

Tsunami: the Killer Wave - that Struck the Asian Coasts on 26th December, 2004

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Abstract

On 26th December, 2004, an earthquake of M (magnitude) 9.3 on the Richter scale hit the Indian Ocean along the Sunda Trench. This was the second largest earthquake in modern history. The earthquake generated a Tsunami that devastated coastal areas of 12 countries and the global ripples were so widespread that it caused tidal disturbances in North and South America. The article presents a complete report on the event and discusses certain issues connected with the Tsunami. An attempt has also been made to analyze why there had been such a variation in the magnitude of devastations in different coastal localities. As an aftermath of this Tsunami, the Indian government is taking an initiative to install a Tsunami Warning System along the Indian Ocean, which will be in operation from 2007.

Introduction

A faint roar from the distant sea that gets louder every second, and the sheer drop in the sea water level were unusual. Though sadly no one was aware of nature's hurried and desperate attempt to warn the people of incoming danger that was going to engulf the entire coastal zone of South East Asia.

December 26, 2004 will be a day that will always remind us of how helpless we are against the wrath of nature!!

As usual, morning walkers came out on the beach for a stroll, groups of children were excitedly playing cricket, and fishermen had started out to the sea with the promise to return with big a catch and womenfolk with their children were attending to their early morning chores. Suddenly, without warning, wave after wave of great ferocity blasted the peaceful surroundings, taking the people

completely unaware, swallowing everything on the way, leaving behind hundreds and hundreds of miles of coastal areas into rubbles, in just a few minutes.

Tsunami, the killer wave had struck!

The wave that challenges a jet plane in speed

The height that rivals the tallest building in the world

And the force, that can destroy hundreds of miles of coastal areas in minutes.

That is TSUNAMI the killer wave.

The Wave of Fury: Sumatra Earthquake on 26th December, 2004

The Indian Ocean, in the vicinity of Sumatra was jolted by a great earthquake of 9.3 on Richter scale in the morning of 26th December 2004. This was the second largest earthquake ever recorded in recent modern

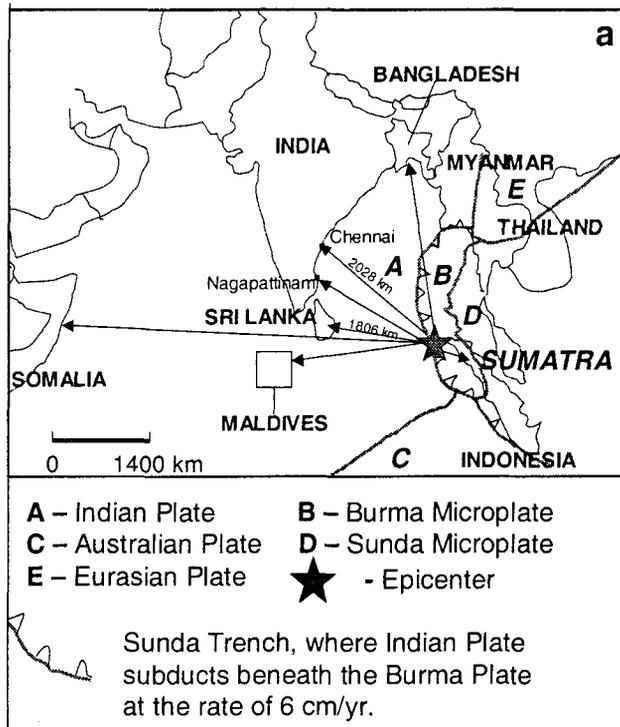


Fig.1a

The Figure depicts the epicenter of the earthquake of 26th December, 2004 and the plate junction along the subduction boundary in the Indian Ocean. The arrows indicate the distance of some affected locations.

history of the Earth. Reports indicate the origin time of the event to be at 06 hours 28 minutes (IST). The epicenter was located at 3.70 N & 950 E. The duration of the earthquake signal lasted for three hours at the Central Seismic Station (Kolar Gold Field observatory, which was established in 1909 for the benefit of Kolar Gold Field, located within 2210 km from the epicenter (Srinivasan 2005). Nature's fury in the process unleashed a terrible calamity that swept the shores of vast coastal belts fringing the Indian Ocean in the form of monstrous Tsunami waves, induced by this megathrust earthquake. The earthquake was

followed by several aftershocks of lower magnitude, which are still continuing. More than 150 shocks exceeding magnitude 5 have already been recorded, the most notable being an earthquake of magnitude 7.3 off the coast of the Great Nicobar (Fig 1b).

There was widespread damage and loss of property and human lives as the Tsunami hit the Andaman and Nicobar group of islands and later hit the west coast of India. The total death toll is estimated to be 2,30,000 in Indonesia, Sri Lanka, India, Thailand and many other regional countries.

Causes of the Event

The region where the earthquake had occurred on 26th December is a tectonically active plate junction where Indian Plate, Eurasian Plate, Australian Plate, Burma Micro plate and Sunda Micro plate are constantly pushing each other, generating a massive stress along the plate boundaries (Fig1a).

Immediately after the earthquake, the United State Geological Survey (USGS) provided the following earthquake report

"The devastating megathrust earthquake of December 26, 2004, occurred on the interface of the India and Burma plates and was caused by the release of stresses that develop as the India plate subducts beneath the overriding Burma Plate. The India Plate begins its descent into the mantle at the Sunda Trench, which lies to the west of earthquake's epicenter. The trench is the surface expression of the plate interface between the Australia and India plates, situated to the southwest of the trench, and Burma and Sunda plates, situated to the northeast".

