Effects of the December 2004 Indian Ocean Tsunami on the Indian Mainland

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The 26 December 2004 tsunami significantly affected the coastal regions of southern peninsular India. About 8,835 human lives were lost in the tsunami in mainland India, with 86 persons reported missing. Two reconnaissance teams traveled by road to survey the damage across mainland India. Geographic and topological features affecting tsunami behavior on the mainland were observed. The housing stock along the coast, as well as bridges and roads, suffered extensive damage. Structures were damaged by direct pressure from tsunami waves, and scouring damage was induced by the receding waves. Many of the affected structures consisted of nonengineered, poorly constructed houses belonging to the fishing community.
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MAINLAND AREAS SURVEYED

The Great Sumatra earthquake of 26 December 2004 did not cause shaking-induced damage to the mainland of India, but the consequent Indian Ocean tsunami had a significant effect on the southern peninsular region of India (Jain et al. 2005). The tsunami severely affected the coastal regions of the eastern state of Tamil Nadu, the union territory of Pondicherry, and the western state of Kerala. Two reconnaissance teams undertook road trips to survey the damage across mainland India. One team traveled from the Ernakulam district in Kerala, then continued south along the west coast to the southernmost tip of mainland India (Kanyakumari) and up along the east coast to Tuticorin. The coastal journey was then resumed from Nagapattinam, moved northward, and concluded at Chennai. The second team traveled from Vishakhapatnam in Andhra Pradesh along the coast down to Chennai (Figure 1). This paper is based on observations made during these trips.

SEISMICITY OF THE REGION

The southern peninsular region comprising Kerala and part of Tamil Nadu on the west coast and the rest of Tamil Nadu, Andhra Pradesh, and Pondicherry on the east coast is a region of low-to-moderate seismicity. The area lies in the Stable Continental Region, which is not believed to be exposed to the hazard of strong earthquakes. The strongest known earthquake in the region ($M=6.0$) occurred on 8 February 1900 near Coimbatore and had a maximum intensity of VII. There was an earthquake of magnitude

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Figure 1. Reconnaissance team survey routes covering the mainland. (Map courtesy of C. V. R. Murty)

M = 5.8 on 31 March 1843 in Bhadrachalam, Andhra Pradesh. Earthquakes of magnitude M = 5.5 (1959) and M = 5.2 (1967) occurred at Ongole, Andhra Pradesh. Figures 2 and 3 indicate the broad shield sources and tectonic features of the peninsular shield of India (Rao 1970, Reddy 2004).

In the last decade, the area has experienced earthquakes of magnitude 5.0 and lower. The most recent significant earthquakes were M = 5.0 (2000) and M = 4.8 (2001), both of which occurred in the same area south of Idukki in central Kerala.

TSUNAMI HISTORY

Prior to 26 December 2004, there was no known record of tsunamis on the southwest coast of India. The west coast experienced a tsunami due to the M = 8.1 earthquake of 27 November 1945 with an epicenter 100 km from Karachi, Pakistan, but the effects were felt only up to Karwar, 250 km north of the Kerala border. The southeast coast, however, has experienced tsunamis earlier. The earliest record dates back to 31 December 1881, when a tsunami 1 m high was recorded in Chennai. It was caused by an earthquake of M = 7.9 below Car Nicobar Island. The August 1883 eruption of the Krakatoa volcano in Indonesia caused 2-m-high tsunami waves in Chennai. On 26 June 1941, an M = 8.1 earthquake occurred in the Andaman archipelago, which triggered a tsunami of about

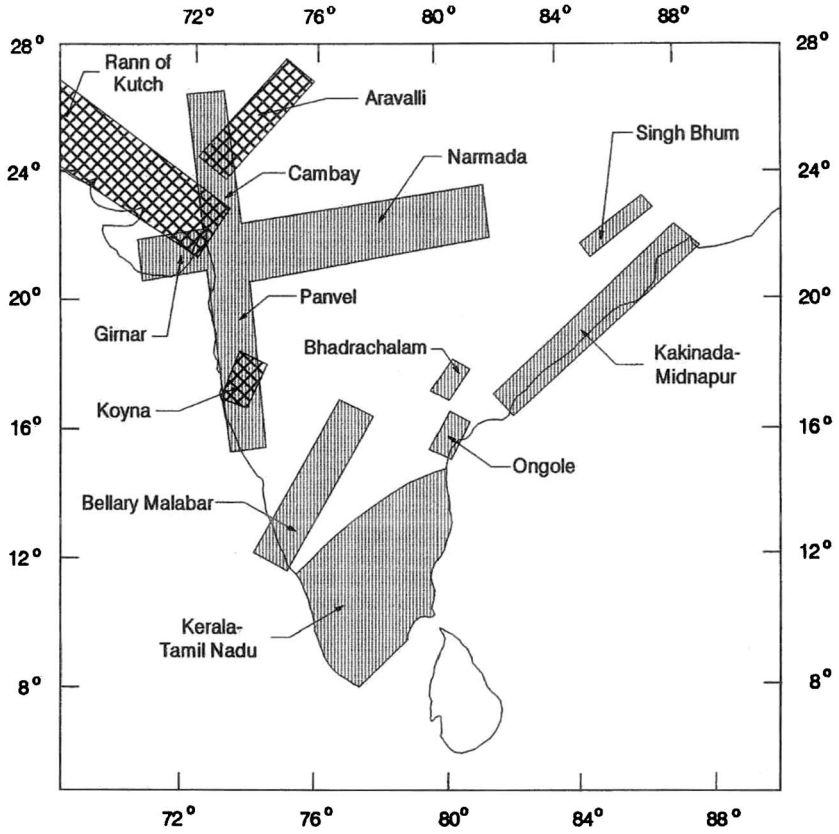

Figure 2. Tentative broad shield sources in the peninsular shield for India (source: I. Gupta).

1 m in the city of Chennai. While some scientists have estimated deaths of over 3,000 people along the east coast of India in the 1941 tsunami, there are no reliable data on the number of deaths, if any, due to that tsunami (Murty and Rafiq 1991, Bilham 2005).

GEOLOGY OF COASTAL MAINLAND INDIA

The structure of peninsular India is complex because of the varied geology, faults, and fractures. More than a third of this area is covered by basaltic flows called the Deccan Trap. The thickness is 2–3 km on the west coast and decreases toward the east. The rest of the peninsula is covered by Precambrian rocks and sedimentation formation of later eras (Figures 2 and 3, Gupta 2005).

The soil along the west coast of Kerala and Tamil Nadu is primarily sandy, underlain by soft clay layers. Further south, away from the coastline, the land slopes steeply upward and is rocky. The coastal strip of southwest Tamil Nadu is rich in minerals. There

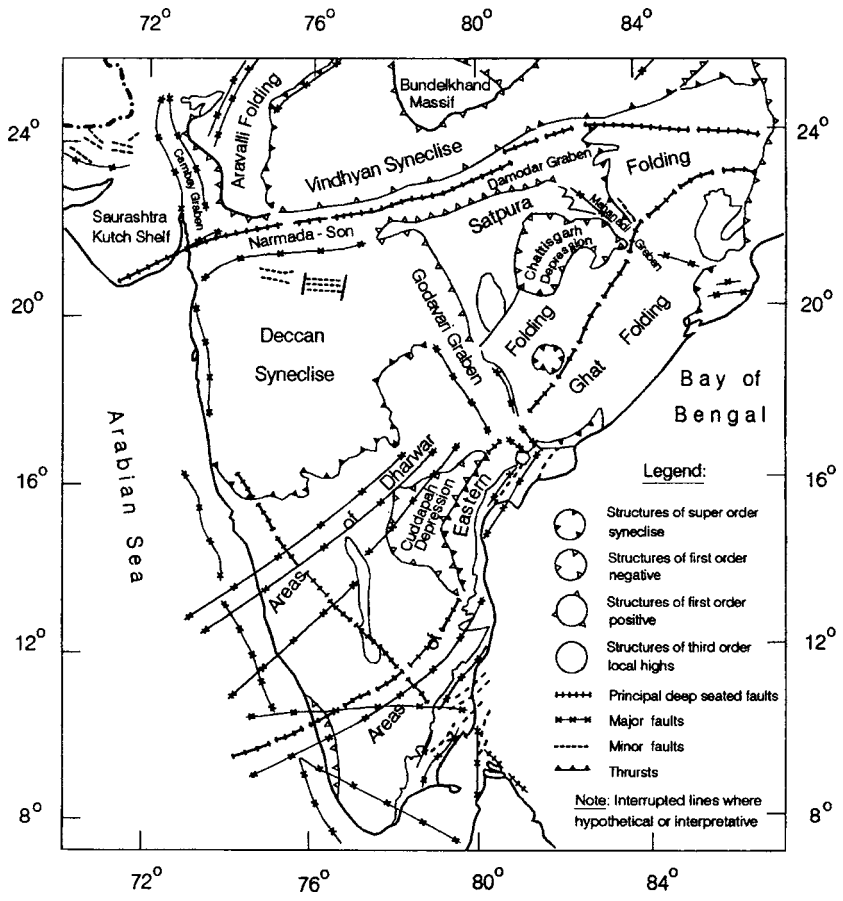

Figure 3. Major evolutionary units and associated tectonic features in peninsular India (source: I. Gupta).

