Chapter 1

Examples of Tsunamis and Tsunami Disasters

1.1 Case Studies of Actual Tsunami Disasters

Figure 1.1 shows the tsunami approaching the coast of Thailand and people trying to escape from the tsunami during the Great Indian Ocean Tsunami, which occurred in December 2004. The people in the photograph are trying to escape from it, realizing that the danger is serious. Fortunately, all of these people survived, but did they really understand what was happening at the time, what would follow this scene, and what they should do?

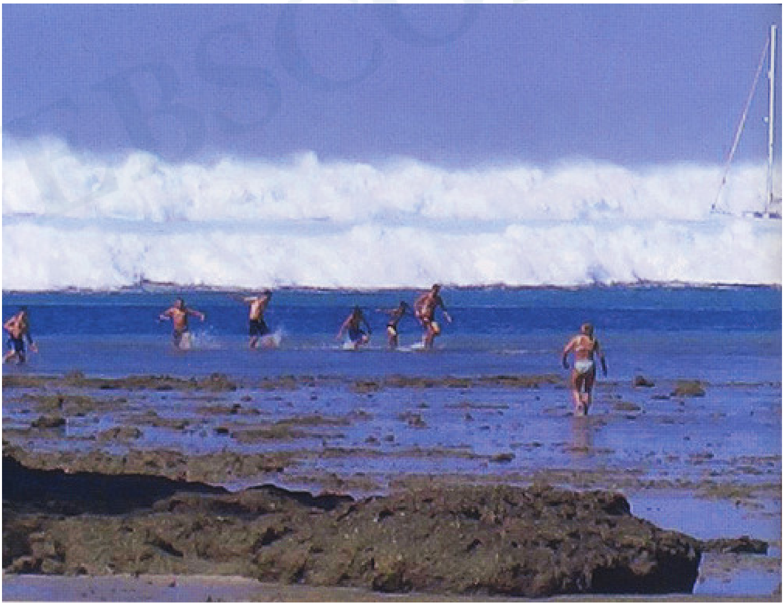


Fig. 1.1 Swimmers fleeing an attacking tsunami (Thailand, 2004).

In order to plan for a smooth evacuation and take effective disaster prevention measures, it is important to understand tsunamis. In particular, each individual must understand the actual damage that tsunamis can cause. For example, if the people in the photograph had understood tsunamis, they would have realized the danger of a tsunami when the sea initially retreated. And if they had understood the damage caused by tsunamis, they would have moved quickly to safety. Even after a tsunami begins to attack, the possibility of survival can be increased by escaping to a nearby high building or other safe place. In other words, an understanding of tsunamis makes it possible to take proper action to avoid danger, and thereby increases the possibility of survival.

Unfortunately, even residents of tsunami-prone regions rarely have direct experience of a tsunami and do not understand the real nature of tsunami disasters. When a tsunami occurs, it can cause terrible damage over a wide region, including heavy loss of human life, as seen in the Great Indian Ocean Tsunami. However, catastrophic tsunamis are very rare. What's more, people from countries which are not prone to tsunami attack (like those in Fig. 1.1) may not even know the word "tsunami." For this reason, a simulated "quasi-experience" of a tsunami is important, for even this indirect experience can be as effective as a vaccination for preventing disease.

Figure 1.2 shows video images taken in Sri Lanka during the same Great Indian Ocean Tsunami. These images were taken at the bus terminal in the center of Galle, Sri Lanka. The tsunami caused an extremely violent flow in the bus terminal from the left rear. The video shows cars and the remains of houses being carried along by the tsunami and people caught in the current. Images like these were broadcast around the world, and many people saw the terror of tsunamis with their own eyes. In other words, seeing video images of a tsunami is a valuable experience for disaster prevention, even for people far from the actual scene.