"In the region of the earthquake, the India Plate moves toward the northeast at a rate of about 6 cm/yr relative to Burma Plate. This results in oblique convergence at the Sunda Trench. The oblique motioned is partitioned into thrust-faulting, which occurs on plate interface and which involves slip directed perpendicular to the trench, and strike slip faulting, which occurs several hundred km to the east of the trench and involves slip directed parallel to the trench. The December 26 earthquake occurred as

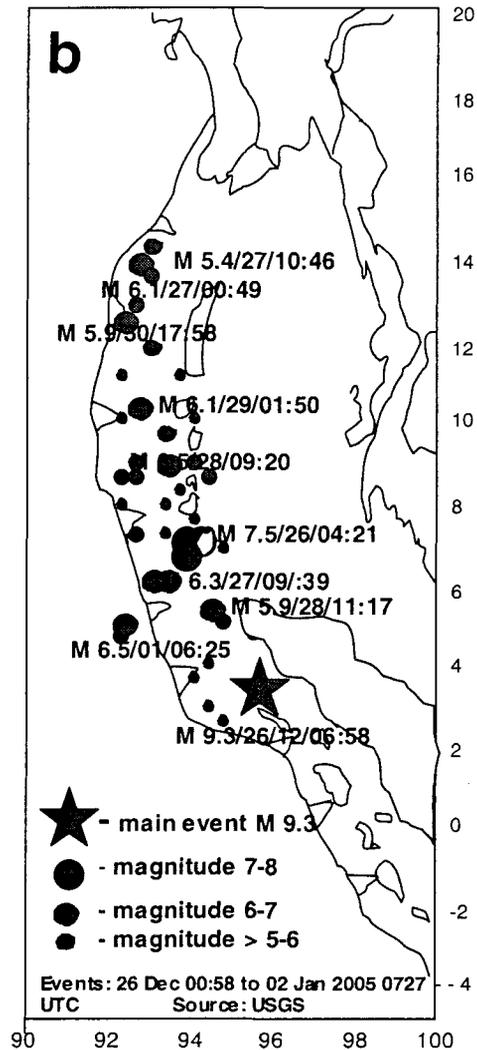


Fig.1b

The timings and magnitudes of the aftershocks of the main event.

the result of thrust-faulting. The depth of the focus of the earthquake was 30 km from the surface".

"Preliminary locations of larger aftershocks following the megathrust earthquake show that approximately 1200

km of plate boundary slipped as a result of the earthquake. By comparison with other large megathrust earthquakes, the width of the causative fault rupture was likely over 100 km. From the size of the earthquake, it is likely that the average displacement on the fault plane was about 15 m. The sea floor overlying the thrust fault would have been uplifted by several meters as a result of the earthquake".

A Los Angeles release dated 28th December 2004, reports that the Sumatra Earthquake that unleashed deadly tidal waves on Asia was so powerful that it made the Earth wobble on its axis and permanently altered the regional physiographic map. Small islands are believed to have moved to the southwest as much as 20 m. The previous reports indicate the magnitude of the quake to be of 9.0 on the Richter scale, placing it as the fifth largest earthquake in history, but the recent updated reports confirmed that the magnitude of the earthquake was 9.3, making it the second largest earthquake in the world. This earthquake has been followed by thousands of aftershocks, more than 250 of them being of magnitude 5 and larger.

Thereafter, ten earthquakes (4 in Sumatra region, 4 in Andaman islands and 3 in Nicobar islands) were recorded between 0628 and 0951 hours. The largest aftershock occurred few hours later off the coast of Nicobar with a magnitude of 7.3. On the morning of 26th December 2004, it was thought to be an independent earthquake. However, it was soon established that it was an aftershock of the Sumatra Earthquake that occurred at 06:28 hour IST. The latest compilation of the aftershock zone (Stein

and Okal 2005-cf. Gupta, 2005 a) indicates that the source of the Mw 9.3 earthquake had a moment of 1.3×10^{30} dyn-cm.. As a matter of fact, this 9.3 magnitude earthquake has broken a sector of plate boundary extending for some 1200 km with a vertical displacement of about 15-20 m. It may be noted that never before an earthquake of this magnitude occurred in this part of the world in human history.

The reason why the Tsunami had created such unusual devastation was not just due to the very high magnitude of the earthquake, but because the earth shaking and faulting time were also a prolonged one. A recent report released by a group of scientists from National Geophysical Research Institute, Hyderabad conveys that the rupture process was in three stages with a total duration of 210 secs. The rupture propagated about 200 km to the northwest from hypocenter (focus) during the first 45 secs in the first stage. The next two stages started about 80 secs and 135 secs (3.5 minutes) after the initial rupture. The second rupture propagated northwestward with 400 km long and final rupture towards southeastward with 350 km long, which generated ultra long period seismic wave. This implies that slow and large dislocation occurred in the second stage (Jose et al, 2005 cf. Srinivasan 2005). The event of 26th December 2004 is summarized in Table 1.

The world's largest recorded earthquakes have all been megathrust events, occurring where one tectonic plate subducts beneath another. Table 2 gives the list of five largest earthquakes in the world in modern history.

