Learning from Earthquakes

The Great Sumatra Earthquake and Indian Ocean Tsunami of December 26, 2004

__Editor's Note:__ In the March issue, we published reports on earthquake and tsunami impacts in northern Sumatra and along the southeast Indian coast. The May issue will carry a report on Sri Lanka. Here we present a report by an Indian team funded by the Government of India. Publication of this report is supported by funds from the National Science Foundation through EERI's Learning from Earthquakes Program under grant # CMS-0131895.

Report #3

The Effects in Mainland India and in the Andaman-Nicobar Islands

This report presents the preliminary findings of the tsunami reconnaissance conducted by a team of 13 Indian engineers, earth scientists, architects, and graduate students. The investigators were divided into six groups to survey the areas affected in India, both in the Andaman and Nicobar Islands (aerial and field surveys) and along the affected coastline on the mainland (field surveys).

Each of the groups spent about eight days in the field between January 1 and 13, 2005. The team included Sudhir K. Jain (structural engineer, Indian Institute of Technology, Kanpur); C. V. R. Murty (structural engineer, IIT Kanpur); Durgesh C. Rai (structural engineer, IIT Kanpur); Javed N. Malik (paleoseismologist, IIT Kanpur); Alpa R. Sheth (structural engineer, Mumbai); Arvind Jaiswal (structural engineer, Secunderabad); Snigdha A. Sanyal (architect, IIT Kanpur); and graduate students Hemant B. Kaushik (IIT Kanpur), Pratibha Gandhi (IIT Madras), Goutam Mondal (IIT Kanpur), Suresh R. Dash (IIT Kanpur), Lt.Col. Jasinder S. Sodhi (IIT Kanpur), and Lt.Col. G. Santhosh Kumar (IIT Kanpur). The study was sponsored by the Department of Science and Technology, Government of India, New Delhi.

Introduction

The M_w9.0 earthquake of December 26, 2004 struck at 06:28:53 a.m. Indian Standard Time. Shaking-related damage was recorded only in the Andaman and Nicobar (A&N) Islands. The maximum intensity of shaking (on the MSK scale) was VII; along the mainland Indian coast, it was V. The tsunami arrived in the A&N Islands between 40 and 50 minutes after the earthquake, with Port Blair recording its arrival at 7:15 a.m., and it caused extensive devastation of the built environment. The tsunami arrived in the states of Andhra Pradesh and Tamil Nadu along the southeast coast of the Indian mainland shortly after 09:00 a.m. At least two hours later, it arrived in the state of Kerala along the southwest coast. Tamil Nadu and Kerala were extensively damaged, while Andhra Pradesh sustained moderate damage (Figure 1).

In the A&N Islands, aerial surveys were carried out along most of the Nicobar Islands and over Little,