However, we must remember that images can only show a very small part of a tsunami disaster. In many cases, TV images show only shocking scenes, and not the whole picture of the tsunami. Explanations of images are also inadequate. Tsunami disasters are quite different, depending on the actual tsunami and the conditions in the area. This means that the tsunamis assumed in each region and the damage they cause will not necessarily be the same as shown in television images. Images of tsunami disasters are valuable and extremely effective in educating people, but it is dangerous to depend only on those images. Therefore, this chapter aims to give the reader a more accurate understanding of tsunamis by describing the real nature of a tsunami disaster, as concretely and scientifically as possible, based on the results of scientific study. The nature and severity of tsunami disasters are determined by the conditions related to the attacking tsunami and the attacked region. The most basic parameter of a tsunami is its height. The

Fig. 1.2 Violent flow caused by an attacking tsunami (Sri Lanka, TV).

basic parameters of the region are its distance from the coast and height above sea level, as well as those of coastal disaster prevention facilities (for example, breakwaters and tsunami control forests), and buildings (type construction, density), and the state of human activities (sleeping, working, commuting to work). While considering these factors, we will try to make the reader feel the reality of tsunamis from the human perspective, utilizing photographs where possible.

When reading each section, the reader should remember that the explanation is given for a certain height of tsunami. This is done to clarify the relationship between the height of the tsunami and the nature and degree of damage, because the magnitude of a tsunami is represented by its height. Therefore, if you can estimate the height of a tsunami attacking your region, you can form a specific image of the possible damage in your area by referring to the examples in each section. Forecasts of tsunamis for alerts and warnings currently use the height of the tsunami as a standard, as shown in Table 1.1, that is, warnings say "an *x*-meter tsunami is forecast." It is possible to imagine how large a tsunami attack will be and how much damage will occur by comparing with the damage examples in each section, and to predict expected damage and make evacuation plans based on this information.

Table 1.1 Standards for tsunami warnings and alerts.

Type of forecast	Typical announcement	Height of tsunami (in meters)
Tsunami alert	A tsunami with a maximum height of 0.5 m is forecast; caution is advised.	0.5
Tsunami warning	A tsunami with a maximum height of 2 m is forecast; extreme caution is advised.	1 or 2
Large tsunami warning	A tsunami with a maximum height of 3 m or higher is forecast; extreme caution is advised.	3, 4, 6, 8, 10, or higher

1.2 Indian Ocean Tsunami Disaster

(1) *Outline of the earthquake and tsunami, and resultant disaster*

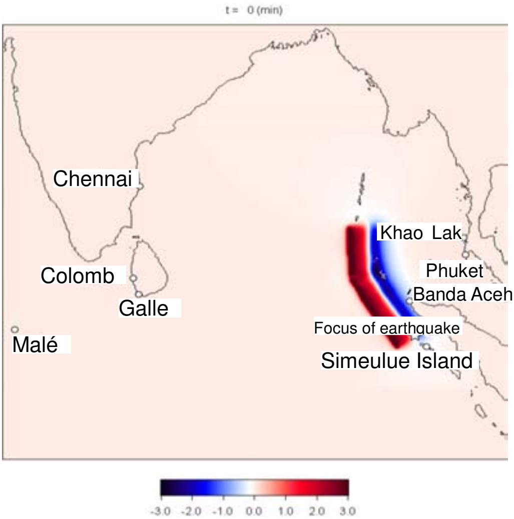
(1) *Occurrence of the earthquake and tsunami*

An earthquake with a magnitude of *M*9.3* occurred on December 26, 2004 at 0:58 GMT (Greenwich Mean Time; 7:58 in the morning in the local time of Indonesia and Thailand, and 6:58 in Sri Lanka). The occurance of the earthquake was captured by seismographs around the world, and general estimates of the focus and magnitude were given immediately by meteorological agencies in Japan, the United States, and other countries. The focus was the sea bottom (latitude 3° N, longitude 96° E, depth 30 km) approximately 10 km northeast of Pulau Simeulue (Simeulue Island) off the coast of the Island of Sumatra, Indonesia. The rupture of the earth's crust which caused the earthquake propagated to the Nicobar and Andaman Islands to the north, reaching a total length of about 1,000 km. This was a trench-type earthquake, which causes large-scale tsunamis. It occurred in the earthquake-prone region where the Indo-Australian Plate subducts under the Eurasian Plate. The magnitude was extremely large, even from a global viewpoint, and was the fourth largest since 1900 (the largest was the *M*9.5 Chilean Earthquake of 1960).