Table 1

The Earthquake of 26th December, 2004

Date of the Event	:	26th December, 2004
Time	:	06 hours 28 minutes IST
Epicenter	:	3.70 N & 950 E
Magnitude(M)	:	9.3 on Richter Scale
Hypocenter (Focus)	:	30 km from the surface
Width of the Fault Rupture	:	100 km
Duration of the Rupture Process	:	210 seconds
Source Length	:	1200 km
Nature of Faulting	:	Megathrust Event, resulting in Strike Slip Faulting
Total Displacement	:	15-20 m of the ocean floor
Geographical Location	:	Sunda Trench in Indian Ocean

Source: United States Geological Survey (USGS) Report

Earthquake Energy

Richter magnitude involves measuring the amplitude of the largest recorded wave at a specific distance from the earthquake. While it is correct to say that for each increase in 1 in the Richter Magnitude, there is tenfold increase in the amplitude of the earthquake (because it is logarithmic scale) it is incorrect to say that each increase of 1 in Richter Magnitude represents tenfold increase in the size or effectiveness of the earthquake. A better measure of the size of an earthquake is the amount of energy released by the earthquake. Each increase in 1 in Richter Magnitude represents 31 fold increases in the amount energy released. Thus, a magnitude 7 earthquake releases 31 times more energy than a magnitude 6 Earthquake. A magnitude 9 earthquake releases 31x31x31 times as much energy as a magnitude 6 earthquakes. The Hiroshima atomic bomb released an amount of energy equivalent to a magnitude 5.5 earthquake.

It is estimated that the total energy released by a 9 magnitude earthquake exceeds the total amount of energy consumed in United States in one month or the energy released by the wind of a hurricane over a period of 70 days (<http://www.quakes.bgs.ac.uk/hazard>).

The 26th December 2004 earthquake created Tsunami almost 15 m high which flooded coastlines within a period of 15 minutes to 10 hours after the quake, causing one of the deadliest natural disasters in modern history. The multiple Tsunamis struck and ravaged coastal regions of over 12 countries. Table 3 gives the distance of some affected coastal regions from the epicenter; The first Tsunami hit the east coast of India between 07.30 hrs. IST to 09.00 hrs. and the second one around 11.00 hrs. The waves arrived at Velankai coast around 09.30, Vishakhapatnam at 09.05 hrs. Toticorin at 09.57, Marina Beach, Chennai at 08.00, Cochin at 11.10, and Goa

Table 2

Major Earthquakes in the World in the Last Six Decades

Place/Event	Year	Magnitude(M)
Kamchatka Earthquake	1952	9.0
Andrean Island, Alaska	1957	9.1
Prince William Sound, Alaska	1964	9.2
Sumatra Island	2004	9.3
Chile Earthquake	1960	9.5

Source: <http://www.geophys.washington.edu/tsunami/general/historic/historic.html>

at 12.25 hrs. The affected areas were the coastal regions of Indonesia, Sri Lanka, India, Thailand, Somalia, Maldives, Malaysia, Myanmar, Tanzania, Seychelles, Bangladesh and Kenya (Fig 1). The effect of the Tsunami was devastatingly felt as far away as Somalia and several other countries on the east coast of Africa, 4500 km or more west of the epicenter. The global ripples were so widespread that wave fluctuations passed into the Pacific Ocean and caused tidal disturbances even up to North and South America (ATS, 2005).

What is a Tsunami?

The phenomenon we call Tsunami (soo-HAH-mee) is a series of waves of extremely long wavelength (50-150 km) and long period (20-60 minutes) generated in a body of water by an impulsive disturbance that displaces water. Wavelength is the distance between two crests of a wave whereas wave period is the time lapse between two wave crests passing a point. The term Tsunami was adopted for general use in 1963 by an International Scientific Convention. It is a Japanese word represented by two characters 'tsu' and 'nami', meaning a harbor

wave. The word is both singular and plural (Garrison, 1999). In the past, Tsunami was often referred to as 'tidal waves' by English speaking people and as 'seismic sea waves' by the scientific community. Both these terms were misleading. The term 'tidal wave' was a misnomer as Tsunamis are unrelated to tides. However, Tsunami's impact upon the coastline is dependent on the tidal levels. The term 'seismic sea wave' was not also appropriate as seismic implies an earthquake related wave generation mechanism, but Tsunami can be generated by several other factors apart from an earthquake (though it is most frequent), such as, landslides, volcanic eruptions, impact of cosmic bodies like meteorites, icebergs falling from glaciers and explosions. When this happens, huge amounts of energy are released underwater resulting in quick upward movement of seabed. This leads to pushing up of huge volumes of ocean water forming waves.

Difference between Tsunami and Other Wind Generated Waves

Unlike the wind generated waves, on a local lake or sea coast, Tsunami are shallow water

Table 3

Distance of Some Affected Areas from the Earthquake Epicenter

Direction and Distance from the Epicenter	Name of the Place
257 km to the SSE	Banda Aceh, Sumatra, Indonesia
990 km to the SSE	Port Blair, South Andaman Sea, Asia
1806 km to the ESE	Colombo, Sri Lanka
2028 km to the SE	Chennai, India

waves with long period and large wavelength. The wind generated waves when spawned by a storm, rhythmically roll in and out with a wave period of about 10-15 seconds and wavelengths of 50 to 150 m normally. Tsunami, on the other hand, can have a wavelength of 100-200 km and intervening periods ranging from 20 to 60 minutes. A Tsunami travels at a speed of about 700 km/hr, sometimes exceeding 970 km/hr.