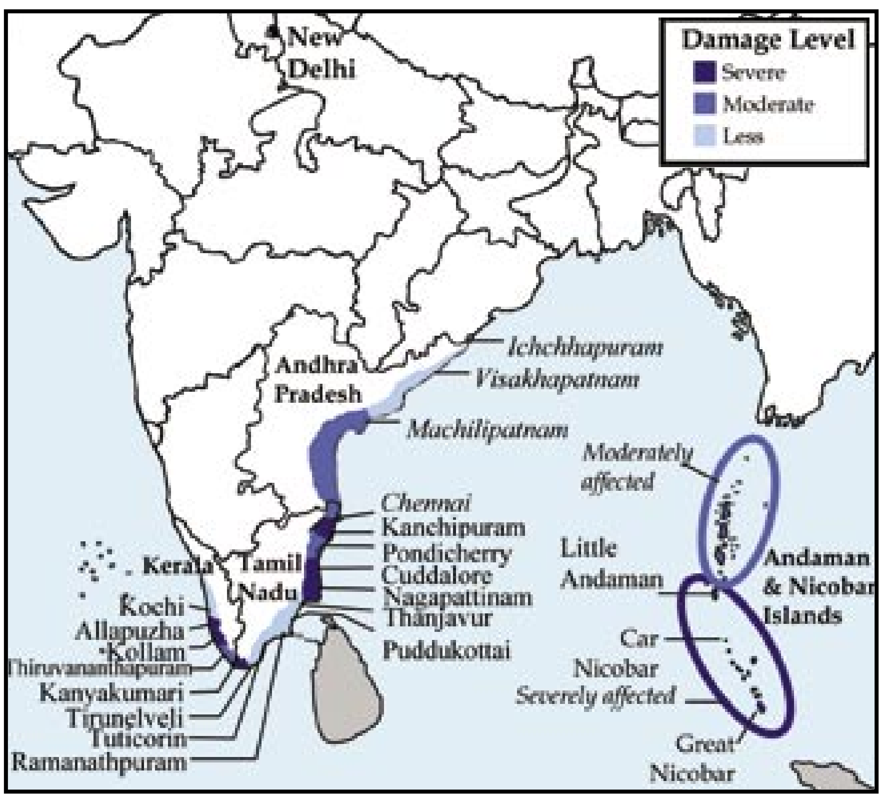

__Figure 1.__ Map showing relative tsunami-induced damage along the coastal districts (in mainland) and in the islands (in A&N Islands).

South, and Middle Andaman Islands (Figure 2). Field investigations were carried out in the North, Middle, South, and Little Andaman islands and the Car and Great Nicobar islands. In mainland India, more than 2600 km of the coastline were surveyed from Kochi (the southwest India city in the state of Kerala) to Ichchhapuram (the southeast India town in the state of Andhra Pradesh). The distribution of damage was complex across these areas. This report describes observations related to the earthquake ground shaking and the tsunami wave damage, the emergency response of the community, and major concerns that arose after the disasters.

The total number of Indian fatalities were 10,805, with over 5,640 persons missing, according to official statistics (**www.ndmindia.nic.in** 2005). The state of Tamil Nadu had the highest number of fatalities — 8,010 (**www.tn.gov.in/tsunami** 2005) — with the district of Nagapattinam alone accounting for 6,065

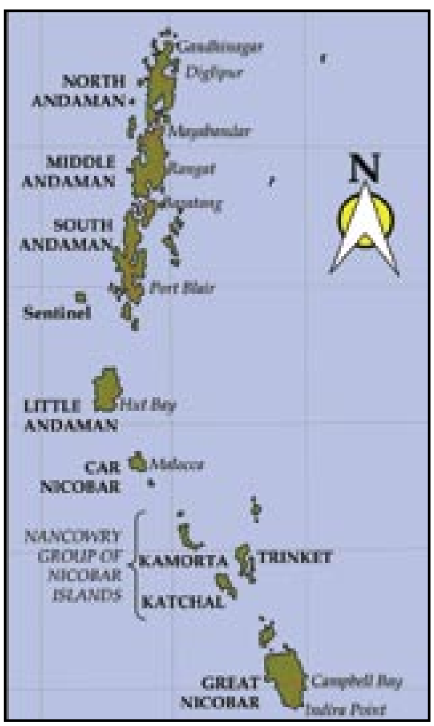

__Figure 2.__ Overall map of A&N Islands showing some of the larger islands of the region.

Figure 3. *RC frame building (MES Inspection Bungalow) now stands in water on the eastern coast of Car Nicobar Island (photo: C.V.R. Murty).*

deaths. However, as a percentage of the total population, the statistics from the Nicobar Islands indicate the most severe losses: out of the total population of 42,068, about 1,395 are reported dead, 5,764 missing, and 27,497 were in the relief camps (as of March 10, 2005). Most of the tsunami victims on the mainland belonged to the fishing community or lived in houses within 500 m of the water. Tourists in Velankanni in the state of Tamil Nadu and morning walkers in urban areas (Karaikal, Chennai and Pondicherry) were also among the dead. Since December 26 was the day after Christmas, many visitors came to the seacoast for a holy bath on an auspicious day, and lost their lives.

In many of the districts, there were fewer male casualties than those of women and children. For instance, in the Karaikal region of the Union Territory of Pondicherry, the total number of fatalities was 484, of which 33% were women, 21% were male children, and 30% were female children. The reasons for this are the vulnerability of small children to the big waves, the tendency of women to protect children and belongings, their being indoors and having less lead time to flee, and the inability of women to climb trees or run fast (particularly when wearing sarees).

