Chapter 5
Global Effort to Forecast and Mitigate a Tsunami Hazard

Abstract This chapter gives a description of the key components of tsunami warning centers, modeling scenario data bases, inundation modeling, types of tsunami advisories and global tsunami warning centers.

5.1 Introduction

Tsunamis are primarily caused by earthquakes. As of now, it is not possible to forecast earthquakes. However, soon after an earthquake occurs, its parameters (origin time, location and magnitude) are estimated. It is then possible to estimate whether a particular earthquake would generate a tsunami, how strong this tsunami would be and what its size and arrival time would be at various locations locally and globally. The first scientific effort in this direction dates back to the 1920s when an attempt to warn about tsunamis was made in Hawaii. Later, responding to the 1st April, 1946 Aleutian Island earthquake and the May 23, 1960 Valdivia earthquake and the resultant tsunamis that caused massive destruction in Hilo, Hawaii, more advanced tsunami warning systems were developed. The basics of developing tsunami warning systems is the fact that in the open ocean tsunamis travel with a speed of 500–1000 km/h, whereas the longitudinal seismic waves travel much faster at a speed of 5–7 km/s (18,000–25200 km/hr). So an earthquake could be located within a few minutes of its occurrence, while the tsunami waves will take several minutes to several hours to reach a vulnerable location, depending upon its distance from the earthquake source.

From the point of view of early warning of tsunamis, they are classified into the following three categories by the Inter-Governmental Commission on Oceanography (UNESCO-IOC 2006; Nayak and Kumar 2011):

Local Tsunami: These are caused by a source located close to the coast (within 100 km, or less than 1 h of the tsunami traveltime to the coast) and are the most

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destructive. There is very little time to react, evacuate and implement other defensive measures.

Regional Tsunami: These are capable of creating destruction in a particular geographic region within a distance of 1000 km from the source and the tsunami traveltime could be 1–3 h.

Distant Tsunami: A distant tsunami is caused by a major earthquake in a subduction zone and is capable of causing destruction in the Pacific Rim countries located around the ocean basin to distances of more than 1000 km and a tsunami traveltime of more than 3 h.

5.2 Components of Tsunami Warning Centers

5.2.1 Seismic Network

A tsunami warning center should be able to locate an earthquake within a few minutes of its occurrence. This requires the availability of earthquake data from seismic stations distributed globally. If the tsunami warning center is catering to the needs of a specific region, availability of a dense regional network of seismic stations is very desirable. For accurate estimate of the moment-magnitude of an earthquake, it is necessary to have seismic stations with broadband, low noise and high-dynamic range digital seismic data acquisition capabilities. Timely estimation of earthquake parameters, say within 5 min is desirable. The density of seismic stations should be such that there are several (8–10) seismic stations within 900 km of the earthquake source.

5.2.2 Sea-Level Network

To determine whether an earthquake has generated a tsunami, it is necessary to monitor changes in the water level as close to the source as possible. For this purpose tide gauges, ocean- bottom pressure recorders and coastal ocean dynamics application radars are used. These devices provide accurate sea-level data in real or near real time to determine whether an earthquake has generated a tsunami and if so, how big it will be when it reaches the coasts of the likely affected countries. There are a number of global networks that provide sea-level information in real time and they are coordinated by the Inter-Governmental Commission of Oceanography (IOC) under the UNESCO umbrella. The Global Sea Level Observing System (GLOSS), operated under the guidance of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organization (WMO) and IOC, is the most prominent among these networks.

5.2.3 Modeling

Numerical modeling is used to estimate the mechanism of tsunami generation from earthquake data in addition to forecasting the traveltime of tsunami waves to different locations, identifying the inundation areas and extent of inundation. These are all important components of early tsunami warning systems. A number of tsunami models are available with relative advantages and disadvantages. The most commonly used models are the TUNAMI (Tohoku University Numerical Analysis Model) developed by Imamura et al. (1995) and the MOST (Method of Splitting Tsunami) pioneered by Titov and Gonzalez (1997). Using the data of global seismic stations, these models make use of earthquake focal parameters like location and depth, strike, dip and rake as well as the length and width of the rupture plane and slip to compute the generation and propagation of tsunamis locally and of the trans-ocean basin as well as inundation.