It seems strange to refer to Tsunami-waves with wavelengths of up to 200 km (125 miles) as shallow water waves. Yet half their wavelength would be 100 km (62 miles), and even deepest ocean trenches do not exceed 11 km (7 miles) in depth. These immense waves therefore never find themselves in water deeper than half their wavelength and therefore behave as shallow water waves. A wave is characterized as shallow water wave when the ratio between the water depth and its wavelength gets very small. Shallow water waves move at a speed equal to the square root of product of gravitational acceleration (9.8 m/sec^2) and water depth. The rate at which a wave loses its energy is inversely proportional to its wavelength. Since Tsunami has a very large wavelength, it will lose little energy as it

propagates. Therefore a Tsunami will not only propagate at jet speed but also travel great transoceanic distances with no energy loss.

Earthquake Generated Tsunami

'All Tsunamis are not seismic sea waves, but all seismic sea waves are Tsunamis'.

Not all undersea earthquakes generate Tsunami. To generate a Tsunami, the earthquake should be strong enough to displace the seabed. When a strong earthquake occurs, large areas on the ocean floor suddenly deform and heave upwards or subside displacing the overlying water. Gravity pulls the crest downward, but the momentum of the water causes the crest to overshoot and become a trough. The oscillating ocean surface generates progressive waves that radiate from the epicenter in all directions. Waves also would form if the fault movement were downward. In that case a depression in the water surface would propagate outward as a trough. The trough would be followed by smaller crests and troughs caused by surface oscillation. Half the time a Tsunami's trough arrives first when it strikes a shore. This causes a drop in the sea level prior to a Tsunami hitting a

coast (Garrison 1999). Unaware people venture out to pick up fish and inspect exposed corals or just to look around, to face catastrophic results. An example was at Lisbon, Portugal, on November 1st 1775, when the sea water receded by 15 m prior to a Tsunami. The similar incident happened on 26th December 2004 also in several coastal locations of the affected areas.

Why Many Earthquakes occur in the Ocean?

The Earth's lithosphere is composed of plates that have thickness of 60-250 km, that float on a viscous layer called 'Aesthenosphere'. There are seven major plates and many small ones and they cover the entire Earth's surface. These plates contain both continents and sea floor. These plates have been moving against (subduction zone) and away (spreading zone) from each other. At places, two plates just slide against each other (transform fault). These are known as plate boundaries. Large vertical movements of the Earth's crust can occur at plate boundaries and they are earthquake prone zones. Plates interact along these fault boundaries. In the Pacific Ocean and a part of Indian Ocean, the denser oceanic plates rub or slip under continental plates in a process known as 'subduction'. The movement of these plates is continuous but subduction is episodic. Continuous pressing of the plates generate tremendous stress and when it crosses a threshold the denser one subducts beneath the other in a violent jerk, causing an earthquake. Subduction earthquakes particularly cause Tsunami (Thurman, 1985). The earthquake of 26th December, 2004 in the Indian Ocean was of this type and unusually large in geographical extent

and the resulting Tsunami struck 12 countries as far as Somalia and other countries on the east coast of Africa 4500 km (2800 miles) or more west of Africa (Fig 1a).

Tsunami Generated by Landslides, Volcanic Eruptions and Cosmic Impacts

A Tsunami can be generated by any disturbance that displaces a large water body from its equilibrium position. Submarine landslides which often accompany large earthquakes can disturb the overlying water column and rock slump downslide and are redistributed across the sea floor. Similarly a violent sub-marine volcanic eruption can create an impulse that uplifts the water column and generate a Tsunami. The cosmic-body impacts disturb the water from above, as momentum from falling debris is transferred to the ocean to which debris falls. Generally speaking, Tsunami generated from these mechanisms dissipates quickly and rarely affect coastlines distantly located from the source (Garrison, 1999).

Lituya Bay, Alaska was struck by a huge landslide generated Tsunami, following an earthquake, on 9th July 1958. The earthquake induced a rockslide, generated a 525 m (1722 feet, largest Tsunami recorded) splash (higher than Teipei 101, the tallest building in the world) immediately across the bay, razing trees along the bay and across La Chausse Spit before leaving the bay and dissipating in the open waters of Gulf of Alaska (Garrison, 1999; ATS, 2005).

On 27th August 1883, an enormous volcanic explosion of Krakatoa in Indonesia generated 35 m (115 feet) waves that destroyed 163 villages and killed more than

36,000 people in Indonesia and India (Thurman 1985; Garrison, 1999).

Researchers have found signs of a huge wave, perhaps as high as 91 m (300 feet) that crashed against the Texas Coast 66 million years ago. It may have been caused by a comet or asteroid striking the Gulf of Mexico near Yucatan Peninsula. The wave scoured the floor of the gulf, picked up sand, gravel and shark's teeth, and deposited the material in what is now Central Texas (Garrison, 1999). Some scientists attribute the mass extinction of dinosaurs to this event.

Behavior of a Tsunami as it approaches land and strikes a coast

Once a Tsunami is generated in the open ocean, its steepness (ratio of height to wavelength) is extremely low. This lack of steepness, combined with wave's very long period, enables it to pass unnoticed beneath ships at sea. A ship on the open ocean that encounters a Tsunami with a 16 minute period would rise slowly and imperceptibly for about 8 minutes to a crest only 0.3-0.6m (1 or 2 feet) above average sea level. It would then ease into the following trough 8 minutes later. With all the wind waves around, such a movement would not be noticed (Garrison, 1999; Thurman 1985; Gross 1982).