Impacts in the Andaman-Nicobar Islands

The A&N Islands consist of a narrow broken chain of about 572 picturesque islands, islets and rocks extending along a general north-south direction in the southeastern part of the Bay of Bengal. Great Nicobar Island, the southernmost major island, lies about 450 km northwest of the epicenter (Figure 2). Only about 36 islands are inhabited by people. The islands are grouped into two, with the 10° international shipping channel as the divider: the Andaman Islands are north of N10° latitude, and the Nicobar Islands are south. North, Middle, South, and Little Andaman Islands are most populated amongst the former islands, and Car Nicobar, Great Nicobar, Katchal, and Kamorta are most populated amongst the latter. The total population in the A&N Islands per the 2001 census is about 356,152, with 314,084 people in the Andaman Islands and about 42,068 in the Nicobar Islands.

Though the intensity of shaking was VI-VII on the MSK intensity scale, the long duration of shaking, coupled with the low water table in many coastal areas, may have contributed to liquefaction. Evidence of liquefaction was noted in the South, Middle, and North Andaman Islands. However, no signs of liquefaction were available in the Little Andaman and three Nicobar islands, perhaps because the giant tsunami waves carried away the evidence and deposited layers of fine soil on the land. Detailed investigations with trenching at strategic locations may provide clarity.

Persons interviewed at Port Blair recall that the water receded before the first wave, and the third wave was the tallest and caused the most damage. However, persons at Hut Bay, Malacca, and Campbell Bay — locations far south of Port Blair — reported that the water level rose by about 1-2 m from the normal sea level and remained there before the first wave crashed ashore. Eyewitness reports put the tallest of the waves at about 8 m high at Campbell Bay (in Great Nicobar Island), about 10-12 m high at Malacca (in Car Nicobar Island) and at Hut Bay (in Little Andaman Island), and about 3 m high at Port Blair (in South Andaman Island). The significant shielding of Port Blair and Campbell Bay by steep mountainous outcrops may have contributed to the relatively low wave heights at these locations, whereas the open terrain along the eastern coast at Malacca and Hut Bay likely contributed to the great height of the tsunami waves there.

Topological Changes: The A & N Islands lie to the east of the Sunda-Andaman arc of the boundary between Indo-Australian Plate and the Burma Micro-Plate of the Eurasian Plate. Due to subduction of the former under the latter, the A&N Islands sustained uplift and subsidence. The lighthouse at Indira Point, the southernmost tip of the Great Nicobar Island, which was on high ground before the earthquake, is now under water, indicating a land subsidence of about 3-4 m. The MES inspection bungalow on the east coast of the Car Nicobar Island is now lapped by seawater, suggesting a subsidence of about 2 m and ingress of the waterline by about 50 m (Figure 3). The shopping arcade in Bamboo Flat near Port Blair (in South Andaman Island) now has water up to 0.3 m above the floor level, suggesting a land subsidence of about 0.9-1.2 m. The western coast of the Middle Andaman Islands shows emergence of new shallow coral beaches near Flat Island, suggesting an uplift of up to 0.3 m (Figure 4). The increased exposure of the RC piles at the jetty structure at Diglipur Harbor at the northern region of North Andaman Island (the northernmost of the A&N Islands) indicates an uplift of about 1.2 m.

Figure 4. Up-throw of coral beds and rock strata due to uplift on the western coast of Middle Andaman Island near Flat Island (photo: Javed N. Malik).

A mud volcano in the Middle Andaman became active after the earthquake, and gray mud and colorless gases were emitted; this resulted in the formation of a subcircular mound of about 70 m in diameter. The volcano had earlier erupted in 1983, 1996, and 2003. A number of other small mud volcanoes have formed since the earthquake. Close to this region, deep and wide cracks in the ground were observed, which caused severe damage to road pavements.

Building Damage: While damage in Little Andaman Island and all Nicobar Islands was predominantly tsunami-related, that in the islands north of Little Andaman was primarily due to earthquake shaking, though tsunami waves and high tides were also an issue. In general, the building stock consists of a large number of traditional and nonengineered structures. Many traditional structures are made of wood, and they performed well in the earthquake shaking (Figure 5a). However, a number of new, poorly constructed reinforced concrete (RC) structures suffered severe damage or even collapse due to shaking (Figure 5b).