5.2.4 Scenarios

Running of the tsunami models after the occurrence of an earthquake takes a lot of time, which can be avoided by preparing a pre-run data base. It is very helpful to have a look-up table (LUT) available for the possible scenarios. This has been achieved by using unit source function methodology, where each unit is equivalent to a tsunami generated by an Mw 7.5 earthquake having a rectangular source of 100 km by 50 km and a 1 m slip. These units are suitably combined to produce the tsunami scenario for a relevant earthquake (Gica et al. 2008; Greenslade and Titov 2008; Nayak and Kumar 2008a, b, c). The entire circum-Pacific seismic belt, the Caribbean (for the Atlantic region) and the Indian Ocean have been modeled with such an approach. To match an earthquake after its occurrence, the basic unit source scenarios are selected, merged and scaled up/down based on scaling relations to generate a scenario corresponding to the earthquake under consideration (Nayak and Kumar 2008c).

5.2.5 Inundation

An important issue in mitigating a tsunami hazard is the knowledge of the possible inundation and therefore the extent of the human population likely to be affected as well as the major civil structures and the facilities that are likely to be damaged by the tsunami. For developing tsunami run-up and inundation scenarios, it is necessary to have close grid information of shallow bathymetry and near-shore topography. The height of the tsunami wave, as it approaches the coast, is governed by the near-coast bathymetry. Similarly, how a tsunami wave would inundate a coastal region is governed by the near-coast topography. In the tsunami prone coastal areas, detailed near-shore bathymetric and topographic surveys are carried out and estimates are made for possible inundation for a given height of a tsunami.

5.2.6 Communication

Having found that an earthquake has occurred and it is likely to generate a tsunami that would affect a given coastal region, it is extremely important to communicate an estimate of the severity and the time of arrival to the likely effected population in the minimum possible time. This requires a reliable communication infrastructure. The tsunami warning centers use multiple lines of communication such as radios, SMS, e-mail, television, texting and telex etc. Particularly, the emergency service operators need to be informed of the pending tsunami. As mentioned earlier, geographically there are several inhabited coastal areas (several locations in Japan, Indonesia and elsewhere) where within a few minutes of the occurrence of an earthquake, the tsunami would inundate the coast. For such areas, a tsunami advisory is issued as soon as an earthquake of M 6 or more occurs in the seismic zone prone to generating tsunamis.

For issuing a tsunami warning, decision support systems have been developed. These are basically coded standard operation procedures that compile earthquake data in real time and combine them with tsunami scenario models to accurately generate tsunami warning advisories that need to be sent to areas of concern as early as possible.

5.3 Tsunami Warning Centers

From the early installation of the rudimentary tsunami alert system of the 1920s, today, there are several tsunami warning facilities deployed all over the world. Seven of these have independent services. These are the Pacific Tsunami Warning Center (PTWC), Japan Meteorological Agency's (JMA) center, Sakhalin Tsunami Warning Center (STWC), German Indonesian Tsunami Early Warning Center (GITEWS), Joint Australian Tsunami Warning Center (JATWC) and the Indian Tsunami Early Warning Center (ITEWS). These centers along with the areas covered by them are shown in Fig. 5.1 (after Nayak and Kumar 2011).

5.4 Tsunami Advisories

Over the years, the science of tsunami warning has significantly advanced. It has become very important that appropriate information is provided to the officials involved with handling disaster related issues as well as to the general public. The advisories have to be in simple language and should include the necessary information, so that the appropriate steps are taken by the users. The first advisory is on the basis of the occurrence of an earthquake and is qualitative. All other advisories, following the first earthquake advisory, are quantitative. Following is the gist of the advisories as issued by the global tsunami warning centers (after Nayak and Kumar 2011):