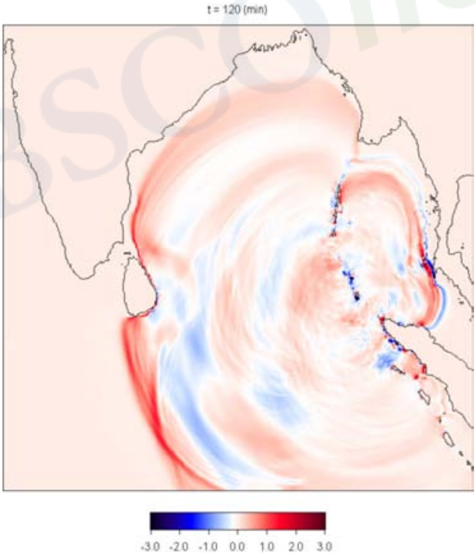
(2) *Propagation of the tsunami*

In order to understand the disaster caused by this tsunami, first, it is necessary to know how it spread from the focal area, propagating through the open sea, and attacked the coasts of countries around the Indian Ocean. The propagation of the tsunami can be seen in numerical simulations by a computer. Figure 1.3 shows the results of such simulations. (a) shows the estimated location where the sea bottom ground rose and fell due to the rupture of the earth's crust. The areas in

* The Geological Survey and North-Western University in USA proposed *M*9.1 and *M*9.3, respectively, as the seismic magnitude.



(a) Initial displacement of sea bottom ground



(b) Propagation of the tsunami (after two hours)

Fig. 1.3 Example of numerical simulation of the Great Indian Ocean Tsunami (Tomita et al., 2005).

red are where the seabed rose. The average height of the rise was approximately 2 m. Blue shows areas that sank, the average drop being from -0.5 m to -1.0 m. Banda Aceh, which is on Sumatra near the focus of the earthquake, sank. This deformation of the seafloor shape was transmitted unchanged to the sea surface, where it caused a corresponding deformation that resulted in the tsunami. Figure 1.3(b) shows the tsunami two hours after the earthquake. Because the energy of a tsunami spreads and weakens with distance, the height of the tsunami decreases as it propagates over long distances. The direction and height of the tsunami also change due to the topography of the sea bottom, and the tsunami becomes more complex due to reflection by land and islands. In the open sea, the height of a tsunami is normally less than 2 m. Because this is small in comparison with its length that reaches several 100 kilometers, it is difficult for human observers to recognize a tsunami, and the effect on ships is extremely slight. However, after a tsunami propagates across the open sea, its height increases when it approaches the coast as the water becomes very shallow. As a result, the tsunami causes damage on the coastline. A tsunami is also affected by the topography of the sea floor (through various effects such as refraction, diffraction, and energy concentration), and the wave height and direction vary greatly, depending on the place. Damage also differs, depending on these conditions.

(3) *Tsunami attack*

At Banda Aceh in northern Indonesia, near the focus of the earthquake, the tsunami attacked less than 20 minutes after the earthquake. The height of the tsunami (trace height or run-up height: a maximum height of a tsunami onshore above sea level) was 4-8 m in districts facing north, but was as large as 10-20 m in districts on the west, which faced the focus of the earthquake. The average water depth of the ocean between the seismic focus and Thailand is relatively shallow, at approximately 400 m. As a result, the propagation velocity of the tsunami was also comparatively slow, being on the order of 200 km/h. In Thailand, the tsunami run-up height was 4-10 m in the vicinity of Khaolak and further to the south, 4-6 m around Phuket. A notable point is that because the sea bottom ground facing Thailand dropped, the tsunami attack on the Thai coast began with a "backwash" (water pulling back from the normal shoreline). On the other hand, the ocean depth between the focus of the earthquake and Sri Lanka was deep, averaging approximately 4,000 m. As a result, the speed of the tsunami was extremely fast, at about 700 km/h, and the tsunami propagated over a distance of about 1,200 km in a little more than 100 minutes. The fundamental period of this tsunami was 40-50 minutes, and its wavelength was several 100 km. In Sri Lanka, the height of the tsunami was 5-10 m on the eastern coast and 4-10 m on the southern coast. Because the sea bottom ground around the earthquake focus facing Sri Lanka rose, the tsunami attack on the Sri Lanka coast began with a rising wave. The tsunami also propagated to India and the islands of the Maldives, and even reached far-away Somalian coast in Africa causing damage. In these regions, the tsunami attacked repeatedly, and in many cases, not the 1st wave, but the 2nd or later wave was the largest. However, in Bangladesh, which is located along the axis of the displacement of the sea bottom ground, the height of the tsunami was not particularly great.