The tsunami waves caused severe destruction in the coastal areas of the southern islands (Figure 6). Structures near the water were subjected to (1) a positive water pressure when the waves arrived, and (2) a suction pressure when the waves receded. A large number of buildings right on the water in Little Andaman and Car Nicobar islands were washed away, regardless of how they were constructed.

Figure 5a. *Single-story wood house in Port Blair with light roof had no damage (photo: C.V.R. Murty).*

Figure 5b. *A three-story RC frame building in the same town collapsed in a brittle manner (photo: Sudhir Jain).*

However, an occasional well-designed RC structure was seen standing even in the devastated areas. In the best of the cases, the frame of the infilled building was intact, while the infills were pushed out of plane (Figure 7). In some cases, where there were a number of buildings in a row normal to the shore, the waves destroyed the structures towards the shore, but buildings in the rear were shielded. However, the number of buildings that survived is a very small fraction of the total houses near the shore.

In the northern A&N Islands, tsunami-induced damage to the contents of buildings was significant, but there was less damage to the structure of buildings. For instance, in the Bamboo Flat area, the street front shops were inundated by the tsunami and the subsidence of land. The steel shutters of the shops were damaged. In some other buildings in the same region, the boundary walls collapsed. Substantial shaking-induced damage was observed.

Often, in masonry dwellings with load-bearing walls and light roof trusses made of either steel pipes or timber, walls are not tied together to create lateral resistance. Large

Figure 6. *General destruction of built environment at Hut Bay in Little Andaman Island (photo: C.V.R. Murty).*

Figure 7. *Shore-front buildng on Car Nicobar Island was inundated by the waves, but the frame resisted the wave effects (photo: C.V.R. Murty).*

movement of the flexible roofs from earthquake forces caused out-of-plane masonry wall collapse. Similar damage was observed at a much larger scale in many school buildings, where the long partition walls separating two classrooms were either badly damaged or had fallen due to out-of-plane instability (Figure 8).

In general, RC frame structures suffered a variety of damage due to earthquake shaking, from frame-infill separations and hinging at the ends of frame members, to collapse of structures. Despite the fact that ductile detailing is mandatory according to the code for this seismic zone (V), not all buildings are properly designed and built to ensure ductile response.

Generic RC structures are built in the A&N Islands for community facilities and for government office buildings. These structures were severely damaged during the shaking intensity of VII manifested in the islands. For instance, the Panchayat Bhavan Building in North Andaman Island sustained severe cracking to its infill walls and its brittle RC columns in the open ground story (see Figure 9). This building had experienced column damage due to inadequate lateral reinforcing ties in the 2002 M_w 6.5 Diglipur earthquake. Though the building was apparently retrofitted, this retrofit did not ensure safer building behavior, and similar damage patterns recurred.

Damage to Infrastructure: A newly constructed 268 m-long RC bridge over the Austen Strait, connecting the North and Middle Andaman Islands on the Andaman Trunk Road, had to be closed to even light vehicles. Three middle spans of the superstructure were displaced laterally by about 70 cm and vertically by about 22 cm and fell off the bearing (Figure 10). Some other spans were also

Figure 8. *Slender masonry walls dislodged due to out-of-plane instabilty and poor or no connection to the surrounding structural elements (photo: Durgesh C. Rai).*

Figure 9a. *The Panchayat Bhavan building showed severe cracking and damage to the soft first-story columns and infill walls (photo: Durgesh C. Rai).*

Figure 9b. *Detail of column failure in the ground story (photo: Durgesh C. Rai).*

moved laterally by about 2 cm to 15 cm. Two of the authors of this report visited this region two years ago after the moderate 2002 Diglipur earthquake. Their published reconnaissance report (Rai and Murty 2003) expressed the following concerns about this bridge:

"Inadequate seating of bridge deck over piers and abutments is a serious concern for its safety during a stronger earthquake in the future. The bearings are simple neoprene pads which are far from satisfactory for a bridge located in seismic zone V. Bridge deck restrainers are the minimum that need to be provided to ensure that the spans are not dislodged from the piers in future earthquakes."