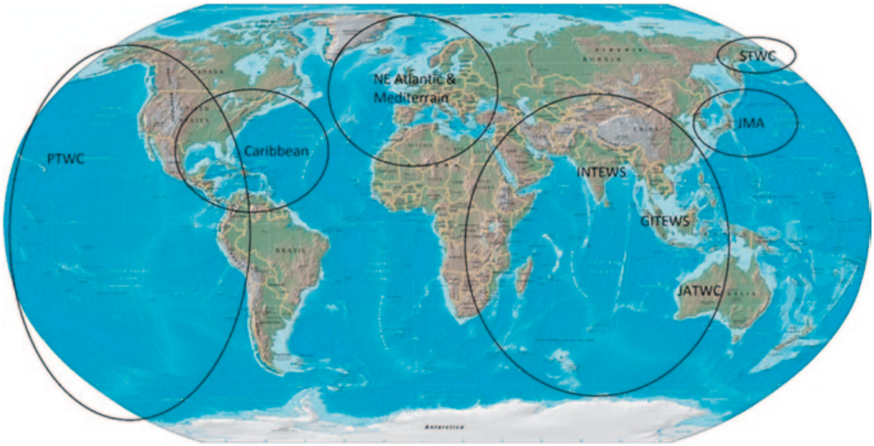

Fig. 5.1 Global tsunami warning services and the areas covered by them (after Nayak and Kumar 2011). For details see text

Earthquake information bulletin

The bulletin contains the focal parameters of the earthquake such as the origin time, latitude and longitude of the epicenter and the focal depth, magnitude and geographical location where it has occurred. This bulletin also comments on the potential of causing a tsunami depending upon the geographical location and the magnitude of the earthquake.

Warning

When the potential of a tsunami is high and a large coastal area is likely to be affected, the highest level of the advisory, the warning, is issued. The warning also alerts the public, likely to be affected by the ensuing tsunami, of coastal flooding, the anticipated height of the tsunami when it arrives as well as the expected time of its arrival at various coastal locations. With the passage of time the warnings could be updated; the geographical location to be affected can be suitably adjusted based on the information collected; downgraded or cancelled.

Watch

When immediate public evacuation is not required, a watch advisory is issued to alert the emergency management officials. The watch advisories are based on seismic observations of a large enough earthquake that has occurred in a region where a tsunami could be generated, without the confirmation of the generation of a tsunami. Officials should be ready to effect evacuation, in case the watch is upgraded to a warning. Later, the watch may be cancelled.

Alert

It is a lower category of ‘Watch’, issued on the basis of an earthquake occurrence, with a qualitative assessment of a possible tsunami. With the passage of time, with more information gathered, the ‘Alert’ could be upgraded to a ‘Watch’ or ‘Warning’ or cancelled. Local disaster management authorities are expected to be ready for evacuation and other necessary interventions to minimize a possible tsunami hazard. Under alert, the public are advised to keep away from the beaches as strong currents are expected.

Cancellation

A cancellation is issued after ascertaining that the tsunami will not impact the area under warning. It is also issued when it is estimated from sea-level observations that the earlier issued warning is no longer valid or effective.

5.5 Tsunami Watch and Warning Centers

In the following we describe a few major tsunami warning centers currently in operation.

5.5.1 The Pacific Tsunami Warning Center

This is the oldest tsunami warning center set up in 1949 in response to the 1946 Aleutian Island earthquake and the resultant tsunami that claimed 165 human lives in Alaska and Hawaii, besides colossal damage to property. Located at Ewa Beach, Hawaii, it was originally known as the Honolulu Observatory. The 1960 Chilean earthquake caused an ocean-wide tsunami across the entire Pacific Ocean basin. Consequently, the scope of the Honolulu Observatory was enhanced to provide tsunami information for the entire Pacific Rim countries and it was re-named the Pacific Tsunami Warning Center (PTWC). It provides warning and advisories to participating members and nations in the Pacific Ocean area. It also acts as the local warning center for the state of Hawaii. Following the devastating Sumatra earthquake and the deadliest tsunami so far in 2004, the scope of PTWC was further expanded to include the Indian Ocean and the Caribbean Sea countries.

5.5.2 The West Coast and Alaska Tsunami Warning Center

There was a massive Mw 9.4 earthquake on 27th March, 1964 in Alaska that underlined the necessity to create facilities to provide timely and effective earthquake and tsunami warnings to the coastal areas of Alaska. This resulted in establishing the Palmer Observatory in 1967 at Palmer city in Alaska and it was known as the Alaska Regional Tsunami Warning System (ARTWS). It served all the coastal regions of USA and Canada. In 1973 the ownership of ARTWS changed and it was renamed as the Alaska Tsunami Warning Center (ATWC). In 1996, its responsibility was expanded to include the coastal areas of California, Oregon, Washington, British Colombia and Alaska and the present name West Coast/Alaska Tsunami Warning Center (WC/ATWC) was adopted.