has been significant dredging in the mineral-rich Kanyakumari coast, and this has led to a change in the topology of the area by flattening some areas and making them more vulnerable to a tsunami.

The east coast has rich alluvial soil in the river deltas and along the coast. The other predominant soils in this region are clay, loam, and red laterite. Along the Andhra Pradesh coast, the soil is also rich alluvial with rocky outcrops but, in certain pockets of the delta areas of Godavari, the soil is deep friable, well-drained sandy loam.

WAVE ARRIVAL TIME

The tsunami waves arrived first on the east coast. Details of the tide gauge levels at the ports of Kochi, Tuticorin, Chennai, and Vishakhapatnam are shown in Figures 4–7

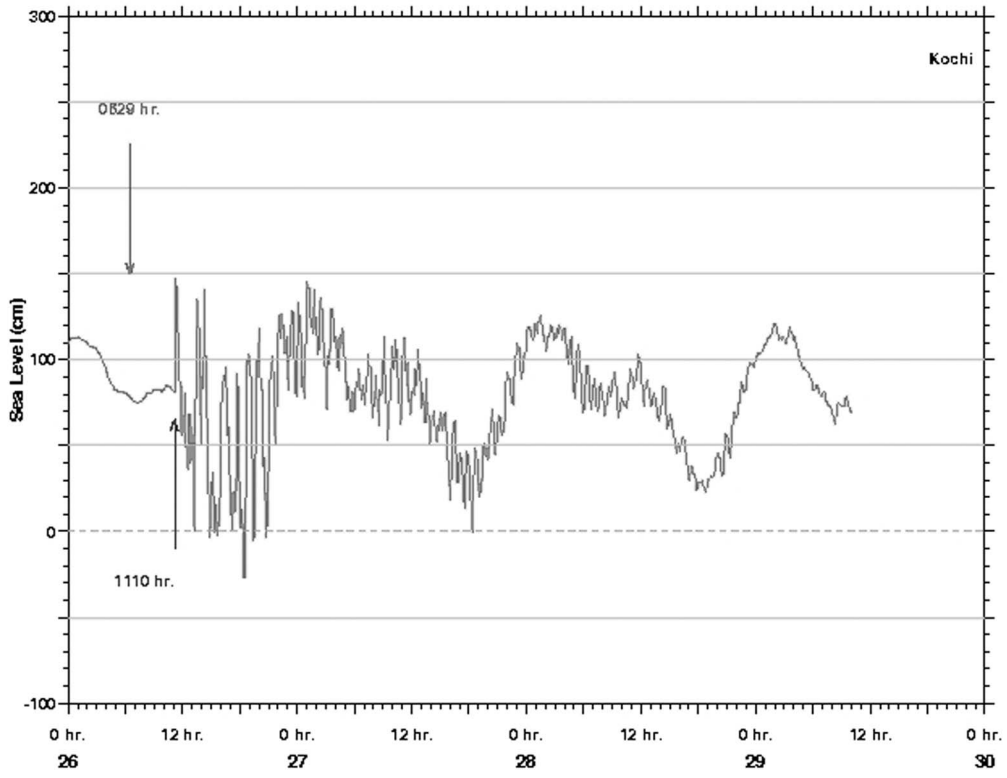

Figure 4. Tide gauge data for Kochi Port (source: NIO).

(NIO 2005), respectively. As can be seen from the tide gauge data, the tsunami waves first reached Kochi at 11:10 A.M., Tuticorin at 9:57 A.M., and Chennai and Vishakhapatnam at 9:05 A.M. (all Indian Standard Time).

Most locations experienced 3–5 waves, details of which are described elsewhere in this paper.

GENERAL FEATURES OF TSUNAMI EFFECTS

The tsunami effects varied greatly across different parts of the coast according to the number of waves experienced, inundation distance and height of the waves, and density of the area—as well as topological and geographical features that made some areas more vulnerable than others (Table 1). The number of lives lost was also influenced by the proximity of habitats to the coastline, exposure to previous disasters, and the local disaster management capability. These are discussed in detail in this paper. The affected areas are discussed in three parts, which are based on their geography:

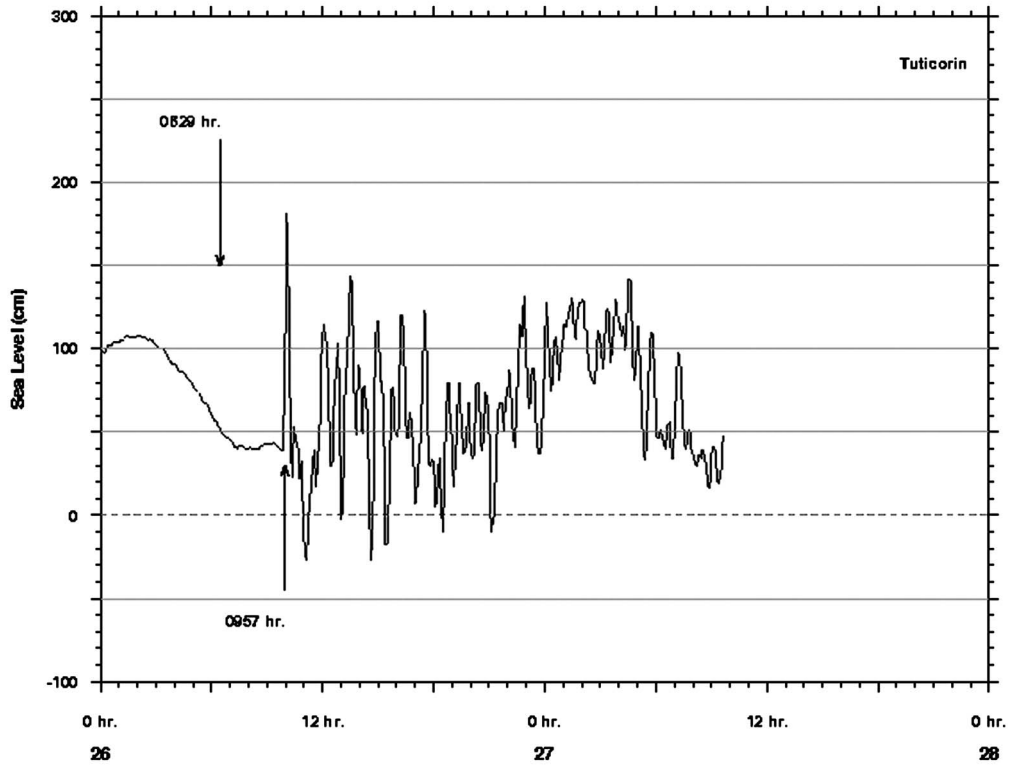

Figure 5. Tide gauge data for Tuticorin Port (source: NIO).

- Southwest coast: this comprises Kerala, which suffered significant damage that impacted the largest number of people of any affected state but suffered relatively lower loss of life, and the Kanyakumari district of Tamil Nadu, which suffered heavy loss of life due, to a large extent, to human-created local topographical features.
- Southeast coast: this comprises the rich alluvial delta region of the Tamil Nadu coast and Pondicherry, which experienced maximum wave heights and recorded the maximum loss of life and damage in mainland India.
- East coast: this comprises Andhra Pradesh, which suffered marginal damage and loss of life.