The armed forces and the coast guard use air transportation in the A&N Islands, particularly to reach the islands south of Port Blair. There are only a few airstrips, namely at Diglipur (North Andaman Island), Port Blair (South Andaman Island), Malacca (Car Nicobar Island), and Campbell Bay (Great Nicobar Island). The airstrip at Car Nicobar has rigid pavement, but all the others have flexible pavement. The Car Nicobar runway was damaged at the junctions of the panels during the ground shaking. The damage was accentuated by the numerous landings made by the large transport aircraft bringing relief in the aftermath of the disaster. When spalling of the plain concrete was noticed at the junctions, landings of the large aircraft had to be discontinued and repairs were made. The flexible pavements at Port Blair and Diglipur also were cracked, though not seriously. The runway at Campbell Bay suffered no damage, though it was closest to the epicenter.

Figure 10a. *Chengappa Bridge over Austen Strait was rendered dysfunctional by displacement of the middle spans (photo: Durgesh C. Rai).*

Figure 10b. *Detail of the bridge deck showing lateral and vertical displacement due to shifting of the decks on their neoprene bearings (photo: Durgesh C. Rai).*

Civilians use ships and steamers for transportation between Port Blair and the Nicobar Islands and Little Andaman Island. Unfortunately, a number of jetties were damaged or collapsed during the earthquake shaking and the tsunami waves that followed. An 80 m segment of the approach jetty in Campbell Bay in Great Nicobar Island collapsed, thereby hampering relief efforts. Similarly, the collapsed jetty in Car Nicobar Island, and the breaching of one breakwater-cum-approach jetty and collapse of another approach jetty in Little Andaman Island also hampered relief efforts (Figure 11). In Port Blair, the Janglighat jetty collapsed. In the North Andaman Islands, jetties at Sagar Dweep and Arial Bay were damaged due to ground shaking, and the berthing jetty and a portion of the approach jetty at Gandhinagar collapsed. Pounding damage at several sections of jetties was observed.

The main source of electric power is from captive diesel-generator power plants. The 20 MW Suryachakra power plant in the Bamboo Flat area of Port Blair was adversely affected by the tsunami waves, which flooded the entire plant. Severe damage to mechanical and electrical equipment from the sea water forced the plant to shut down. On Car Nicobar Island, power generation was disrupted by both flooding of the generators with saline water and displacement of generators by the tsunami waves. The diesel oil tanks were carried away by the waves to the military airport runway about 2 km away.

Longitudinal cracks developed at the crest of the 27-m-high, 146-m-long rock-fill dam of the 5.25 MW Kalpong hydro-electric project near Diglipur in North Andaman Island. The cracks developed near the curved end along the axis of the straight portion of the dam. Movement was also noted across the block joints near both ends of a concrete dam and water seepage through the dam doubled after the earthquake. Misalignment of turbines caused disruption of electric generation, which was only partly restored after ten days.

Figure 11. *Shortage of appropriate construction material forced the use of porous coral stones from local quarries for building the breakwaters. The stones were easily uplifted during the tsunami and breached a large segment of the approach to the RC jetty at Hut Bay (photo: C.V.R Murty).*

Other facilities like hospitals and seaport/airport control towers collapsed due to shaking and/or wave pressure. The airport control tower at Car Nicobar is a three-story RC frame with masonry infills, and its upper story collapsed in the shaking (Figure 12a). The seaport control tower at Hut Bay on the east coast of Little Andaman Island also collapsed due to the tsunami waves (Figure 12b). This square-plan three-story RC frame building with masonry infills had only four-corner columns and, hence, limited redundancy. The large positive pressure created by the tsunami waves toppled the building. Similar tower designs are being used elsewhere in the country, particularly in the seismic zones, so there is an urgent need for corrective action to strengthen them.

Emergency Response: Though the entire Andaman & Nicobar Islands have been classified in the highest Indian seismic zone (V) and have had a history of earthquakes and some tsunamis, the level of preparedness for such an event was rather low. Being Union Territory, the islands are governed by the Home Ministry of the Government of India through a lieutenant governor based in Port Blair.

While government officials in New Delhi knew about the earthquake, it seems that they did not learn about the tsunami until after 9:00 a.m., when TV stations started reporting the tsunami on the mainland coasts. A Navy officer at Port Blair mentioned that while they faced the crisis, it did not occur to them to communicate this to the mainland and, furthermore, communications with the islands were disrupted. The lieutenant governor undertook an air reconnaissance to the Car Nicobar island on the evening of December 26 and realized that the southern islands had suffered extensively.