(4) *Human damage due to the tsunami*

The Indian Ocean Tsunami resulted in a very large number of deaths and missing persons (Table 1.2), totaling around 300,000 persons. In general, a disaster which causes around 10,000 deaths is called a "catastrophic disaster." The Indian Ocean Tsunami far exceeded this standard, and was one of the worst disasters in recent history. The following three reasons can be given for this enormity of the disaster.

(1) A giant earthquake caused an extremely large tsunami which attacked many regions, including remote countries. Because the earthquake tsunami was caused by a giant trench-type earthquake, a large tsunami with a height exceeded 4 m attacked many regions. Heavy damage, including destruction of buildings occurred in areas where the tsunami exceeded 4 m. Areas where the tsunami was 8 m to over 10 m were basically wiped out.

Table 1.2 Deaths and missing by country.

Indonesia	256,000
Thailand	5,400
Sri Lanka	38,000
India	10,750
Maldives	80
Somalia	300

(2) The tsunami suddenly attacked the people who did not know that a large earthquake had occurred and also did not receive any warning in advance. Collapse of buildings and other earthquake damage occurred in the western and northern parts of Sumatra Island in Indonesia and neighboring areas near the focus of the earthquake as well as in the Andaman Islands of India. However, there was no earthquake damage in other countries, and the tremors in Thailand were very slight. In these countries, the earthquake tremors were not felt; in addition, there was no warning system. As a result, no one realized that an earthquake had occurred; no one was aware of the possibility of a tsunami attack in advance, resulting in a very large disaster.

(3) In these regions, many people live on low-lying land near the coast, and there were almost no coastal disaster prevention facilities. In the regions where this tsunami disaster occurred, the effect of cyclones is not particularly serious and the ocean is relatively calm. Because of these conditions, many people had lived in relatively simple houses near the shore.

In particular, (2) and (3) are very different from the conditions in Japan, where tsunamis occur with comparatively high frequency and disasters due to storm surge in typhoons are common.

In addition, because Thailand has many beach resorts, the victims included a large number of tourists. Table 1.3 shows the number of deaths and missing tourists by country. The fact that many tourists who knew nothing about tsunamis died is one distinctive feature of this tsunami disaster.

Table 1.3 Deaths of tourists by country.

Country of origin	Dead and missing (presumed dead)	Country of origin	Dead and missing (presumed dead)
Germany	619	Denmark	47
Sweden	575	Australia	41
Great Britain	248	Hong Kong	40
Italy	210	Netherlands	39
New Zealand	209	Canada	36
Finland	189	South Korea	20
United States	169	China	18
Switzerland	157	Ukraine	17
Austria	114	Philippines	15
France	96	South Africa	15
Japan	93	Poland	11
Norway	84	Others	110

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(2) *Disaster in Banda Aceh, Indonesia*

(1) *Outline of Banda Aceh*

Minutes before 8:00 in the morning on December 26, 2004, a giant earthquake *M*9.3 occurred in the ocean approximately 100 km west of the coast of Sumatra Island. The epicenter of this earthquake was 250 km south-south-east of the city of Banda Aceh (Fig. 1.4). However, the focal region then spread 1,000 km to the north from the original focus, and the sea bottom ground was moved by the earthquake even in the area to the west of Banda Aceh. The tsunami that accompanied this ground movement attacked Banda Aceh. According to an eyewitness who observed the tsunami from a high ground on the coast west of Banda Aceh, the tsunami attack occurred about 15-20 minutes after the tremors caused by the earthquake were felt. In some places, the tsunami that attacked the shore was higher than 10 m. At the time, Banda Aceh had a population of 264,618 persons. Of these, 61,065 died (source: Banda Aceh City homepage).