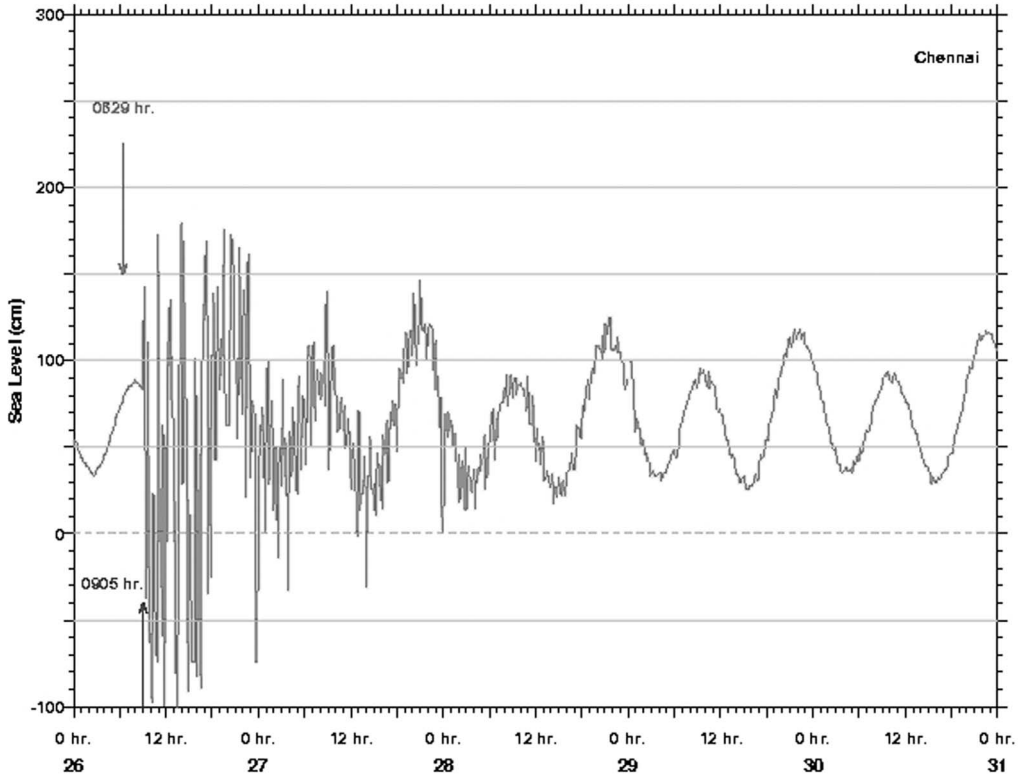

Figure 6. Tide gauge data for Chennai Port (source: NIO).

GEOGRAPHIC AND TOPOLOGICAL FEATURES AFFECTING TSUNAMI BEHAVIOR ON THE MAINLAND

SOUTHWEST COAST OF MAINLAND INDIA

Kerala

The state of Kerala experienced tsunami-related damage in three southern districts, Ernakulam, Allapuzha, and Kollam (Table 2), due to the diffraction of the waves around Sri Lanka (Murty 2005). The southernmost district of Thiruvananthpuram, however, escaped damage. This was possibly due to the wide turn of the diffracted waves at the peninsular tip, thereby missing Thiruvananthpuram.

The coast of Kerala is relatively flat and practically at sea level. Throughout the coastal areas of Kerala, and especially in the affected districts, are long stretches of lakes, lagoons, and ponds connected by a network of canals called "backwaters" (*kayals*). The backwater routes date from centuries ago and have long been used for all trans-

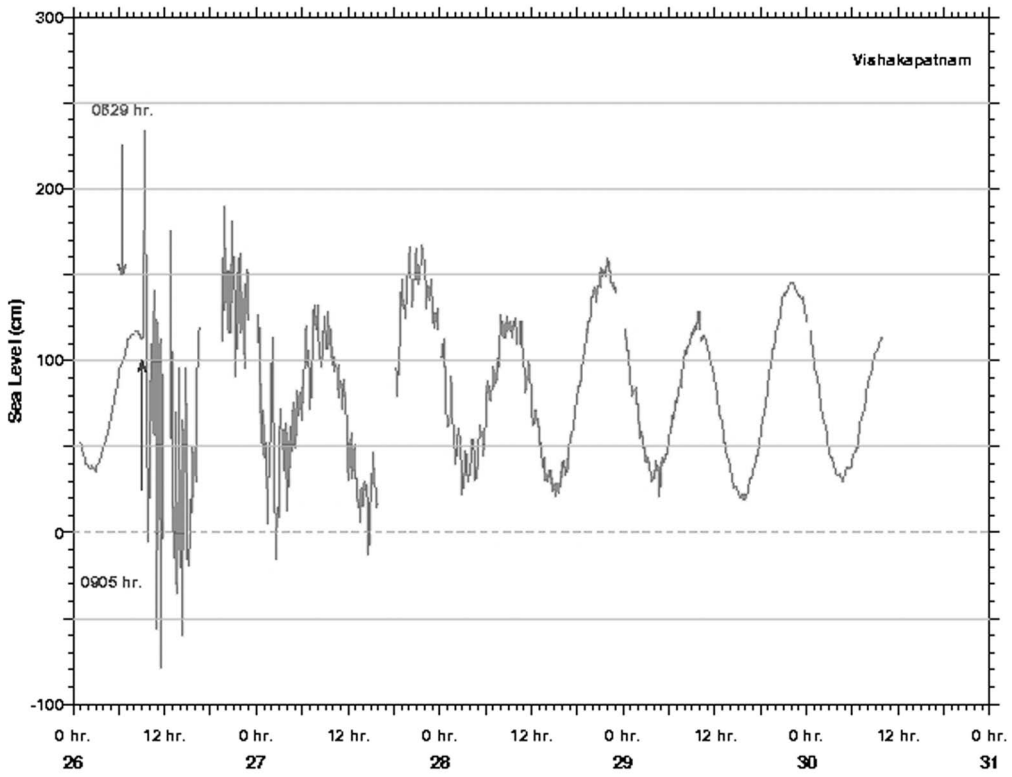

Figure 7. Tide gauge data for Vishakhapatnam Port (source: NIO).

portation needs, in particular for trade in coconut, rubber, rice, and spices. Today, these waterways link remote villages and islands to the mainland.

Major damage in Kerala occurred in two narrow strips of land bound on the west by the Arabian Sea and on the east by a network of backwaters.

Ernakulam District

The northern strip comprises the island of Wypeen north of the city of Kochi in the Ernakulam district. It is about 20 km long and has a maximum width of about 3 km. Edavanakkad is a prominent fishing village in Wypeen Island that suffered maximum damage. Fifty houses were completely destroyed (Figure 8), and 350 houses were damaged in this village, which lost 5 lives. The coast in this area had a seawall along most parts, with openings in the seawall for the passage of boats. Damage due to the tsunami was more intense in the areas that were not protected by the seawall. At Edavanakkad, the seawall was about 100 m from the shoreline and was made of random loose rubble

Table 1. Tsunami effects in mainland India (source: Ministry of Home Affairs)

State or union territory	Coastal length affected (km)	Water penetration into mainland (km)	Average height of tsunami wave* (m)	Max. runup height (m)	Human lives lost, per district		Number of villages affected	Population affected (millions)	Dwelling units lost or damaged
Kerala	250	0.5−1.5	3−5	3.4	131	Kollam	187	1.3	17,381
					35	Allapuzha			
					5	Ernakulam			
Tamil Nadu (west coast)	100	0.2–2.0	3–10	4.5	824	Kanyakumari	376	0.9	128,394
Tamil Nadu (east coast)	800	0.4–1.5	2–10	5	6,051	Nagapattinam			
					612	Cuddalore			
					128	Kancheepuram			
					206	Chennai			
					144	Other			
Pondicherry	25	0.2–2	5–10 (max. at Karaikal)	4	484	Karaikal	33	0.04	10,061
					107	Pondicherry			
Andhra Pradesh	985	0.2–1.0	4	2.2	27	Krishna	301	0.2	1,557
					20	Nellore			
					35	Prakasham			
					23	Other			

* Based on survivors' estimates

Table 2. Characteristics of tsunami waves in Kerala

District	No. of waves	Arrival time of waves	Wave height (m)	Wave travel distance (m)	Inundation height (m)	Special features	Recession of water
Ernakulam	3	First wave at 11:10 A.M., second wave at 1:30 P.M., third wave at 1:45 P.M.	>4	~1,000	2.4	Water level rose from 10:30 A.M.	Water receded about 150 m into sea after first wave; when water receded, it took a lot of sand and scoured roads.
Allapuzha and Kollam	3	First wave at 11:30 A.M., second wave at 1:40 P.M., third wave at 1:45 P.M.	>4	>1,000	3	—	Water receded ~500 m before first wave.

masonry comprising large boulders, some of which were displaced by the tsunami. The houses in Edavanakkad were built about 15 m from the seawall. The plinth height was about 0.6 m from mean sea level.