5.5.3 The Japan Meteorological Agency

Japan is one of the most earthquake and tsunami prone countries in the world. The March 11, 2011 earthquake of magnitude Mw 9.0 and the resultant tsunami caused wide spread damage. The nuclear power plants in Fukushima suffered considerable damage. About 20,000 human lives were lost. The meteorological services in Japan were initiated in 1875. Currently, known as the Japan Meteorological Agency (JMA), under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), it is responsible for prevention and mitigation of natural disasters. In addition to serving the Japanese Islands, it also provides advisories on a global scale. After the occurrence of an earthquake, JMA estimates the possibility of a tsunami being generated on the basis of seismic data. In case a tsunami is expected in the coastal regions of Japan, JMA issues tsunami warning/advisories within 2–3 min of the occurrence of the earthquake. For far-off tsunamis, JMA co-operates with PTWC in issuing appropriate warning/advisories globally.

5.5.4 Sakhalin Tsunami Warning Center

In response to the devastating tsunami generated by the November 4, 1952 Kurile (M 9.0) earthquake, Russia set up the Sakhalin Tsunami warning Center (STWC) in 1958. Located in Yunzo-Sakhalinsk it has two components, namely the Tsunami Warning Center (TWC) and the Seismic Station of the Russian Academy of Sciences. The primary aim of STWC is to issue tsunami warning/advisories to the Civil Defense and Emergency Regional Headquarter and to the Central Telegraph Station of Yuzano-Sakhalinsk about possible tsunamis from near and far-off earthquake sources.

5.5.5 German-Indonesian Tsunami Early Warning System

Indonesia is very vulnerable to tsunamis. The earthquakes occurring along the subduction zone in the Sunda Trench are very close to major Indonesian cities and a tsunami could reach within a short time of 10–20 min, providing very little time to affect defensive measures and cause evacuation. This limiting factor was the basis of setting up GITEWS. Supported by the Government of Germany, GITEWS was completed and handed over to Indonesia in March, 2011. It has demonstrated its effective operation since then by effectively giving tsunami advisories within 5 min of the occurrence of earthquakes. GITEWS is based in Jakarta at the Indonesian Meteorological, Climatological and Geophysical Agency. The system is classified as a modern tsunami warning system globally.

5.5.6 Joint Australian Tsunami Warning Center

Based in Melbourne and Canberra, the Joint Australian Tsunami Warning Center (JATWC) is operated by the Bureau of Meteorology and Geo-science Australia (GA). The purpose is to provide Australia an independent capability to detect, monitor, verify and provide appropriate advisories to Australian coastal regions about tsunamis.

5.5.7 Indian Tsunami Early Warning System

Soon after the 2004 tsunami, India took up the work of establishing a modern tsunami warning center and the Indian Tsunami Early Warning System (ITEWS) came into operation in August 2007. Since then it has been operating uninterrupted and is capable of giving accurate tsunami advisories within 10 min of the occurrence of an undersea earthquake of magnitude 6.5 or larger occurring anywhere in the Indian Ocean. Kumar et al. (2012a) have analyzed the performance of ITEWS over the past 5 years and found it to perform very well. Here we give some details of the components and the operation procedure adopted by this very successful facility.

Observation System of ITEWS

The system receives seismic data from about 300 seismic stations globally in real time. The focal parameters of the earthquakes are determined using autolocation software. The sea-level observations are made using ocean-bottom pressure recorders and coastal tide gauges. It must be mentioned here that in the Indian Ocean, it has been found that there are only two known sources capable of generating tsunamigenic earthquakes. The first is the seismic belt between Sumatra and Andaman Islands, a stretch of some 4000 km in length. The second source is the area off the Makaran coast in the Arabian Sea (Fig. 5.2). This is important, particularly for the coastal regions of India. It must be mentioned here that tsunamis are rather rare for the Indian coastal region. In the entire twentieth century, there were only three tsunamis to have indented the east coast of India. The 26th December 2004 tsunami caused immense loss of human lives. Many of them lost their lives because of ignorance. After the first wave hit the Tamil Nadu coast line, the sea withdrew. It was a Sunday morning and the local time was around 9 am and people were walking on the seashore. After the sea withdrew, people just walked in out of curiosity or to pick sea shells, they did not know what was in store for them. The second tsunami wave claimed lives of the morning walkers who were unknowingly trapped. It is very important to reduce the number of false tsunami warning alarms, as happened on 28th March, 2005. The Nias earthquake of Mw 8.7 occurred very close to the epicenter of the 26th December, 2004 earthquake at 19.09 pm Indian Time. A tsunami was forecasted and evacuation was affected. There was no significant tsunami. However, the tsunami warning was withdrawn early in the morning of 29th March, 2005. This caused immense inconvenience to millions of evacuees. Fortunately, other than the Andaman and Nicobar group of islands, the other coastal areas are