The islands have a sizable presence of the Indian armed forces and coast guard, and they took the lead in the rescue and relief work. A number of Navy ships left Port Blair for the southern islands on a relief mission on December 27. The air force made many sorties, carrying relief materials to the islands, and bringing back affected people. Anyone who wanted to leave the island was evacuated and put in the relief camps. Civil ships started operations the same afternoon from Port Blair, with seven ships sailing from Port Blair (including one to Chennai with 1,197 passengers). After about three days, the Directorate of Shipping Services was able to restore an almost normal schedule of shipping.

To improve coordination between the civil and the defense services, an Integrated Relief Command (IRC) was formed on January 1, 2005, with the lieutenant governor as chairman, and the commander-in-chief of the A&N command as the vice-chairman, operations head, and spokesperson. The A&N Islands Command was the first in India in which the concept of Integrated Defense Service had been

Figure 12a. *Partial-collapse of the upper storey of the air traffic control tower at airport on Car Nicobar Island (photo: C.V.R. Murty).*

Figure 12b. *Laterally toppled three-storey seaport traffic control tower at Hut Bay in Little Andaman Island (photo: Suresh R. Dash).*

implemented, with army, navy and the air force reporting to the same commander-in-chief. Initially, the defense officers had handed over relief materials to the civil authorities on the island and had not been involved in their distribution. After the formation of the IRC, and in view of complaints of uneven relief distribution, the armed forces posted two officers and 20 soldiers on each island to keep an eye on the distribution.

A number of knowledgeable persons expressed concern about rather slow decision making by the civil authorities in the A&N Islands; this may have been a consequence of the fact that the Islands do not have their own elected state government. With no local political leadership to demand action, the officers may have been cautious and conservative. However, there were instances of good performance as well. It must be understood that the tsunami caused a much greater level of trauma than did the major earthquake disasters in India in recent years. Even senior professionals in Port Blair frankly admitted that two weeks after the event they still felt traumatized.

Tsunami Impacts on the Mainland

The mainland suffered significant tsunami-induced damage, but no shaking-induced damage. Areas outside a strip about 500-1000 m wide along the shore looked as if nothing had happened. The arrival time of the tsunami wave front varied along the coast. On the southeast coast it was at 9:05 a.m. at Visakhapatnam, 9:05 a.m. at Kakinada, 9:05 a.m. at Chennai, and 9:37 a.m. at Tuticorin; on the southwest coast it was at 11:10 am at Kochi and 12:25 pm at Marmugoa (Figure 13). There were two to five waves of varying amplitude. The water receded after the first wave struck.

Figure 13 shows variations in runup height along the coast. It was only 1.6 m in areas in the state of Tamil Nadu that were shielded by the island of Sri Lanka, but was 4-5 m in coastal districts such as Nagapattinam in Tamil Nadu that were directly across from Sumatra. On the western coast, the runup elevations were 4.5 m at Kanyakumari District in Tamil Nadu, and 3.4 m each at Kollam and Ernakulam Districts in Kerala. Some of these amplitudes are based on eyewitness accounts and may be subjective. The time lapse between the waves also varied from about 15 minutes to about 90 minutes.

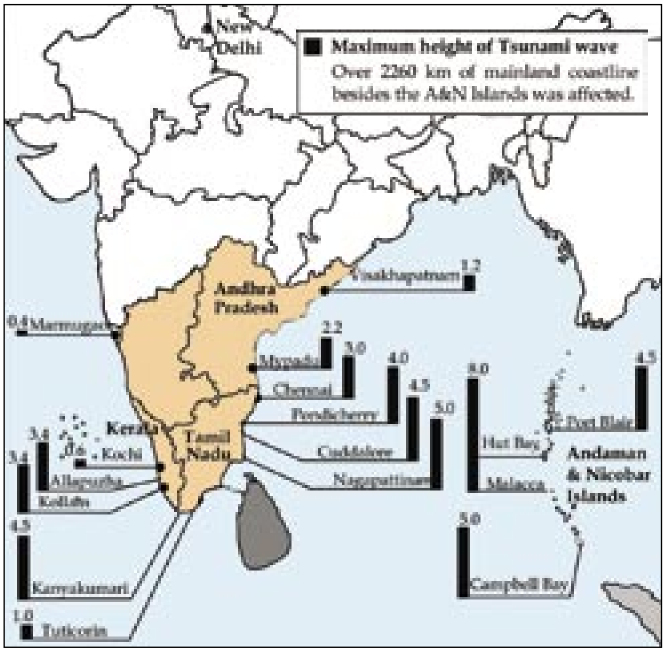

Figure 13. *Maximum tsunami wave heights at various locations. The vertical bar indicates the amplitude of wave height and the number indicates the value in meters.*