Allapuzha and Kollam Districts

The other strip most affected in Kerala is a shoestring isthmus south of the city of Allapuzha about 40 km long and extending from Trikunnapuzha in the Allapuzha district to Karunagapalli in the Kollam district. The strip has a maximum width of less than 1 km and is bound by the open coast on the west and Kayanakulam Lake and backwaters on the east. A small opening in the strip connects the lake to the sea. The width of the land strip is less than 0.5 km at many places. As a result, the tsunami waves lashed over the entire strip of land, traveled across the backwaters, and rolled onto the opposite bank.

Two areas that bore the brunt of the tsunami in the region were Arattupuzha in the Allapuzha district and the Alappad *panchayat* in the Kollam district (Figures 9 and 10). These areas are the gatekeepers of the opening where the lake disgorges into the sea. The villages are densely populated (with a density of 2,652 per km^2, versus the state average of 762 per km^2) on both sides of the coastal road that barely separates the lake from the sea. The isthmus has no intermediate bridge connection to the mainland and is connected to it only at the two ends. The area thus has to depend on boats for safe exit in times of emergency. The largest number of casualties (130) in Kerala was reported from the densely populated Alappad *panchayat* (including the villages of Cheriya Azhikkal and Azhikkal). In the village of Arattupuzha in the Allapuzha district, the death toll was 28. The seawall, where it existed, was dislodged and did not exist in many places along

Figure 8. Damaged house in Edavanakkad (photo: A. Sheth).

the north Kollam coast. A wave height of 4 m was reported by the survivors.

The area has a history of floods that occur during the monsoon, especially when heavy rains coincide with high tide. The villagers are thus well trained in quick and safe evacuations, but there was simply no time for evacuation in these densely populated villages when the tsunami arrived. There was, however, no loss of life in villages such as Walia Azhikkal, where rapid evacuation was carried out successfully. After observations of abnormal behavior of the sea, the Kerala police had sounded an alert at 11:30 A.M. to warn people, but it was too late for some villages. The tsunami struck almost immediately afterward.

Tamil Nadu

Kanyakumari forms the southwest district of Tamil Nadu. Unlike the Kerala coast, the Tamil Nadu west coast has flat land at sea level along the north coast in some areas such as Kolachel, where the soil is rich alluvium, but in other areas and further south, the land is mountainous. It slopes steeply upward from the coastline and is rocky. This

Figure 9. Scouring in Allapuzha—houses were 4–15 m from the shoreline (photo: A. Sheth).

was observed at Muttom Beach and at the tip of Kanyakumari. On some beaches such as Sothavilai, there are sand dune formations. Table 3 summarizes the tsunami wave characteristics in Tamil Nadu.

Kanyakumari District

One of the most affected areas in the district was Kolachel and the surrounding villages, located 30 km west of Nagercoil, which is the capital of the Kanyakumari district. The land near the coast is flat and is at sea level, and no seawall was visible. Water traveled inland by more than 300 m. New streams and estuaries were carved out by incoming waves (Figure 11). When the waves receded, they deepened these features further by scouring. The town and neighboring villages recorded more than 500 fatalities, of which more than 50% were children. The wave height was reported to be 5 m, and the runup height was 2.6 m (Figure 12). A large number of deaths were triggered by the human-created topology of this town. Harbour Road, which experienced the maximum number of casualties, had a long, open, dry channel called the Ananda Victoria Marthandam (AVM) Canal (Figure 13). This canal is more than 2.5 m deep and 6 m wide, running parallel to the shore. The canal was meant to bring in fresh water but was not in use. Besides this canal, there were numerous open trenches laid parallel to each other (Figure 14) that catered to the special needs of the coir-making industry, which is the main means of livelihood in this region besides fishing. These trenches were about 1.5–2 m deep, 15 m long, and 4 m wide. They were used to soak the coconuts and separate the

Figure 10. Destruction in the Allapad *panchayat*—a concrete block house with a reinforced concrete (RC) roof (photo: A. Sheth).

husk for making coir. When the tsunami waves surged into the town, the AVM canal and these trenches became death traps. More than 300 bodies were recovered from the slush of the trenches and channel. The masonry retaining wall of the jetty at Kolachel was badly damaged.

A few kilometers from Kolachel is Muttom Beach, a popular tourist spot in Tamil Nadu often used as a romantic backdrop by the bustling Tamil film industry. This area did not suffer damage, because it is more than 50 m above mean sea level. A few tourists who had gone down to the sea to watch the tsunami were washed away in the wave at 10:30 A.M.

The Mannakudi *panchayat* near Kolachel was a cluster of villages, including Melamanakudi, which was badly affected. A 160-m-long bridge had been commissioned in

Table 3. Characteristics of tsunami waves in Tamil Nadu

District	Number of waves	Arrival time of waves	Wave height (m)	Wave travel distance (m)	Runup height (m)	Water condition before/after tsunami
Kanyakumari	3	First wave ~ 10:30 A.M. and second and third wave at 15-min. intervals after first	4–10	~200–400	2.4	Water receded about 1 km before first wave in areas such as Sottavellai
Nagapattinam	5	First wave at 9:00 A.M.; five waves within 1-hr span	~10	100–1,000	5	
Cuddalore	3	First wave at 8 A.M. and subsequent waves at 10–15-min. intervals	~9	250	4	
Kancheepuram	3	First wave at 9:15 A.M.	~4	~1,000	2	
Chennai	5	First wave at 9:05 A.M. and fifth at 11 A.M.	-	200	2	

2002 to connect the villages of Melamanakudi and Kelamanakudi on opposite banks of the Pazhyar River. The bridge went missing after the tsunami (Figure 15). It was originally built with four spans, all of which were washed away by the tsunami. The two end spans traveled upstream by 100 m and were beached on the banks; the central spans were not visible, apparently having sunk into the waters. The substructure appeared to be intact except at the apron. There were no restraints between the superstructure and the foundation. Melamanakudi is a prosperous and picturesque hilly village built on the waterfront. A road from the village of Palam to Melamanakudi was reportedly built by leveling the sand dunes in the region, in violation of the coastal regulation zone (CRZ) rules. Numerous houses were built on the seashore not more than 50 m from the shoreline, apparently after the leveling of sand dunes. These houses suffered complete devastation (Figure 16). Structures 250 m from the shoreline suffered little or no damage, because the land sloped upward. About 150 people died at Melamanakudi.

Sothavilai has a beautiful beach and was being actively developed by the state for tourism. The beach slopes upward from the shoreline and folds into sand dunes about 8–10 m high along parts of the beach. A beach resort has been constructed inland beyond the sand dunes. Numerous tea shops and other food stalls lined the path leading to the beach. The tsunami waves lashed and made their way over the ridges of these dunes and beyond them through the numerous small drainage channels running into the sea from the town, causing loss of life and much scouring while receding. An estimated 200 people, mainly stall owners and visitors, died at this beach.

Figure 11. The tsunami carved new waterways—a soak pit was exposed by tsunami waves in Kolachel (photo: A. Sheth).

The southernmost tip of mainland India, Kanyakumari, experienced tsunami waves that were over 4.5 m high. Because Kanyakumari is on high land, the damage was limited—street furniture and compound walls were destroyed. About 1,200 people stranded at the rock memorial were successfully evacuated a few hours after the tsunami.