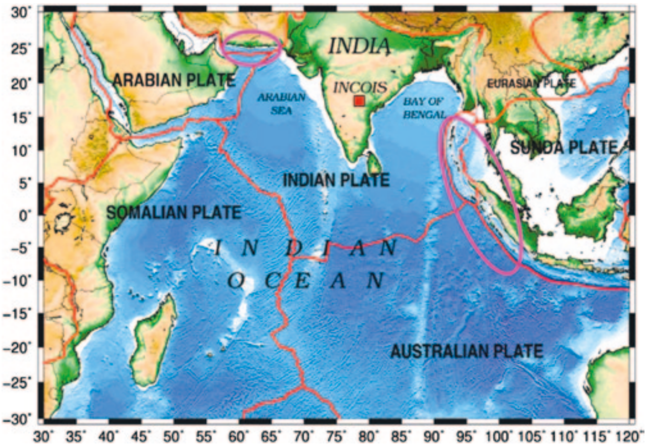

Fig. 5.2 Regional tectonic setting of the Indian Ocean. The location of ITEWS at INCOIS, Hyderabad is shown by a red square in the map of India. Two source regions capable of generating tsunamigenic earthquakes (Makaran and Sumatra–Andaman regions) are shown by pink ellipses (modified after Kumar et al. 2012a)

2 h or more traveltime away from the two tsunamigenic earthquake sources for India. To reduce/avoid false alarms, under ITEWS, ocean-bottom pressure recorders are placed to cover the two tsunamigenic zones.

Modeling at ITEWS

For estimating the possible tsunami traveltime and run-up heights at various locations, ITEWS uses the TUNAMI-N2 model of Imamura (2006). The model has been customized for the Indian Ocean. The computation is based on earthquake parameters and assumes maximum slip at the fault plane. A large data base of pre-run models has been created at the computation center. The data base has the surge heights and traveltimes of about 1800 points on the Indian coast. This helps in providing early warnings.

Decision support system at ITEWS

To pick up the closest scenario for an earthquake, a dedicated decision support system (DSS) has been developed at ITEWS (Fig. 5.3). This helps in assessing tsunami generation, the amplitude and the time of arrival at various locations in the Indian Ocean.

5.6 Assessment of a Tsunami Hazard on a Global Scale

Figure 5.4 (Løvholt et al. 2012) provides a global tsunami hazard overview. As can be noted from this figure, several areas in the vicinity of the Pacific seismic belt and areas in the vicinity of the Java-Sumatra seismic belt fall into the category where tsunamis exceeding heights of 5 m could occur. Løvholt et al. (2012) also pointed out areas for which adequate information is not available. In another

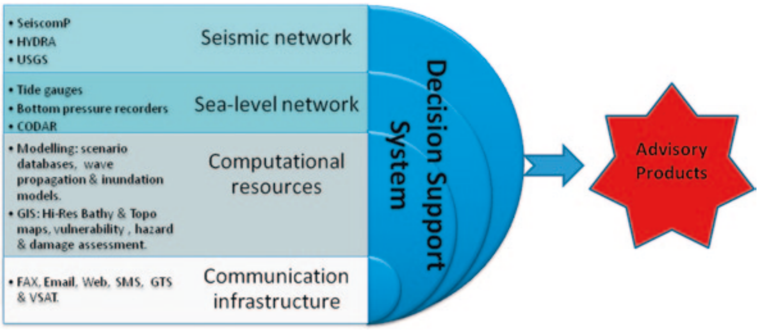

Fig. 5.3 Typical components of an end-to-end tsunami early warning system (after Nayak and Kumar 2011)

