part of the Oman coast. Steep northern continental slope increases the risk of landslide generated tsunami in this area. The December 26, 2004 Indian Ocean tsunami was observed at the eastern coast of Oman as 1-2 m waves (with measured maximum of 2.6 m near Ras el Duqm). Reportedly, there were no fatalities in Oman resulted from the 2004 Indian Ocean tsunami. The 1945 Ms8.3 Makran earthquake resulted in 15 m tsunami occurred at the southern Pakistan coast within 60-min TTT zone. There is no historical data on the manifestation of this tsunami along the Oman coast. Since there is almost no historical tsunami data on the tsunami manifestation along the Oman coast (except the 2004 Indian Ocean tsunami) the assessment of tsunami hazard for the Oman coast will require the full-scale application of the seismotectonic-probabilism methodology, that is based on assessment of maximum possible earthquakes in the main earthquake-prone areas nearby the Oman coast, assessment of their recurrence time and further application of advanced numerical modeling for calculation of possible run-up heights.
Fig. 21. Map of Tsunami Travel Time zones in 30-min (red), 60-min (green) and 90-min (yellow) intervals for the coast of India. Red circles show the historical seismicity for this area.

Fig. 22. Map of Tsunami Travel Time zones in 20-min (red), 40-min (green) and 60-min (yellow) intervals for the coast of Sri Lanka. Red circles show the historical seismicity for this area.
Fig. 23. Map of Tsunami Travel Time zones in 1-hour (red), 2-hour (green) and 3-hour (yellow) intervals for the coast of Thailand. Red circles show the historical seismicity for this area.

Fig. 24. Map of Tsunami Travel Time zones in 20-min (red) and 40-min (green) intervals for the coast of Sumatra. Large circles show the historical tsunamigenic sources for this area. Out of 46 historical tsunamis generated in this area from 1722 to 2005, 26 (61%) occurred within 20-min propagation time zone.
Fig. 25. Map of Tsunami Travel Time zones in 30-min (red), 60-min (green) and 90-min (yellow) intervals for the coast of Australia. Red circles show the historical seismicity for this area.

Fig. 26. Map of Tsunami Travel Time zones in 30-min (red), 60-min (green) and 90-min (yellow) intervals for the coast of New Zealand. Large circles show the historical tsunamigenic sources for this area. The map clearly shows that almost all (just with two exceptions) historical tsunamigenic earthquakes occurred within 30-min TTT zone.
7. Discussion

To the best of our present-day knowledge, out of 2250 tsunamigenic events, historically known, only 223 (10%) resulted in any fatalities, all others were weak local events observable only in several particular areas of the nearest coast. In total, the 223 deadly events are responsible for 694,000 lives lost due to tsunamis at the coast of the World Ocean during all the historical period of available observations\(^*\).

Out of 223 deadly historical tsunamis, only 11 fall into a category of the trans-oceanic events capable to produce a considerable damage and human fatalities well outside their area of origin. In total, these 11 trans-oceanic tsunamis are responsible for 371,670 (53%) of all fatalities. Among them, 280,000 people were killed during just one event – the December 26, 2004 Indian Ocean tsunami. Other 10 trans-oceanic tsunamis are responsible for 92,000 deaths that is only 13% of all tsunami-related fatalities.

The available data on fatalities from 11 trans-oceanic tsunamis allows one to carry out a more detailed study on their distribution over propagation time. Fig.27 shows a histogram of a number of fatalities over one-hour time intervals for 11 trans-oceanic tsunamis, listed in Table 1. It clearly shows that although a damaging impact of large trans-oceanic tsunamis can last up to 23-24 hours, over 80% of all their fatalities occur within the first hour of propagation time. Another 12% of fatalities happen within the second hour of TTT, and the rest 4% occur during the remaining time (exceeding two hours).

\(^*\) The data on fatalities for old historical events (prior to XIX-th century) are, of course, poorly known for all tsunamigenic regions except, possibly, Japan. However, taking into account an essentially lower density of population in most of tsunamigenic areas in ancient time as compared to its present level, one can hope that this uncertainty does not considerably affect the total estimates for tsunami-related fatalities.
8. Conclusions

1. The current version of the Global Historical Tsunami Database (GTDB) covers the period from 1628 B.C. till present and contains nearly 2250 historical events with 1206 of them occurred in the Pacific, 263 in the Atlantic, 125 in the Indian ocean and 545 in the Mediterranean region. In total, these events are responsible for 694,000 lives lost in tsunami waves during all the historical period of available observations.

2. Out of the total 2250 events, only 223 tsunamis resulted in any fatalities, all others were weak local events observable only in several particular areas of the nearest coast. From these 223 deadly tsunamis, 212 (95%) fall into the category of local and regional events with most of damage and all fatalities limited to one-hour propagation time. In total, they are responsible for 322,000 (47%) fatalities.

3. The 11 trans-oceanic tsunamis that occurred in the World Ocean during the last 250 years are responsible for 372,000 (53%) fatalities. Among them, 280,000 people were killed during just one event – the December 26, 2004 Indian Ocean tsunami. Other 10 trans-oceanic tsunamis are responsible for 92,000 deaths that is only 13% of all tsunami-related fatalities.

4. The detailed study of the death toll for 11 most destructive trans-oceanic tsunamis occurred in the World Ocean during the last 250 years shows that although the damaging impact of large tsunamis can last up to 23-24 hours, over 84% of their fatalities occurring within the first hour propagation time. Another 12% fatalities occur within the second hour, with the rest of 4% occurring at the remaining time (exceeding two hours).

5. The overwhelming majority of other tsunamis (99.5% of all historical cases and 95% of all damaging events) are local and regional events whose major damage and all fatalities are limited to a near-source area within one hour travel time. The present level of accuracy and completeness of the data available in the Global Tsunami Database does not allow studying a more detailed distribution of fatalities from local tsunamis over the propagation time within this one-hour TTT zone (say, over 10-min intervals), but roughly we can say that out of these 212 local and regional deadly tsunamis, 60% had their sources within 30-min propagation time limit. This conclusion is based on counting the number of tsunamigenic sources located within 30-min TTT zone in several most active tsunamigenic regions like Japan, South America, Indonesia, Philippines, Kuril-Kamchatka and Aleutians.

6. The above conclusions, obtained in the present study by the analysis of the most complete historical dataset available in digital domain, are important facts and should be taken into account in design and implementation of any regional or basin-wide tsunami warning system.
References


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