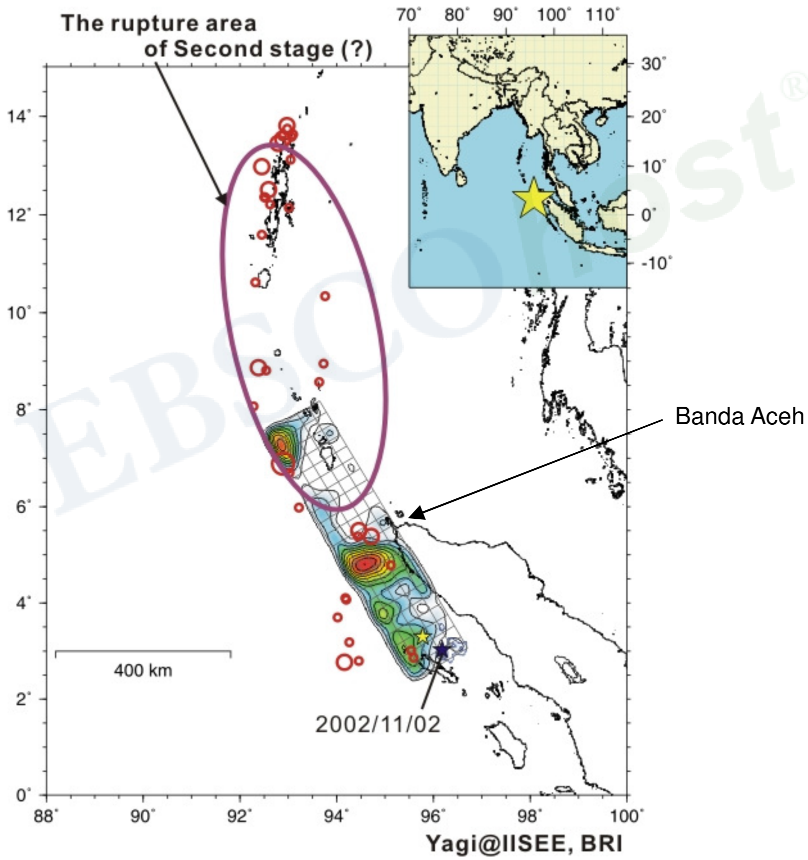

Fig. 1.4 Results of an estimation of the position of the focus of the earthquake and the amount of slip of the fault (Yagi, 2004). The star mark in the figure shows the position of the focus; large slipping of the fault occurred in the areas marked in red.

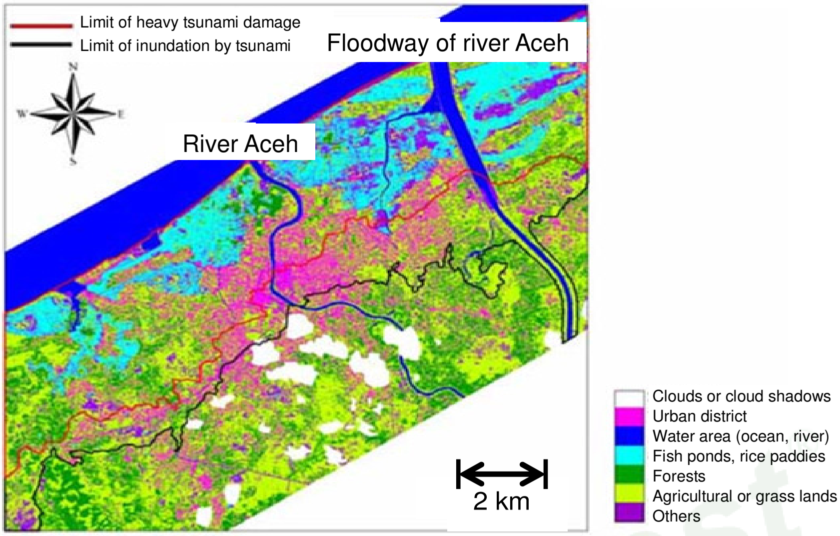

Fig. 1.5 Land use in the area around Banda Aceh (Geographical Survey Institute, Government of Japan, 2004).

Banda Aceh is built on flat land around the mouth of the Aceh River. In the hinterland beyond the coastline, fish ponds and rice paddies cover the area of 11 km^2 (Fig. 1.5). The center of the city is located approximately 2.5 km inland from the coast. However, the height of the ground was about 2 m above sea level at the time of the tsunami attack, and the low flat land extends from the coast to the inland.

(2) *Attacking tsunami and inundation*

The height (trace) of the attacking tsunami was 12 m at a mosque near the coast. The trace of the tsunami was found at a height of 7 m even at the mouth of the Aceh River to the east of this structure. This giant tsunami caused devastating damage 2-3 km far from the coast and inundation up to 5 km from the coast (Fig. 1.6).