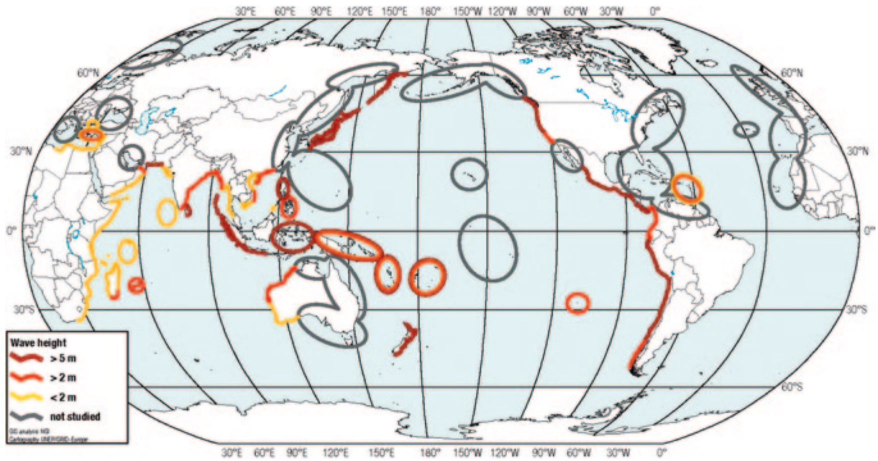

Fig. 5.4 The global tsunami scale hazard map. From the Global Assessment Report (UN-ISDR, 2009). After Løvholt et al. (2012)

interesting diagram (Fig. 5.5), the population living in areas that are tsunami prone in various countries is shown. Indonesia has more than 5 million people in tsunami prone areas followed by Japan. Another interesting diagram (Fig. 5.6) shows the absolute and relative GDP in tsunami prone areas.

5.7 Indian Tsunami Early Warning Center and the 11th April, 2012 Mw 8.5 Earthquake

An earthquake of Mw 8.5 occurred on April 11, 2012 at 08.38 Universal Time, with the epicenter at 2.40°N, 93.07°E and a focal depth of 10 km (Fig. 5.7). This was followed by another earthquake of Mw 8.2, with the epicenter at 0.87°N, 92.49°E

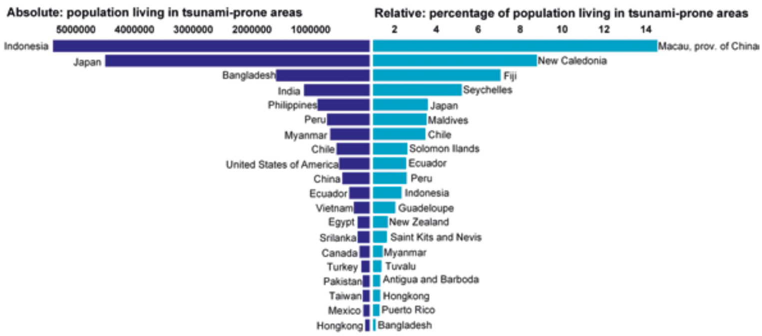

Fig. 5.5 The total and relative number of people exposed to tsunamis for a return period of about 475 years (after Løvholt et al. 2012). Here the risk in Bangladesh is shown as relatively high, however, new analysis of the tectonics and seismogenesis of the earthquakes in the region suggests a much lower risk to tsunamigenic earthquakes (Gupta and Gahalaut 2009 and Gahalaut et al. 2013)

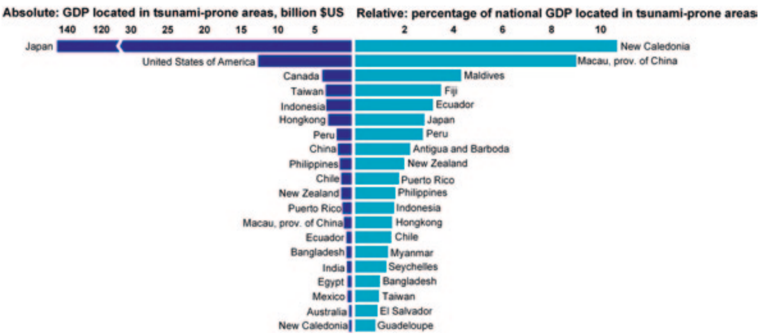

Fig. 5.6 The total and relative GDP exposed to tsunamis in some selected countries (after Løvholt et al. 2012)