As the Tsunami leaves the deep water of open sea, and propagates into the more shallow waters near the coast, it undergoes a transformation. It travels faster in deeper waters and approaching shore, it slows down and rises upwards. It is the sharp rise of the ocean floor near the coast that slows the bottom of the wave while the top keeps moving at the original speed. A Tsunami whose height was less than a meter in the

open sea becomes taller than a house near shore and weighs millions of tons. The Tsunami's energy flux, which is dependent on both its speed and height, remains constant. Consequently, its speed diminishes as it travels into shallower waters but its height grows.

When a Tsunami finally reaches the shore, just like other water waves, it begins to lose energy as it rushes onshore. Part of the energy is reflected offshore and the balance shoreward propagating wave energy is dissipated through bottom friction and turbulence. Despite these losses, a Tsunami still reaches the coast with tremendous amounts of energy.

The earthquake off the coast of Sumatra heaved the ocean floor to create Tsunami waves traveling at 750-800 km/hr in all directions. As the Tsunami approaches the coastline the speed reduces, depending on the distance from point zero, to 50 to 60 km/hr in shallow waters but its height grows into a wall of water 10 to 30 m high. The coastal areas nearer the area of source of Tsunami get a higher impact force where speed could be over 700 km/hr. Indira Point, a 100 square km island which was the southern most point of our country and located 51 km from point zero bore the full brunt and has been washed off the map. Tsunamis have great erosional potential, stripping beaches of sand that may have taken years to accumulate and undermining trees, coastal vegetation and foundations of structures (ATS, 2005).

The first wave in a Tsunami may not be the largest in the series of waves. One coastal area may see no damaging wave activity while in another area destructive waves can be large and violent. It can be evident from the 26th December, 2004 Tsunami that had

the maximum devastating effects on Nagapattinam and Cuddalore in Tamil Nadu while areas in their vicinity had a miraculous escape. Tsunami may reach a maximum vertical height onshore above sea level, called run-up height, of 30 m (98 feet). The only notable exception is the Lituya bay Tsunami in Alaska in 1958 which produced 525 m wave (ATS, 2005).

What factors determine the height of a Tsunami when it strikes a coast?

There are several factors that are responsible for the height of a Tsunami when it finally reaches a coast. We are aware that there have been earthquakes of lesser magnitude but caused more devastation in the coastal zones and vice versa. Following is the list of the factors that play a role in deciding the size of a Tsunami:

Displacement of the water and formation of the initial wave will be dependent on

- a. Magnitude of the earthquake
- b. Depth of the focus of the earthquake
- c. Rupture time
- d. Nature of the faulting, such as; strike slip, dip slip, area and height of the sea floor displacement and velocity of the displacement.
- e. Sea floor lithology of the earthquake zone, which will influence the nature of faulting (extent, height etc.).
- f. Coincident slumping of sediments
- g. Secondary faulting
- h. Depth of the ocean water column above the faulting zone

- i. Efficiency with which energy is transferred from Earth's crust to water column

Once the wave is generated, several other factors come into play to control wave's direction and destructiveness as they strike the coast, the major ones are:

- a. Distance of the coast from the epicenter
- b. Bathymetric configuration
- c. Characteristics of the shoreline (straight, indented, bay & headland, sheltered etc.)
- d. Width of the continental shelf
- e. Steepness of the continental slope
- f. Angle of incidence of the wave/
Orientation of the coast with relation to the wave path
- g. Tidal level when the wave arrives
- h. Presence of vegetation/mangroves/
corals
- i. Presence of estuary
- j. Creation of shadow zone, etc.

The ultimate energy and the runup height of a Tsunami will be the result of a combination of the factors listed above. Keeping these factors in mind, we need to evaluate why certain areas were affected more than others in case of the December 26th Tsunami.

However, effects of some factors cannot be measured directly, even though it is certain that they have contributed to the overall effect of the Tsunami in some way or other. Two of these factors can be that;

The United Kingdom Royal Hydrographic Survey Ship has been using SONAR

to map the sea bed. On the fateful day of 26th December, 2004, the Royal Ship named HMS, SCOTT had mapped the ocean floor of the earthquake zone and the image detected a huge scar which runs for several miles on the under ocean mountain on the edge of Burma Plate. Comparison of the images indicates that this scar was induced by the said earthquake. Huge volume of sediments slumped from the ranges and introduced to nearby under water streams. If that is so, the possibility of the triggered effect of the landslide on the wave height cannot be overlooked.

Tsunami is a long crested fast moving wave, which travels transoceanic distances in just a few hours. Therefore during its traverse, coriolis force would have deflected it to the right from its path (in the present situation), hence also played some role in influencing the direction of the waves.

Why some areas suffered more while some were spared? (Why Nagapattinam and not Bangladesh?)

After the initial shock of the catastrophic event, the first question that came to my mind was 'why was there such a great variation in the magnitude of devastation in different coastal locations?' In the following months some issues of the Journal of Geological Society of India published notes and articles on the topic and this same question was put forth by other geologists also (eg. Radhakrishna, 2005; Ballukraya, 2005; Subrahanyan et al, 2005; Raval, 2005). The devastating effects of the Tsunami were felt up to the African coast and beyond to the west of the epicenter whereas coastlines, that are much closer to the epicentre, such as Myanmar, Bangladesh

or Singapore have escaped the calamity with very little casualty. An attempt has been made in the following paragraphs to evaluate the probable reasons for the difference in the magnitude of the wave's ferocity in different coastal locations.