At a high school in an area (marked by the circle in Fig. 1.6) 2.5 km far from the coast, the concrete school building remained after the tsunami, and water marks were left on its walls. The ground height in this area is 1.3-1.6 m above sea level, and the water marks of the tsunami on the side walls of the concrete building were at a height of 4.0-4.4 m above the ground (Fig. 1.7). In other words, this flat, low-lying city was destroyed by water flows that exceeded 4 m in height (Fig. 1.8).

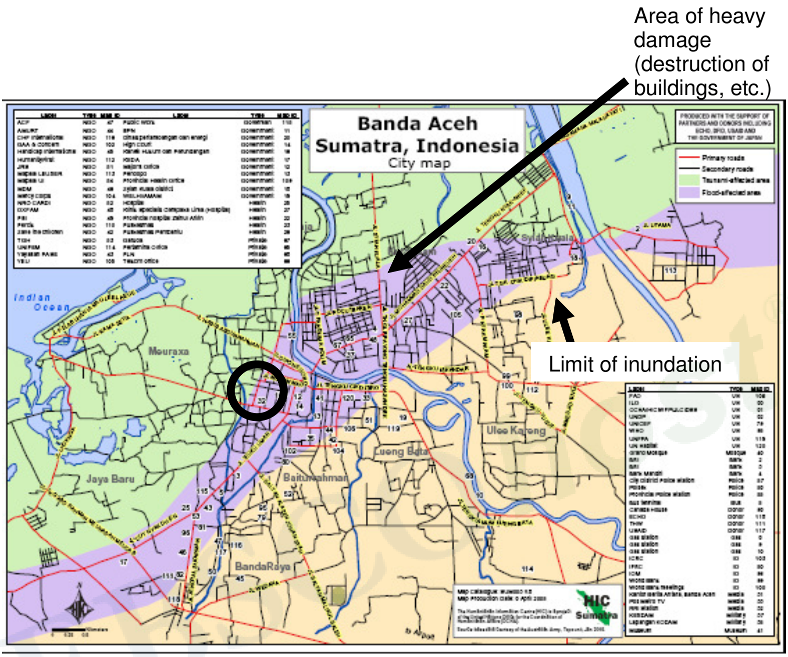

Fig. 1.6 Outline of damage in Banda Aceh (HIC, 2005).

Fig. 1.7 Water marks left on the side wall of a school 2.5 km far from the coast (height above ground: 4.4 m).

Fig. 1.8 View of the damage in Banda Aceh (US Navy, Reconnaissance Team of the Japan Society of Civil Engineers, 2005).

(3) *Damage caused by the giant tsunami*

The residential area of Banda Aceh near the coast received devastating damage. Figure 1.9 shows satellite photographs before and after the tsunami. Although these are difficult to see in the photo, erosion countermeasures had been constructed on the shore of the sandbar facing the sea in order to protect the coast from storm surge. However, these countermeasure works were damaged by the tsunami. As a result, the land behind the works was eroded and the coastline was moved back. The land in the center of the sandbar was completely submerged as a result of erosion. As these photographs show, a tsunami has the power to change the shape of the land.

Figure 1.10 shows the remains of a residential area on the sandbar in Fig. 1.9(a) after the tsunami. Attacked by a tsunami as high as 10 m, houses were easily swept away, and even the pavement of roads was ripped up and carried away. There is a high possibility of damage to reinforced concrete (RC) buildings when the height of a tsunami exceeds

(a) Before the tsunami

(b) After the tsunami

Fig. 1.9 Sandbar eroded by the tsunami (© Digital Globe).

Fig. 1.10 Remains of destruction caused by the tsunami.

Fig. 1.11 Ferry terminal building under construction, which survived the tsunami.

5 m. However, one RC building on this sandbar withstood the tsunami. This was the ferry terminal building (Fig. 1.11). The first floor collapsed, but the second and higher floors remained. It may be noted that the first floor was destroyed by the earthquake, and not by the tsunami. This terminal building was under construction at the time. The framework of RC columns had been completed, but the walls had not been constructed. The 10-m tsunami attacked the building at this stage of construction and it passed cleanly through the building because it happened to have a wall-less "piloti" structure. As a result, the building escaped destruction by the tsunami. ("Pilotis" are piers. In a piloti structure, the building is raised above the ground on piers. In other words, the first floor consists of piers and open space without walls.) This example shows that a piloti structure can be effective as tsunami countermeasures, provided the structure is strong enough to withstand the earthquake ground motion.