on the same day at 10.43 Universal Time and also with a focal depth of 10 km. Both these earthquakes were located close to the epicenter of the devastating Mw 9.1 earthquake of 26th December 2004 (Fig. 3.1). ITEWS detected the first Mw 8.5 earthquake within 3 min 52 s of its occurrence and issued a necessary first advisory within 8 min from the origin time of the earthquake. The use of pre-run model simulations and the standard operation practice (SOP) at ITEWS placed only 3 zones in the Nicobar Islands under warning, necessitating movement of the coastal population to higher grounds (Kumar et al. 2012b). The Andaman Islands and the east coast of India were placed under 'Alert' status meaning threat and clearance of beaches only. These timely advisories avoided unnecessary panic and the evacuation of a large population as happened on March 28, 2005 after the Mw 8.5 Nias earthquake in the same region. The earthquakes generated a small ocean-wide tsunami that was no threat (Fig. 5.8). This clearly demonstrates the utility of ITEWS.

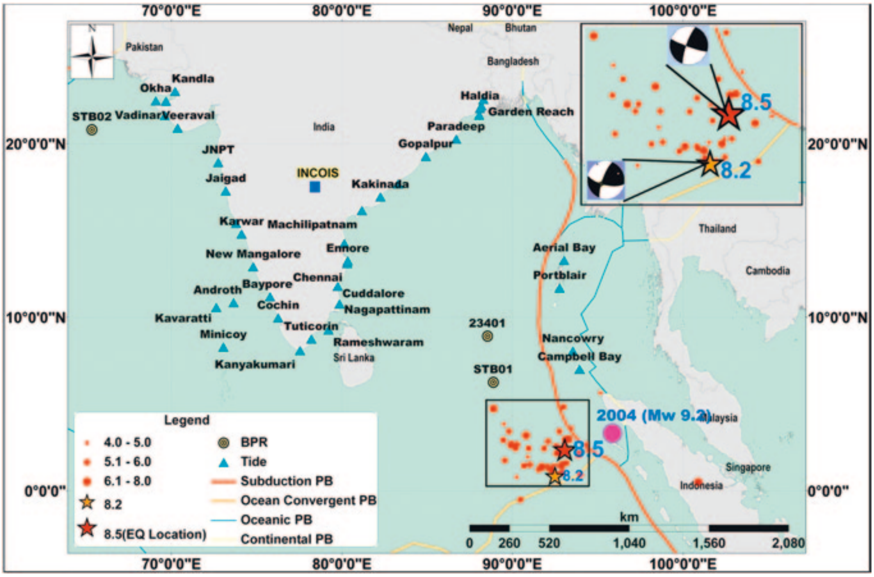

Fig. 5.7 Location of the earthquake of magnitude 8.5, its largest aftershock of magnitude 8.2 and other small aftershocks on 11 April 2012 as well as sea-level station locations (after Kumar et al. 2012b)

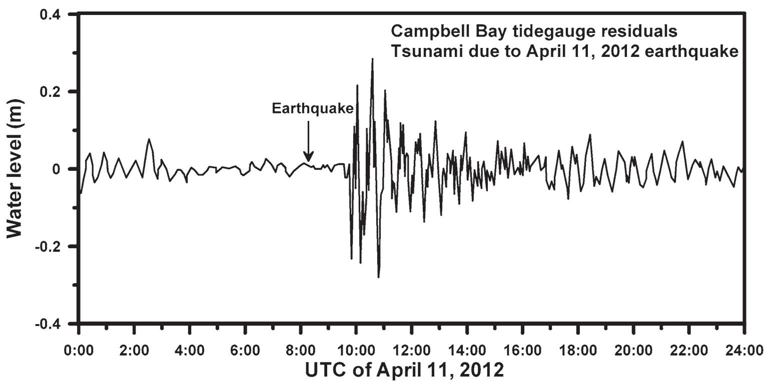

Fig. 5.8 Tsunami record at Campbell Bay (Great Nicobar island, India) tide gauge, about 500 km north of April 11, 2012 earthquake (after Nayak and Kumar 2011)

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