SOUTHEAST COAST OF TAMIL NADU AND PONDICHERRY

The southeastern coastline of Tamil Nadu is 800 km long. It comprises the Coromandel Coast in the north and the Fisheries Coast in the south. The coast north of Point Calimere up to Pondicherry is practically straight (~79.5 °E) and directly across from

Figure 12. The runup height at Kolachel Beach was 2.6 m, as shown by the watermarks (photo: A. Sheth).

the Andaman and Nicobar Islands at a distance of 1,900 km. This region was the most affected by the tsunami. It comprises the coastal districts of Nagapattinam, Cuddalore, Villipuram, Kanchipuram, and Chennai.

The arrival of the first tsunami wave along the east coast coincided with high tide, which amplified its effect, as seen in Figure 6. The coastline in this region is flat except for gentle slopes. From local residents, it was inferred that the beaches previously had a steeper slope than is now visible. Many of the slopes and much of the vegetation have been cut during the last two decades to make way for coastal hamlets.

The coastal districts of Tirunelveli, Tuticorin, Ramanathapuram, and Pudukkotai—which were in the shadow zone of Sri Lanka—suffered relatively minor effects from tsunami waves. The tide gauge at Tuticorin Port, for example, measured a wave height of 1.8 m, which was only marginally higher than high-tide levels, partly because the tsunami waves were out of phase with the high tide here (Figure 5).

Nagapattinam District

Nagapattinam was the most affected district, not just in Tamil Nadu but in the entire mainland of India, with 6,051 fatalities reported. Some social factors added to the vulnerability of the region.

Velankanni

The town of Velankanni, 12 km from Nagapattinam, houses the Church of Mary of

Figure 13. The AVM channel in Kolachel, which became a death trap; more than 300 bodies were found in the slush of the AVM channel and open trenches (photo: A. Sheth).

Figure 14. Open trenches for making coir. As with the AVM channel, these trenches also became death traps (photo: A. Sheth).

Figure 15. All spans of the Melamanakudi Bridge came off their bearings. The end spans drifted upstream, while the middle spans sank into the river (photo: A. Sheth).

Good Health and is a very popular pilgrimage center among believers for its healing powers. The central axis of the church is aligned with the main road leading to the beach (Figure 17). Thousands of worshippers had thronged to this town for Christmas, and many of them were at the beach on the morning of 26 December after attending Mass. More than 2,000 people died in this town. A tsunami wave approximately 5 m high first struck the shore at 9:20 A.M., followed by four more waves between 9:20 A.M. and 10 A.M. The waves crashed onto the shore and continued on their rampage along the main road leading to the town. Though the water did not enter the church, it gushed up to the bus stand, inundating several shops and houses. A large number of bodies were found along this road. The inundation distance was more than 1,000 m.

Seruthur

In the adjacent coastal village of Seruthur, which lost 131 people, the wave height was the same as in Velankanni. The number of deaths was lower because of much lower population density, but also because the plinth of the houses in this village was 1.5 m above ground level, and the elevation of the ground was 1.5 m from sea level. The runup height was 2 m above the plinth level, or 5 m above mean sea level (Figure 18).

Akkaraipettai

Akkaraipettai is an important and prosperous fishing port in the Nagapattinam district. About 1,000 boats and fishing trawlers were destroyed in this town.

Figure 16. Some homes at Melamanakudi were within 6 m of the shoreline. This photo shows a fallen RC roof slab (photo: A. Sheth).

On Ariyanattu Street, a communications tower (Figure 19) and control room (Figure 20) had toppled, while in adjacent Naliyanthottam, a godown (warehouse) storing gas cylinders was destroyed, with all cylinders being swept away by the tsunami. The godown was more than 800 m from the shoreline.

Nagore

No damage was reported at the oil jetty at Chennai Petrol Chemicals Ltd. at Nagore, primarily because of the high elevation, more than 3 m from sea level. However, 1,200 houses were destroyed or damaged. Water entered almost 1,000 m inland. The rail link to Nagore, a pilgrim town, was cut off as a 7-km meter-gauge track between Nagapattinam and Nagore was completely damaged (Figure 21).

Cuddalore District

The Cuddalore district borders Nagapattinam in the north and was the second-most-affected district.

Silver Beach

Silver Beach had been recently developed for tourism and recreation activities, such as boating and a small amusement park. Two rivers discharge into the sea at this scenic location. The shore is at sea level. The first tsunami wave arrived at 8:35 A.M., with two subsequent waves within the next 15 minutes. The waves threw boats upstream into the

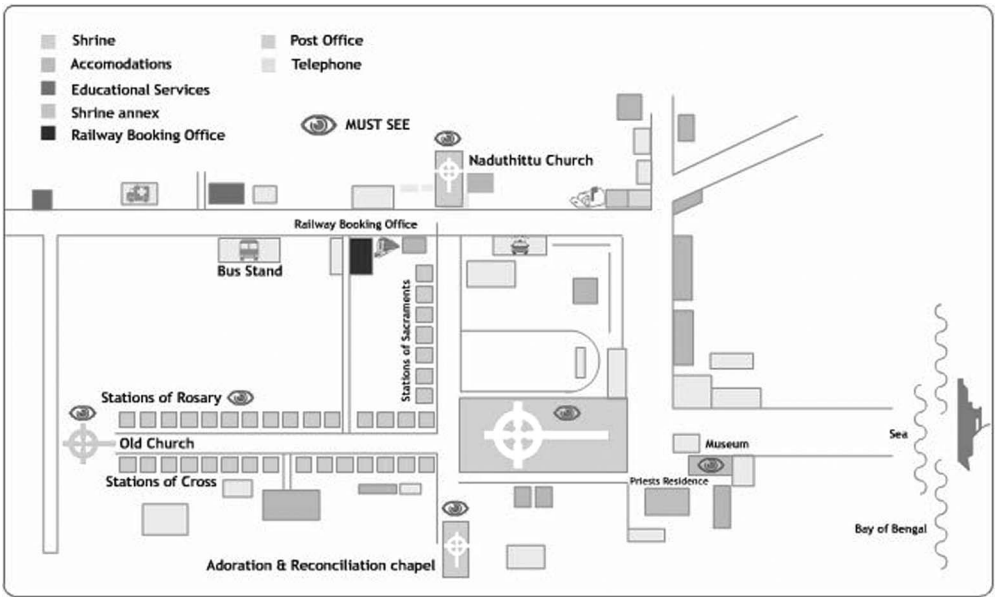

Figure 17. Velankanni—maximum loss of life along the road from the beach leading to the church (source: www.vailankannichurch.org).

Figure 18. Houses in Seruthur, the village neighboring Velankanni, were not significantly affected, due to a higher plinth (photo: A. Sheth).

Figure 19. Damaged communication tower on Ariyanattu Street (photo: A. Sheth).

rivers and subsequently onto the shores. The waves destroyed most of the small structures built on the beach, such as a police booth, a boat house, water tanks, and electricity poles. The newly built road was washed away completely (Figure 22), as was the new Neyveli Lignite Corporation (NLC) amusement park. The road had been built after

Figure 20. Toppled control room on Ariyanattu Street (photo: A. Sheth).

Figure 21. Damaged railway line between Nagore and Nagapattinam (photo: A. Sheth).

clearing away mangroves. The water remained about 0.6 m above mean sea level for four days after the tsunami. On the beach, 37 people died. Bodies of victims were found in fishing nets, mangrove bushes, and in low-level areas. The bodies were covered with sand deposited by the waves. Adjacent thatched houses of a village less than 1 km from the shore were not damaged. Survivors reported a wave height of 6 m.

Devanampattinam

This is a coastal fishing village not far from Silver Beach, built barely 50 m from the shoreline at sea level. Unsurprisingly, houses were significantly damaged (Figure 23).

Figure 22. Tsunami waves washed away the newly built roads at Silver Beach, Cuddalore (photo: A. Sheth).

Talanguda

In the coastal village of Talanguda, houses were also built about 50 m from the shoreline, but, because of a tree grove between the sea and the houses, the damage was

Figure 23. Houses in Devanampattinam were barely 50 m from the shoreline (photo: A. Sheth).