The maximum inundation distance varied between 100-500 m in most areas, except at river mouths, where it was more than 1 km. The inundation distance varied with topology and vegetation. Areas with dense coconut groves or mangroves had much smaller inundation distances, and those with river mouths or backwaters saw much larger inundation distances. The Kerala coast and some of Tamil Nadu coast have seawalls located 100-600 m from the shoreline, and these helped to reduce the impact of the waves. However, when the seawalls were made of loose stones, the stones were carried inland 20-30 m.

Tide levels did not return to normal until after December 29th.

Structural Damage: The damage was mainly to fishing communities and their infrastructure: homes, boats, and fishing nets were destroyed in the belt 200-300 m from the shoreline. Major ports and some coastal towns along the Kerala coast have breakwaters offering protection to the harbors, but many small fishing towns do not. Therefore, it is a practice to anchor all boats 200-500 m from the shore; fishermen swim to and from their boats. During the tsunami, these boats were tossed around and onto the land, and many of them were severely damaged or destroyed.

In ports and harbors, the major problem was caused by vessels breaking their ropes and hitting others. Small boats were tossed onto land by the incoming wave, while others were sunk in the harbor by the returning wave. Most breakwaters were not damaged, but siltation/erosion was observed.

Seawater intrusion was less in areas covered with thick vegetation as compared to those with bare lands (Pakala beach). Bare land sustained heavy erosion due to the returning wave. Intrusion of water with silt resulted in changes in land use pattern. Sand depositions from the tsunamis damaged standing crops in delta areas, and rendered the fertile soil non-irrigable.

Almost all the housing in the affected areas was nonengineered. Much of it was made of plastered masonry walls (usually brick) and sometimes of reeds, with roofs either of thatch, Mangalore tiles, or reinforced concrete (Figure 14). A large number of traditional structures built within 500 m of the water were destroyed (Figure 15). Along the Kerala coast, the damage and collapses of the housing stock appeared to be largely due to the scouring action of the waves (Figure 16), primarily the receding ones. Along the Tamil Nadu coast, there was significant damage due to the direct pressure of the water waves; however, no instances of fatalities in collapsed structures were noted.

Bridges and culverts were affected. At least three bridges were damaged, with one of them losing all four spans (Figure 17). Roads suffered significant scouring at numerous places along the coast, as did railway lines. Road e mbankments were eroded. Compound walls

Figure 14. *Houses destroyed by the waves at Nagapattinam in Tamil Nadu (photo: Alpa R. Sheth).*

Figure 15. *Mud house with thatch roof built within 100 meters of the sea at Pakala Beach in Andhra Pradesh (photo: Arvind Jaiswal).*

toppled at numerous places along the coast. Communication towers were also damaged or destroyed.

Sea ingress into a fresh water pond contaminated the water supply of one community. The intake water pipeline of one industry was damaged and shut down the facility for some time. Water pipe lines were broken or severely bent in numerous locations, rendering them unusable.

Emergency Response: Recent major earthquake emergencies in India affected only one state, but this disaster struck several states at the same time, affecting a much larger geographical region than ever before. As a result, the role for the central government in New Delhi became more critical. Moreover, the Government of India decided to extend substantial help to neighboring Sri Lanka.

Initial rescue efforts needed massive assistance of the Coast Guard and the defense services. Since 2002, disaster management is the responsibility of the Ministry of Home Affairs, but there were remarks about the lack of coordination between the Home Ministry and the Defense Ministry.

A major crisis and an embarrassment were created on the morning of December 30, 2004, when the Home Ministry issued a warning to the affected states of an earthquake and impending tsunami in the afternoon of the same day. This led to massive panic, and the state governments diverted their resources from relief to evacuation of the public from the coastal areas. Apparently an individual in the United States was behind the hoax, but the government should have considered it more thoroughly before issuing the warning. Considering that many coastal regions have effective warning systems for cyclones, this false warning may have deleterious effects on future warning response.