The high tsunami also pushed and moved gigantic objects which would normally seem impossible. Figure 1.12 shows a power generating barge that was carried about 3 km inland from the coast by the tsunami. The barge is approximately 60 m long and 20 m wide. This barge was moored in the port before the tsunami. The water marks left by the

Fig. 1.12 Power generating barge carried onshore by the tsunami.

tsunami on buildings near where the barge was moved were about 3 m above the ground. This is roughly the same as the draft of the barge. It seems that the barge finally stopped when its bottom stuck on the ground. Large ships were carried inland in other areas as well, and these were also flat-bottomed boats. This shows that flat-bottomed boats are easily run up on land by tsunamis.

In Kreung Raya Port to the east of Banda Aceh, the tsunami reached 5 m above ground level. Here, three empty oil tanks (out of a total of nine tanks) were carried by the tsunami. These tanks, which were 17 m in diameter and 11 m in height, were carried about 300 m along the coastline (Fig. 1.13).

At a cement works on the west coast of Sumatra, an oil tank was heavily deformed by the force of the tsunami (Fig. 1.14). The height of the tsunami was estimated at more than 20 m. The destructive force of the tsunami can be imagined from this picture.

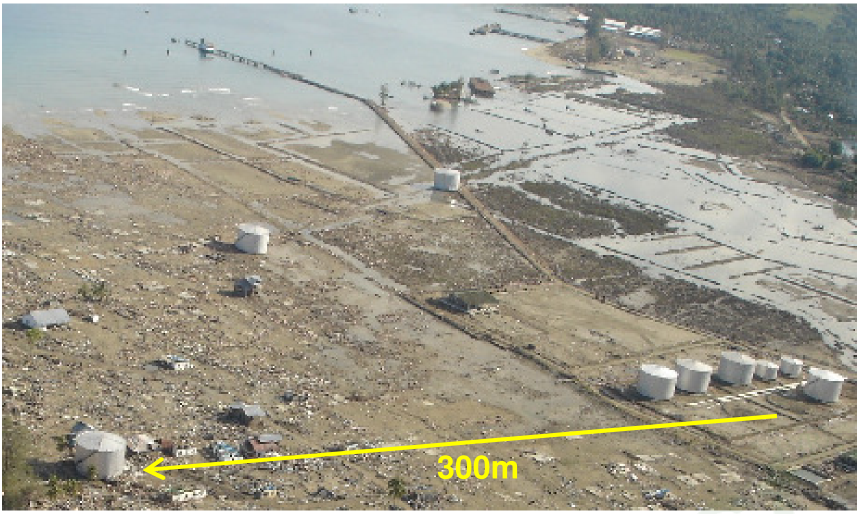

Fig. 1.13 Oil tank carried by the tsunami.

Fig. 1.14 Oil tank heavily deformed by the tsunami.

Fig. 1.15 Building after the first floor collapsed in the earthquake.

(4) *Large tremors caused by earthquake*

Before the tsunami attack, the city of Banda Aceh was also hit by large tremors (earthquake ground motion). On the Japanese scale, the earthquake intensity was a little less than 5 to a less more than 6. This intensity indicates that the tremors were so large as to make it difficult for a person to keep standing on the ground. Many RC structures were destroyed by this shaking. As shown in Fig. 1.15, several of these were destroyed when the first floor (ground floor) collapsed. As mentioned previously, Banda Aceh is on flat land with no high ground where people can escape from a tsunami. In flat areas like this, high buildings are essential as places of refuge from tsunamis. Thus, buildings which can withstand earthquakes (that is, earthquake resistant buildings) are important.

(5) *Condition of the tsunami attack*

When the focus of an earthquake is nearby, people feel large tremors, and this can trigger an evacuation from a tsunami. Unfortunately, however, people do not always evacuate. For example, the earthquake was extremely strong in Banda Aceh, but the residents had no previous experience of tsunamis. As a result, nobody realized that a tsunami might follow the earthquake, and nobody evacuated.