A. Bangladesh & West Bengal

1. The Tsunami wave did not radiate from a point source but from N-S trending narrow zone of 1200 km fault rupture zone. Thus the greatest strength of the Tsunami waves was in the East-West direction. Bangladesh and West Bengal are to the north of the epicenter where the wave energy was the least.
2. Every year several tons of sediments have been brought down by Ganga-Brahmaputra system and deposited in the Bay of Bengal to form the largest submarine fan in the world, known as 'Bengal Fan'. This underwater fan offered resistance to the Tsunami force. Satellite pictures reveal that the Ganga sediments are carried all the way from the Bengal Delta to several thousands of km down to south of Sri Lanka. The water that carries these sediments may be denser than the sea water by virtue of the charged sediments and southward flowing sea water may have a great deal of energy in itself. They therefore can offer a hydrodynamic force resisting the flow of the Tsunami northwards (Mahadevan, 2005).
3. When the Tsunami wave encounters a sudden steep slope (as in case of a straight and steep continental slope) the transfer of the wave's kinetic energy to potential energy is abrupt and hence the

wave suddenly increases in height. The nature of the indented coastline with deltas and mangroves that are present in these coastlines would not have provided an ideal situation for the wave to generate high energy.

B. Myanmar

1. Orientation of the coast with relation to the wave path was mainly responsible for a lesser degree of destruction in the region. The angle of incidence of the wave on the coast was oblique in the present case due to the orientation of the coast with reference to the wave path.

C. Singapore

1. Singapore and Malaysia were in the shadow zone of the wave's path. Waves never reached these regions since they were blocked by Indonesia and Thailand.

D. Western Coast of India

1. Tsunami visited the 350 km stretch between Kanyakumari and Cochin and there were manifestations of the surges of the waves to heights of 5 m. The wave reached Goa and was felt at Mumbai Coast also. There were rhythmic rise and fall of the waves like tides in these regions. These waves were not direct waves. The phenomenon called wave diffraction has occurred here (ie, waves go round the object when they are obstructed). The redirected waves from Maldives islands may have also contributed to the diffracted waves (Indian Express, April 2005). But these are non-destructive waves.

E. Diego Garcia

1. Before the waves reached the island, they encountered a NS trending trench close to the coast. Since Tsunami is a shallow water wave, its energy is less in the deeper waters. As the waves crossed the trench, considerable amount of the energy was lost and when they arrived at the shore it became less destructive.

F. Maldives Islands

1. These groups of islands are just one meter ASL and directly on the path of the Tsunami, yet the extent of devastation was much lower than would have expected under the circumstance. Some researchers are of the opinion that the corals were responsible for the dissipation of the wave energy. In what manner corals helped in the dissipation of the waves is uncertain.

G. Nagapattinam and Cuddalore

These two were the worst affected areas on the eastern coast of India. The distance factor was obvious but areas in the close vicinity escaped the calamity. Dr. Radhakrishna in his editorial note (Jour.GSI, Feb.2005) also raised this question. The study of the bathymetric topography of the area reveals that though several questions are still puzzling, it appears that the nature of the waves was bathymetric controlled.

1. These coasts stood directly across the general E-W path of the Tsunami waves.

2. Since the southernmost part of the east coast was sheltered by Sri Lanka, Nagapattinam fell in the direct and shortest distance from the epicenter of the quake, in the eastern coast.
3. The Tsunami hit Sri Lanka a little before Nagapattinam and Cuddalore. By the time Tsunami reached these coasts the redirected waves from the Sri Lanka eastern coast also arrived at the same time at these locations, hence the effect was due to the combined attack. But this does not explain why it did not happen in their vicinity.
4. The width of the continental shelves is narrowest in this part of the eastern coast of India. Here it is less than 100 km as against 300 km in the Bay of Bengal sector. When the wave, traveling at over 800 km/hr hit the Indian Sub-continental shelf, due to the sudden and sharp rise in the level of the ocean bed, the kinetic energy of the wave was transformed into potential energy abruptly. The waves got piled up into a great wall of water, which rushed to the coastline. If the shelf width would have been large as the average width in the Bay of Bengal, the energy of the Tsunami would have been dissipated by the time it hit the coastline. However, in these two areas, the shelf width is narrowest and hence the wave still had a lot of energy by the time it hit the coasts. Similar findings have been reported by the scientists of NIO in a daily newspaper (Indian Express April, 2005).
5. Subramanyan et. al. (2005) is of the view that the typical continental slope characteristics of the area in the vicinity of these two locations may have played a major role in the building up of the waves. By and large, the continental slope is much steeper in the southern Peninsula compared to northern part. The bathymetric contours demonstrate that continental slope is gentlest around Nagapattinam and Cuddalore, bounded by very steep slopes to the north and south. This zone represents a bathymetric window. When the wave strikes the steep continental slopes to the north and south of the area, the wave height shot up. These piled up waves moved along the slope and surged towards the shoreline through this 'bathymetric window' in Nagapattinam and Cuddalore, causing such devastation.
6. Observations of Tsunami cases in different locations occurred in the historical past and recent; reveal that Tsunami's height increase in bays. The reason for this phenomenon has not yet been understood but observations confirm the association. These two stations locate along a sector of coastline whose shape is concave in plan.
7. The bathymetric topography of the region is characterized by a unique geological setting. A triple tectonic junction is located close to this region and eastern end of the Palghat-Cauvery Sheer Zone also lies very close to it. Raval, (2005) felt the need to look into these factors to establish whether the location of this triple junction right at these severely affected areas was just a coincidence or it must have been partly responsible for the wave to generate high energy.