Figure 24. At Singarathop, the bridge from which this photo was taken is much higher than the town and served as a refuge (photo: A. Sheth).

in some measure contained, even though the tsunami waves were said to be more ferocious here than at Devanampattinam. The gable walls of most thatch houses had suffered major damage or had collapsed. The waves had lashed the boats across the beach, and some boats had crashed against houses from the gaps between trees. However, not a single nonengineered structure with a concrete roof was affected.

Singarathop

Singarathop was a fishing village with a flowing river. A new bridge connects the town of Cuddalore to Singarathoppu. The tsunami, coupled with the high tide level of the river, caused a severe rise in water level, and the whole town was submerged. The recently constructed bridge had a very high elevation, and residents rushed to this bridge, thus saving their lives (Figure 24).

Kancheepuram District

The Kancheepuram district has special significance because of the presence of the nuclear power plant at Kalpakkam. The plant area was not affected by the tsunami; however, the housing colony (DAE township) was very badly affected. Almost 1,000 houses were damaged, and a seawall 2 m high and 4 km long collapsed. The waves rushed into the colony, with a runup height of about 1.5 m. Almost all courtyard walls of the houses for 1 km collapsed. There was almost no vegetation near the shore. A new estuary was formed. A school's compound wall was damaged, and electric poles were uprooted near the school grounds. The tsunami waves deposited a large quantity of sand near a pedestrian bridge. Water pipelines along the bridge were thrown off the bridge.

Figure 25. The foundation pit of this 500-MW reactor was inundated by 6 m of water (photo: P. Gandhi).

A foundation of 100×100 m for a 500-MW fast breeder reactor was being constructed about 500 m from the sea. The foundation's pit, which was 20 m deep, was inundated by 6 m. From an observation post, a vigilant project officer had seen the tsunami wave striking the compound wall and warned the 180 people in the pit to immediately evacuate; as a result, there were no casualties. Also, the people had enough time to escape because of the time required for the water to fill the foundation pit (Figure 25).

Chennai

At about 13 km in length, Marina Beach in Chennai is the second-longest beach in the world. Numerous stately structures facing Marina Beach were built in colonial times. The tsunami battered Marina Beach, and giant waves swept across the beach and the wide Kamarjar Salai road and entered into these buildings. However, there was no significant damage to the buildings. The waves caught many morning walkers on Marina Beach unawares. Approximately 160 people died on the beach in the tsunami. The hamlet adjacent to the beach consisted of thatch shanties less than 50 m from the sea. These were ravaged in the tsunami. The fishing port of Chennai suffered significant damage, and approximately 150 fishermen were reported dead. However, the main port of Chennai, which has a seawall, was not significantly damaged. The mooring line of one of the ships, the Keshava, broke off and collided with two other ships, causing localized damage to the ships. Mooring dolphins were damaged.

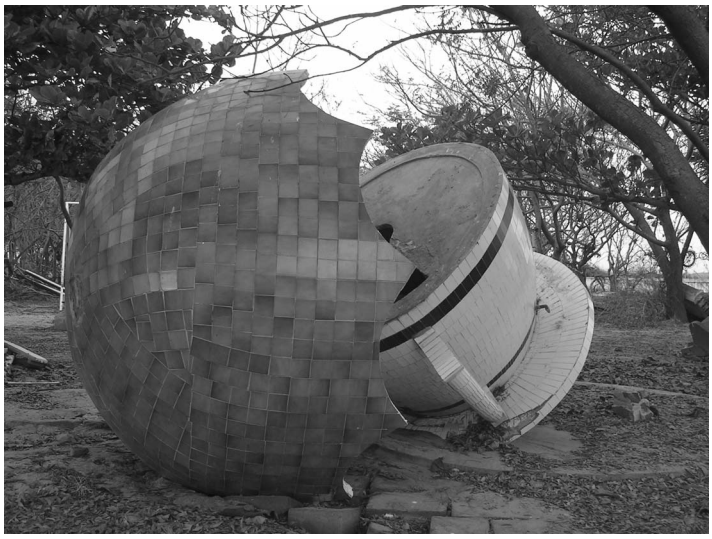

Figure 26. The beachfront club at Karaikal was badly damaged (photo: A. Sheth).

Pondicherry

Pondicherry was a French colony until 1954, when it was integrated as a union territory into the Indian Republic. Pondicherry recorded 599 deaths (Government of Pondicherry 2005). The damage was in two regions of Pondicherry—Karaikal and the city of Pondicherry.

Karaikal

The city of Karaikal was a French colony until 1954. It is tucked into the Nagapattinam district of Tamil Nadu and is flat, devoid of forests or hills. It has a beautiful, normally serene shore with the Arasalar River running across the city and discharging into the sea at Karaikal. The first tsunami wave struck the city at 8:45 A.M. and was followed by two more waves. The city lost 265 lives in the tsunami (492 lives were lost in the region, including the neighboring villages). The coast has a promenade at the mouth of the river, and at the end of the promenade is a club with recreational facilities (Figure 26). Along the promenade, a wall about 2.4 m high collapsed.

Arasalar Bridge connects the north and south of Karaikal. Tsunami waves traveled through the Arasalar River about 500 m beyond the bridge into the mainland. In essence, water went inland 2.5 km from the shoreline. A pier gave way, causing the collapse of two adjacent arches of the bridge, but the Indian Army put up a temporary Bailey bridge in under six hours. This Bailey bridge was further extended across the entire bridge (Figure 27). A helipad washed away on the south side of a backwater, along with a wooden army jetty. The wave height, according to eyewitness accounts, was about 10 m and was the color of black mud. The runup height was 2.4 m.

Figure 27. Arasalar Bridge—the two southern arches of this bridge collapsed in the tsunami, but a temporary Bailey bridge was erected by the Indian army within six hours (photo: A. Sheth).

The high tide along with the tsunami waves made matters worse, and all structures and bodies were pushed southward. Children were caught in the mangroves. Across the river, on the south bank was a rich settlement of 50 families of a fishing community called Karukalacheri, where 25 people died; Karukalacheri is also called *kutty* Singapore ("kutty" means "little"). Most of the houses were destroyed or badly damaged.

Pondicherry City

The city of Pondicherry lies north of the Cuddalore district. Although 107 bodies were recovered from Pondicherry and the surrounding hamlets, 56 of these bodies had been washed away from Tamil Nadu.

The city experienced waves about 9 m high but escaped relatively unscathed due to the stone seawall constructed almost three centuries ago and fortified over time. The height of this wall is about 9 m above sea level. However, about 25 people died on the Pondicherry promenade.

Most of the dead were fishermen living beyond the seawall boundary in hamlets such as Kucchikupam, Ariyankuppam, Ponniyarpala, and Ganagachettikulam. Kucchikupam experienced three waves that washed out thatch huts and killed 3 people, despite being over 4 m above mean sea level. The buildings with masonry brick walls were damaged but did not collapse. In Ganagachettikulam, a beach hamlet where 16 people had died, within 10 days of the event people had started building their temporary houses on the same plinth level as their earlier homes.

COAST OF ANDHRA PRADESH

The tsunami waves struck the Andhra Pradesh coast at about 9:05 A.M. The waves destroyed homes and the livelihoods of fishermen and caused many kinds of secondary damage, such as loss of fertile land and loss of employment. The most damaged districts were Machhalipatanam (Krishna), Ongole (Prakasham), and Kavali (Nellore), which had a wave penetration of 0.2–1.0 km into the mainland, with an average wave height of 1.2–2.2 m. Srikakulam, Vishakhapatnam, Kakinada, and Yanam (Pondicherry) showed comparatively less damage.

Fishing and agriculture are the two dominant occupations in the villages along the coastline in Andhra Pradesh. The tsunami washed away most of the fertile topsoil and deposited heaps of sand, which ultimately left people with the choice of either changing the land use or changing the crop pattern.

Srikakulam District

The villages of Kaviti, Iddivanipalem, Sompeta, Naupada, and Kalingapatanam recorded maximum damage in the Srikakulam district, which is famous for its beautiful beaches. Because the shore is flat, the tsunami wave penetration was greater, and when the waves receded, they took back piles of coconuts that had been stacked along the coastline for shipping. All allied cottage industries based on coconuts, such as coir making, basket making, and oil extraction centers, were out of business for the rest of the season.