The tsunami attacked Banda Aceh about 15 minutes after the giant earthquake. According to witnesses, first, the ocean pulled back toward offshore, and then the tsunami attacked like a wall of water. Similarly, on the coast west of Banda Aceh, witnesses said that first the ocean pulled back about 2 km from the normal coastline. Thus, it seems that the tsunami that attacked Sumatra was a "backwash-first" type tsunami, which began with the water pulling away from the shore. Following this, many people went out onto the exposed sea bottom to collect fish, not knowing anything about an imminent tsunami attack on land, and it is said that some of these people fell victims to the tsunami.

The tsunami attack at Banda Aceh did not end with one wave. Witnesses stated that the tsunami attacked three times, and the 2nd wave that attacked about 15 minutes after the 1st wave was largest. According to survivors from the western side of the city, the 1st wave came from the north side that directly faced the coast, but the stronger 2nd wave attacked from the west. The west side of the city does not directly face the coast. However, there is a creek that flows to the north coast, and it seems that the tsunami ran up by this route. On the other hand, on the northern coast, the 1st wave of the tsunami attacked almost directly from the north, but the 2nd wave attacked somewhat more from the west. These facts suggest that the tsunami that flood the land displayed complex behavior because of the effect of the land topography (including the creek) and the direction of the tsunami attack from offshore area.

(6) *Evacuation from the tsunami*

Because it is generally said that tsunamis travel at a speed of around 700 km/h, some people believe that it is impossible to escape after seeing a tsunami. However, 700 km/h is the speed of a tsunami traveling across open ocean with a depth of 4,000 m (average depth of the Pacific Ocean). The speed of a tsunami depends on the water depth, becoming slower as the water depth becomes shallower. Therefore, do not give up hope even if you actually see a tsunami approaching. Even in areas where the maximum height of the tsunami on land was more than 4 m, some people escaped by running survived. He said he saw black water approaching from the north and escaped by running to the south. Video images of the tsunami in the town show many people running from the leading edge of the tsunami and escaping to buildings or other high places (Fig. 1.16). According to an analysis of these video images, the maximum inundation depth was approximately 1.6 m and the velocity of the tsunami was around 5 m/s, or 18 km/h. Thus, the lower the water depth, the slower the speed of the tsunami flow. Therefore, if you are so unfortunate as to see a tsunami running toward you, it is important not to give up hope, and to escape to some high place.

Fig. 1.16 People fleeing the leading edge of the tsunami in Banda Aceh.

(a) Mosque, as seen from the sea

(b) View from inside the mosque

(c) Hole used to escape onto the roof

Fig. 1.17 Mosque by the sea, which was attacked by a 12-m tsunami.

Figure 1.17 shows a mosque near the coast (Baiturrahim Mosque; "Mosque by the Sea"), which was attacked by a tsunami of 12 m in height. Many mosques are constructed more strongly than ordinary houses, and survived both the earthquake and the tsunami. People also survived by fleeing to this mosque. However, because the 12-m tsunami reached just below the roof of the mosque, people broke through a wall leading to the roof and climbed onto the roof in order to escape.

Other people escaped by car. One person saw the approaching tsunami from afar, jumped in his car, and drove quickly along a straight road in front of his house. When he turned a corner onto a larger street, the tsunami was already there. This highlights the fact that wide roads become "channels" for a tsunami, and the tsunami travels faster on these roads than in areas with buildings and other structures. This example should also make us think about how to evacuate safely.

As the tsunami moved through the town of Banda Aceh, it destroyed many houses and other buildings. The flow of the tsunami included debris from these destroyed buildings, mud, floating automobiles, and other objects (Fig. 1.18). The color of the water was dirty and muddy. The flow also carried large ships, fishing boats, etc. (Fig. 1.19). In addition to drowning, there are following many other dangers if you are caught in this kind of tsunami. You may be thrown against a building or rock, you may not be able to keep your head above water, or you may be injured by floating objects. There are also several examples of lucky people who held onto a floating object and were rescued offshore. However, this is generally very difficult. Even if you are confident about your swimming ability, it is important to flee before you are caught in a tsunami.

Fig. 1.18 Debris carried by the tsunami.

Fig. 1.19 Fishing boat carried onshore by the tsunami.

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(3) *Disaster in the Phuket Island/Khao Lak area, Thailand*

Southern Thailand is a resort area centering around Phuket Island. Tourism-related development has also progressed on the Khao Lak coast