An overall evaluation of the entire scenario demonstrates that some factors had played major roles in causing devastation in certain areas and very little effects on others. Since the destructive path of the present Tsunami was east-west, coastlines that stood in the path felt maximum effect. The width of the continental shelf in general and continental slope angle in particular, were significant factors in deciding the fate of the eastern coastal zone during the event. By and large, the intensity and angle of the waves were topography steered.

Here, it is proper to analyze what will happen if Tsunami hits the western coast of India. The western coast of India is associated with passive plate margin (spreading boundary), hence the earthquake generated along the oceanic ridges are not Tsunamigenic. However, the Kutch fault zone lies within the vicinity. Since the role of continental shelf width plays a significant role in dissipating the wave energy when it hits a coast, the large continental shelf of Mumbai coast may offer a barrier to a Tsunami far away from the shoreline. Hence other factors being equal, the devastating effects of a Tsunami generated by an earthquake in the Arabian Sea may not be as great when it strikes the Mumbai Coast. Another noteworthy feature of the western coast is that for a long stretch of land, the coast is characterized by lateritic plateaux that extend up to the sea. This is in contrast to the vast extent of low gradient alluvial coastal plains of the eastern coasts. Hence the extent of inland inundation could be less in the case of a Tsunami in the western coast compared to the eastern coast.

Need of a Tsunami Warning System in Indian Ocean

The question that crops up is 'isn't it high time that we have a Tsunami Warning System in the Indian Ocean?' This is uppermost in the minds of both common people and scientific communities alike, after the disastrous event. Dr. Radhakrishna (2005) regretfully expressed the failure of our science establishments and institutional unprepared-ness. While the US Geological Survey (USGS) was quick and within two hours of the event announced in their website, the exact location of the earthquake, the time, magnitude and the epicentral depth, the scientific communities in India and official bureaucracy came to know about it watching the TV or hearing on the radio. Dr. Radhakrishna expressed that 'Our science bureaucracy appears to be worse than administrative bureaucracy'. There had been a clear gap of 2-3 hours between Tsunami waves striking Car Nicobar and Port Blair and those devastating Tamil Nadu and the east coast of Sri Lanka! Given our communication facilities, warning alerts could have been sounded for the vulnerable coastal states of India and Sri Lanka to leave the coastal stretches and head for higher ground. This action could have saved many lives.

As an aftermath of the catastrophe, there is strong demand for installation of Tsunami Warning System along the Indian Ocean for the benefit of India and the neighboring countries. Several workshops and seminars had been organized all over the country with senior scientists, officials from Department of Ocean Development (DOD), Department of Space (DOS), National Geophysical Research Institute (NGRI), Geological

Survey of India (GSI), academicians from the universities, legal and medical experts, specialists in social sciences, representatives of student community and general public, participating in the proceedings. The Geological Society of India, Bangalore also took initiatives in organizing several public awareness programs for the officials and school college students in different states. We have already lost several lives. The extent of the misery is beyond the scope of measurement. Yet, it is always better late than never.

How the System Works?

The first rudimentary system to alert communities of an impending Tsunami was attempted in Hawaii in 1920s. More advance systems were developed much later in the wake of 1st April, 1946 and 23rd May, 1960 Tsunamis which caused massive devastations in Hilo, Hawaii.

The United States established the Pacific Tsunami Warning Centre in 1949 and linked it to an International Data and Warning Network in 1965. Around this time, 24 countries around the Pacific setup the Tsunami Warning System. A group of seismic monitoring stations and a network of tide gauges are used for detection. Tsunamis are predicted by various seismologic institutes around the world and their progress is monitored by satellites. Buoys with bottom pressure recorders are installed as communication links to detect Tsunami waves, which in general are not detectable on the surface of the ocean, till they strike the land. Once the monitoring station picks up the Tsunami, the local media warns the population of the danger so that

they can seek higher ground well before the Tsunami arrives. The nations of the Indian Ocean and Atlantic Ocean have not yet participated in the regional Tsunami early warning system like that in the Pacific Ocean. Even though Thailand is a member of the Pacific Tsunami Warning System, they did not pick up the warning signal of the December 26 Tsunami as the ocean buoys upon which the sensors were mounted were on the east coast of the country.

As on date, Tsunami prediction remains an imperfect science. It is possible to determine quickly the epicenter of a large earthquake and probable Tsunami arrival time in the surrounding as well as in the far away coastlines. However, it is almost always impossible to establish whether massive underground water shifts have occurred generating a Tsunami. Many times the detection system gives a false alarm. It is also not possible to predict the destructive capacity of the Tsunami so also its size. For example, the vertical disturbance on the ocean bed infested with mountains are less likely to lead to destructive Tsunami because Tsunami will partially or completely collapse in the middle of the ocean if it encounters obstruction from a mountain on its journey to the coastline. Also, no system can alert people against a sudden Tsunami. For Example, a devastating Tsunami occurred off the coast of Hokkaido in Japan due to an earthquake on 12th July, 1993. The Tsunami struck within 3-4 minutes and most victims were caught while fleeing for higher ground. There have been more instances of this kind.