Northern Sompeta near Iddivanipalem is protected by a seawall made of huge concrete blocks approximately 1 m $\times$ 1 m $\times$ 1 m. This seawall did not show any major damage from the tsunami except for dislocation of a few blocks at some locations.

The coastline along Barua, the southernmost area of the Sompeta district, is guarded by sand dunes and sparse vegetation cover. Tsunami water failed to cross the ridge line of the sand dunes but left a considerable amount of sandy soil eroded, exposing tree roots.

Naupada, called the “salt bowl” of Andhra Pradesh, has an extensive network of salt pans (salt farms) spreading over 4,000 acres. Of these, 1,400 acres were badly silted up in the tsunami. According to local salt farmers, the tsunami caused a loss of investment of Rs. 2,000 per acre.

Kalingapatanam Beach did not suffer significant damage because of its peculiar shape (with two projecting arms forming a crescent), slope, and geology. The seabed at Kalingapatanam is made of rocky strata. When the tsunami struck the coast, the projections protected the inner core area where settlements were, and the waves dispersed into the empty but wide riverbed of Vanshdhara River, which empties into the Bay of Bengal at Kalingapatanam. As a result, only a few fishing boats tied near the river mouth were tossed, but the rest of the areas were unharmed.

Vishakhapatnam District

Vishakhapatnam is an important city of eastern India with a very busy harbor and naval base. To protect and strengthen the coastline, concrete tetrapods have been laid along the Vishakhapatnam coastline. It has three divisions: Vishakhapatnam Port Trust, Vishakhapatnam Sea Port, and Vishakhapatnam Container Terminal. The latter two are leased to private parties, and on 26 December their berths were empty. Vishakhapatnam Port had minor damage that created difficulty in navigational movements, cargo loading, and unloading. Fishing harbor boats and trawlers drifted away, a couple of which sank; 179 mechanized boats were partially damaged. Mooring buoys drifted away, and some people fell into the water during this time but were rescued without injury. In all, the port suffered one full day's worth of operational loss.

The tsunami disrupted the fishing industry, as many fishermen lost their boats and nets. Those with huts within 200 m of the coastline lost their homes. Moreover, the rumor of fish being diseased or dying due to the tsunami ruined the sales of even the small catch in the days immediately after tsunami and destroyed the fishing industry further.

East Godavari District

The East Godavari coastline suffered the least damage. The Kakinada Port Trust reported some that disruption in activities had disorganized its functions. All the operations were partly suspended for one day. The port was saved due to its peculiar shape and due to Hope Island, which acted as shield.

Because this is a delta area, water channels or in some cases backwaters are extensively used to sail fishing boats right up to the edge of settlements. These channels helped reduce the impact of tsunami water entering into the mainland. At Uppada village, however, the stone pitching of the embankment was damaged in some places.

Yanam and West Godavari District

Yanam has rich, black fertile soil deposited by the Godavari River. Paddy cultivation, high-quality brick manufacturing, ceramic tile molding, and fishing boat construction are some of the main occupations in Yanam. After the tsunami devastation, the two cottage industries of brick manufacturing and boat construction expanded rapidly.

The soil is deep friable, well-drained sandy loam in the West Godavari district coastal belt. The land is a green mass of mangroves and a dense human-created forest of cash crops such as cashews, jackfruit, and coffee grown in the shade of coconut farms. The tsunami ruined the crops and replaced the standing cashew trees with sand deposits. Fresh ingress of water was seen in areas with dense mangroves. Part of the mangrove belt directly in the path of the tsunami waves was completely washed away, leaving another part partially or fully submerged in water for more than 48 hours. Silt had accumulated on the pneumatophores (the breathing roots of mangroves), choking the respiration of the mangroves.

The tsunami left the area prone to further erosion of soil on seashores after removal of vegetation cover. Slowly growing species such as mangroves, even if replanted, will take a long time to cover the entire land.

Figure 28. A damaged refreshment center on the beach at Machalipattanam, Andhra Pradesh (photo: A. Jaiswal).

Krishna District

In the Krishna district, the tsumani created havoc in Manginapudi and on Machalipattanam Beach. A large number of people, especially fishing families, were displaced as the tsunami wave swept the entire east coast. For the Hindus of Manginapudi Beach, which is a village in Andhra Pradesh state on India's southeast coast, it was an auspicious occasion, a full moon day, and the women and children had stepped into the sea for ritual bathing. Many of these bathers were washed away by the tsunami. The Krishna district recorded a loss of 27 human lives. While the main village of Manginapudi did not suffer tsunami damage, because it was at an elevation, the huts of the fishermen were mostly destroyed. Boats were thrown by the tsunami waves just outside the village, and many were lost. All the fishing nets were lost.

According to narratives of the local residents, the tsunami water came like a running wall at Machalipattanam Beach. It pounded on existing structures such as refreshment kiosks (Figure 28), and it scoured the shallow foundations and washed beach vendors away. The giant waves also left remains of dead deep-sea turtles and completely destroyed a beach children's park.

Prakasham District

Prakasham was the most affected district in Andhra Pradesh, recording 35 deaths. Singraikonda, a beautiful beach hamlet, reported maximum damage in the Prakasham district. This hamlet is nestled in a casuarina forest on a promontory, and, apart from fishing, it survived on business from pearls and other sea products. Casuarina groves were spread over a belt 450 m wide between the settlements and the sea. They served as

Figure 29. Casuarina trees tilted in the direction of the onslaught of the tsunami waves in Singraikonda (photo: A. Jaiswal).

a buffer to reduce devastation, but as a result they suffered twisting (Figure 29) and occasionally uprooting. The grooves also prevented a freshwater lake from being mixed with the sea. The whole village was dependent on this lake for drinking water. After the tsunami, seawater made a new channel up to the lake and disturbed the freshwater bulb permanently. The villagers are now dependent on water tankers for their potable water.

Settlements away from the casuarina shield and within 700 m of the coastline suffered the most damage. Fishermen's huts made of sun-dried adobe and mud-plastered walls with thatched roofs were razed (Figure 30).

Nellore District

Apart from the loss of livelihood, the fishermen-dominated shore areas faced the problem of salinity as the tsunami polluted water sources. The aquatic sector received a severe blow, because most of the catch had been washed away. Shrimp farming, or aquaculture, was another hard-hit sector. Farmers lost their pumps, their cultivated lands, and a running chain of production.

The beach showed a very distinct form of ground failure. A part of the beach sank by 45–80 cm, with a continuous cutting edge parallel to the coastline. The village's tar-road approach, which was parallel to the seashore, was completely washed away, exposing compact murrum at the base.

Figure 30. Fishermen's huts of adobe and mud plaster walls were razed at Prakasham (photo: A. Jaiswal).

PERFORMANCE OF STRUCTURES

HOUSING

There were two types of damage: damage induced by direct pressure from tsunami waves, and scouring damage induced by the receding waves. Many of the affected structures consisted of houses belonging to the fishing community. The houses were nonengineered structures having the following features:

- Load-bearing brick masonry walls and tiled roofs
- Load-bearing brick masonry walls and thatched roofs
- Load-bearing brick (or concrete block) masonry walls and RC roof slabs; these were not very common.
- Thatch walls and thatched roofs; these constituted shacks.

Most of the affected homes were 4–100 m from the sea, except in areas such as Nagapattinam and Akkaraipettai, where the effect on houses was felt up to 500 m away. The masonry work was generally poor, with little binding mortar. The foundations in Kerala, which has good sandy soil at low depths, were shallow, usually about 0.6–0.75 m deep. In such houses, failure was initiated by scouring of the foundations,

Figure 31. In areas with deeper foundations, masonry superstructures failed first (photo: A. Sheth).

which triggered collapse of the walls and subsequent failure (Figure 8). However, masonry structures with RC roofs and better integrity performed well even when on the shore (Figure 9), although they too suffered foundation scouring.

In areas with deeper foundations such as the delta region of Tamil Nadu and some parts of Kerala, the masonry superstructure failed first, due to the impact of the tsunami waves. Lack of integrity in the structure (e.g., the lack of continuous bands or corner strengthening measures), coupled with poor construction quality, made the corners of the houses most vulnerable, and failures initiated at this location (Figures 31 and 32). Thatch houses suffered maximum damage.

The height of the waves and of the inundation recorded in Kerala were much lower than in Tamil Nadu. This, coupled with a wealthier population having invested more resources in housing construction, could be the possible reason that, even though the number of villages affected in Kerala was about half of the number affected in Tamil Nadu, the loss of dwellings was just about 15% of the loss in Tamil Nadu.

SEAWALLS

Kerala has a seawall along large parts of its coast. The seawall is made of loose rubble and is about 0.75–1 m high. Stones were dislodged at some locations, and boulders were thrown as far as 30 m away. Similar observations were made at the Andhra Pradesh coastline. The seawall reduced the effect of the tsunami waves, and it was seen that the areas in Kerala and Andhra Pradesh that did not have a seawall were the most

Figure 32. The lack of structural integrity caused failures to trigger at the corners of structures (photo: A. Sheth).

affected. However, while no incidents of persons being injured by displaced rubble have been recorded, this could be a hazard in future events, and the states may consider the use of gabions or similar systems to contain the rubble. Tamil Nadu has a seawall in restricted areas. The city of Pondicherry was fully protected by its seawall. However, the wall constructed to protect the Arasalar River in Karaikal was washed away.

WATERWAYS, ROADS, BRIDGES, AND RAILWAYS

Major damage to the transportation infrastructure was observed in the states of Kerala, Tamil Nadu, and Pondicherry (Table 4). The only damage in Andhra Pradesh was minor scouring and erosion of the top coat on some metalled beach roads.

Kerala

The backwaters are an important means of transport in Kerala. Due to large sand deposits by the tsunami, the available draft was reduced in these backwaters; this affected ferry movement, and dredging was required.

About 60 km of major district roads and some village roads along the coastline in the districts of Allapuzha and neighboring Kollam were badly damaged, primarily because of scouring that washed out the shoulders of roads and eroded the top layer of pavements. The tsunami also deposited large volumes of sand and other debris, which blocked the roads.

Figure 33. Large boats broke their moorings and damaged a bridge at Akkaraipettai (photo: A. Sheth).

Tamil Nadu

Tamil Nadu was the worst affected in terms of damage to the transport sector. The district of Kanyakumari on the west coast and the districts of Nagapattinam and Cuddalore on the east coast experienced damage to about 80 km of the major and other district roads. As in Kerala, the damage was primarily due to the scouring action of the waves.

Tamil Nadu suffered severe damage to two bridges. As mentioned elsewhere in this paper, a 160-m-long bridge had been commissioned in 2002 to connect the villages of Melamanakudi and Kelamanakudi on opposite banks of the Pazhyar River. The bridge went missing after the tsunami. Another bridge at Akkaraipettai in the Nagapattinam district was affected by the large boats that broke their moorings in the tsunami and dashed against the bridge (Figure 33). Two bridges under construction were reportedly damaged but were not inspected.

As mentioned elsewhere in this paper, the rail link to Nagore in the Nagapattinam district was cut off as a 7-km meter-gauge track between Nagapattinam and Nagore was completely damaged.

Cuddalore district suffered a major loss of roads along the beach, especially at Silver Beach, where a newly constructed road was completely destroyed. Eight rail cars were reported to be damaged in Cuddalore.

Pondicherry

There was damage to about 2 km of beach road in Karaikal and 3 km of road between Karaikal and the beach. In Karaikal, about 4.5 km of the road between Varichikudi and the beach was washed away.

Two small bridges at Solai Nagar (Pondicherry) were also damaged. The arch bridge on the Arasalar River in Karaikal had six arches, with a total length of 46 m. One of the piers of the bridge gave way, causing damage and settlement of the adjacent arches. The Indian Army restored this bridge by providing a Bailey bridge across the river.

PORTS

No major ports in mainland India were significantly damaged. However, many intermediate and minor ports were affected.

Kerala

Four minor ports (Vizhinjam, Neendakara, Beypore, and Azhikkal) and eight fishing harbors in Kerala were affected due to huge sand deposits by the tsunami; these deposits reduced the available draft.

Tamil Nadu

Kolachel Port in the Kanyakumari district required dredging and repairs to the jetties. The port of Nagapattinam is situated at the mouth of the Kaduvayar River in the Bay of Bengal. It is a prominent port in the Nagapattinam district and is classified as an intermediate port. The port of Nagapattinam is situated on the western bank of the Kaduvayar River, which flows parallel to the coast in a northerly direction for about 0.8 km and debouches into the bay. This stretch was protected from the sea by a narrow sand spit. A rubble-mound breakwater was also constructed near the pier to increase the depth. About 100 m from the shoreline is a concrete groin about 1 m high, which was damaged in the tsunami. Boats used to be moored beyond this wall along mooring dolphins. The tsunami waves went over and across the breakwaters, the seawall, and into the backwaters. Boats broke free of moorings and struck the bridge. The damage to the groin caused silting and reduction in the draft, and this made the port unserviceable.

The port of Chennai, the most important port in south India, did not suffer significant damage, although it experienced some amount of scouring and silting. Concrete tetrapods forming the breakwaters were dislodged in some places. A ship (the Keshava) broke away from its moorings and collided with two other ships. Two mooring dolphins were lost on the Ambedkar dock, which also showed damage in the form of cracks. Cuddalore Port also suffered damage to breakwaters and the seawall and required dredging. Pondicherry Port and five fishing harbors (Pazhavar, Thirumullai Vasal, Chinnangudi, and Nagore in Nagapattinam, and Chinnamuttom in Kanyakumari) required dredging and repairs to walls and docks.

Table 4. Cost of damage to the transport sector in three states*

	State			
Transport sector	Tamil Nadu	Pondicherry	Kerala	Total
Roads and bridges (Rs. crores)	27.66	24.45	6.14	58.25
Ports and fishing harbors (Rs. crores)	65.41	5.00	24.24	94.65
Total (Rs. crores)	93.07	29.45	30.38	152.90
Total (US$ millions)	21.40	6.77	6.98	35.15

* Source: ADB et al. (2005)

BOATS AND FISHING INDUSTRY

The greatest damage was suffered by the fishing industry. A large number of boats were damaged or lost (Table 5). A large part of the coastal population depends on fishing and other allied industries for its livelihood. Most of the fishermen in affected areas lost fishing nets. For some time after the tsunami, the fishermen were advised to avoid fishing until the sea had stabilized. The few fish that were caught did not find buyers, because there was fear that the fish had become poisoned.

CONCLUSIONS AND OBSERVATIONS

The tsunami effects varied greatly across different parts of the coast according to the number of waves experienced, the inundation distance and height of waves, and the density of the area, as well as topological and geographical features that made some areas more vulnerable than others. Besides these factors, the number of lives lost was influenced by exposure to previous disasters and the local disaster management capability. Most of the people killed were members of the fishing community and, in some cases such as Marina Beach at Chennai and Velankanni in Nagapattinam, they were visitors on the beach.

The tsunami caused much damage to the housing stock along the coast and to bridges and roads. The houses were mainly nonengineered and were poorly constructed. But improving the construction methodology and the integrity of structures cannot provide the necessary assurance of tsunami resistance. If people continue to build along the

Table 5. Lost or damaged boats in the four affected states*

	State			
Effect	Kerala	Tamil Nadu	Pondicherry	Andhra Pradesh
Boats lost or damaged	10,065	45,920	6,678	1,362

* Source: ADB et al. (2005)

shore on flat land, they will continue to be highly vulnerable in a tsunami and may expect such damage and loss of life. Although the government has considered rigorous implementation of the CRZ (which requires structures to be a minimum distance of 500 m from the shoreline) in the reconstruction project, it is a moot point whether this requirement will be followed. It is quite likely that fishermen will move back to the beaches in a few years.

In such a case, a robust tsunami warning system along the lines of the cyclone warning system must be put in place, and tsunami shelters (which may also double as cyclone shelters) must be provided in every coastal area for quick and safe egress of people and their valuables.

Bridges need special attention. It may be worthwhile for the government to consider providing restraints for bridges in light of the failure of the bridge at Melamanakudi over the Pazhyar River. There is also a need to review the existing bridges and evaluate their serviceability, in light of the failure of the Arasalar Bridge.

Damage was caused at many ports due to damaged mooring dolphins. Special attention needs to be paid to the design of the moorings.

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