Feasibility of the System in the Indian Ocean

The idea of detecting Tsunami in Deep Ocean and actually reporting such data in real time is scientifically challenging but feasible. India has the means and technology to establish a Tsunami warning system once the political will is in place. Study of the global earthquake distribution demonstrates that 75% of the earthquake energy is released around circum-Pacific belt, 20% in Alpine Himalayan belt, and remaining 5% through the mid-oceanic ridges and other stable continents. For a Tsunami to hit the Indian coast, it is necessary that a Tsunami-genic earthquake occurs in an area from where Tsunami could propagate to the Indian coast. With experience and available data, two

regions capable of generating Tsunamis are identified (Gupta, 2005 a). One is Java-Sumatra seismic belt extending to Andaman and Nicobar and further north, and the other includes the Makran Coast and extension of 1819 and 2001 Kutch and Bhuj earthquake faults respectively into the Arabian Sea. These are the Tsunamigenic areas which could generate Tsunamis for the rest of the Indian Ocean rim countries.

Destructive Tsunamis strike somewhere in the world at an average of once a year. Although majority of these Tsunamis occur in the Pacific Ring of Fire, it is a myth that Tsunami does not occur in Indian Ocean. There have been reports of at least ten Tsunamis in Indian Ocean (Table 4).

Table 4

Tsunami in Indian Ocean

Date	Event
1st April and 9th May, 1008	A local earthquake generated Tsunami on the Iranian Coast
1952	A large Tsunami hit Dhabol Coast of Maharashtra
16th June, 1819	Rann of Kutch
31st Oct, 1847	Great Nicobar and Car Nicobar
31st, December 1881	Great Nicobar and Car Nicobar
27th August, 1883	Krakatoa Volcanic explosion. Tsunami at Madras and Nagapattinam
1884	Earthquake in western part of Bay of Bengal Tsunami at Port Blair and Dublet
26th June 1941	Earthquake in Andaman Sea. Tsunami at eastern Indian coast
27th Nov. 1945	Earthquake to the south of Kachch. Tsunami with amplitude of 11-11.5 m.
26th Dec. 2004	Earthquake at Sumatra Tsunami affected 12 countries

Source: (Garisson, 1999; Gupta, 2005 b)

(<http://www.geophys.washington.edu/Tsunami/general/historic/historic.html>)

International efforts under the UN auspices for the establishment of Indian Ocean Tsunami Warning Centre on similar lines as the Pacific one are already underway with several agencies, governments and private companies coming forward. India is taking the lead in this effort in view of its location as well as its scientific competence. Since Tsunami does not occur very frequently in Indian Ocean, the importance of developing a system which is robust and does not die out because of non-operation is recognized by the agencies. Therefore the system would be a combination of Tsunami warning system with storm surges which occurs frequently in Bay of Bengal and Arabian Sea. India has the infrastructure and capabilities to develop an early warning system for oceanogenic disasters in Indian Ocean. The Department of Ocean Development (DOD) has also developed data buoys and tide gauges of their own which are of global standard. These were dedicated to the nation on July 27, 2004, by the President of India Dr. A.P.J. Abdul Kalam on DOD foundation day.

The Warning System project cost is estimated at 30 million US dollars (Rs. 140 crores) and is expected to be complete by September 2007. The nodal agency of the project is the Department of Ocean Development through its institutions. The partners in the project are Department of Science and Technology, (seismic stations and detection of earthquakes, coastal topography), Department of Space (communication between seismic stations, sensor selection for Bottom Pressure Recorder, communication from Bottom Pressure Recorder), Council for Scientific & Research & Department of Science and

Technology (research inputs in geophysics, ocean sciences). Each of this institute will look after its specific tasks. The product of the Indian initiative would be shared through the Indian Ocean-Global Ocean Observation System (IO-GOOS) partners (Gupta, 2005 a).

The system will cover two known Tsunamigenic zones that affect Indian Ocean. It is an end-to-end system that is scientifically and technically sound. It is a part of the 'Agenda for 2005' announced by the Prime Minister of India. There is synergy of Scientific Departments in implementation. There is excellent technological and institutional base to realize the system and operate on 24x7 bases. There is commitment at the highest level in Government of the system. The key element will be in place by March 2006 and the entire system will be operational by September 2007.

Conclusion

Scientific communities in India have woken up after this horrifying incident, but those who perished had to pay dearly for it. Simple facts about the phenomenon could have saved many lives, such as;

- If the sea recedes below the normal level of the 'lowest low tide level' and stays like that for quite some time, one should understand that the Tsunami has already hit the coast. Only the trough has arrived before the crest. (It should be remembered that it does not occur every time.) Sometimes a Tsunami can come without the sea receding also. It depends on the nature of the faulting of the sea bed at the earthquake zone).

- If you are in a boat and hear a Tsunami warning alert, rush to the deeper ocean instead of trying to reach the coast, because this wave is harmless in the deep ocean but destructive on the shore.
- Never go to witness a Tsunami wave. If you see the wave, it may be too late to escape because Tsunami travels faster than you can run.
- Try to find a higher ground as soon as you hear a Tsunami warning.

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