Relief was more timely on the mainland than in the A&N islands. The television focused on the disaster in the areas adjoining Nagapattinam, which brought a large number of NGOs to the area. To systematize the relief efforts, an NGO Coordination Cell was set up with the help of three NGOs: the South Indian Federation of Fishermen Societies (SIFFS), Nav Nirmaan Abhiyaan (Gujarat), and ACCORD (Nilgiris). Of these, Abhiyan had done considerable work in Gujarat after the

Figure 16. *Scouring action at the base of houses due to returning wave of the tsunami in Kollam district in Kerala (photo: Alpa R. Sheth).*

Figure 17. *Complete loss of spans of the four span RC bridge at Melmannakudi in Tamil Nadu (photo: Alpa R. Sheth).*

2001 earthquake, and SIFFS had been very active with the fishing community across the affected states. The large number of volunteers working in these NGOs significantly helped in the assessment of needs, the soliciting of useful relief materials, and the distribution of them.

After losing their homes, their boats, and their fishing equipment, fishermen and their dependents continued to suffer. At first there were no fish; when there were fish again, there were no buyers of the fish. The state governments gave livelihood restoration compensation to the fishermen, with the state of Tamil Nadu being the most generous. More than Rs.450 Crores (~US$100 million) were allocated for various expenditures: (1) replacement of nets, (2) repair and rebuilding of boats, and (3) repairs to outboard motors/inboard engine fitted in traditional craft.

Findings and Recommendations

A number of issues have emerged from this earthquake and the consequent tsunami that need to be attended to. Those related to earthquake vulnerability are directly below.

1) In general, earthquake-resistant design and construction are not being practiced in the A&N Islands, even though these islands lie in the most severe seismic zone (V) of the country. In certain instances, even major construction by government agencies, with the support of private structural engineers, shows noncompliance with seismic codes. This could be because the islands are logistically connected to Chennai and Kolkata (Calcutta), both in zone III. Hence, the structural engineers practicing in these cities may not be aware of the special requirements of constructions in zone V.

2) The traditional wood houses in the A&N Islands performed well during the seismic shaking, while many recently built masonry and RC structures suffered due to lack of adequate expertise locally to use the modern materials in earthquake regions. Unfortunately, the region is moving from traditional timber construction toward masonry and RC construction. Thus, the vulnerability of the islands to earthquakes will continue to increase.

3) The damage to the Austin Creek Bridge highlighted the fact that the Indian seismic code provisions for bridges are highly inadequate, and require urgent modifications.

4) In recent years, considerable investment has been made by the Government of India in seismic instrumentation. As a result, the observatory of the India Meteorological Department at Port Blair did have a digital strong-motion instrument, but it did not record the main event. This has been a major missed opportunity, and raises concern about the quality of training given to the concerned personnel.

5) The structures damaged during the 2002 M_w6.5 earthquake in Diglipur in the North Andamans and repaired subsequently showed poor performance in this earthquake. Lack of expertise among local engineers and few guidance documents on retrofitting continue to obviate major opportunities for seismic retrofitting. It is again not clear whether the damaged buildings in the islands will receive appropriate remedial measures after this earthquake.

6) Much critical infrastructure has shown vulnerability to seismic shaking. During this earthquake, harbor structures and airport and seaport control towers were added to the list of vulnerable lifelines structures that was drawn up after the 2001 Bhuj earthquake in Gujarat. There is a serious need to conduct strict structural

evaluation of lifeline structures in moderate to severe seismic zones of the country, and to strengthen them if they are found deficient. In addition, Indian standards need to be developed for seismic design of new harbor structures.

Issues related to tsunami vulnerability follow.

a) There was a total lack of awareness about tsunamis not only amongst the public, but also amongst officials and scientists. Senior government officials, scientists, and ministers were often seen on the TV stating that this was the first time a tsunami has hit India and hence nothing could have been done about tsunami warning systems. The fact that several damaging tsunami have hit Indian coasts in historical times came to be acknowledged much later.

b) An early warning could have saved lot of precious human and economic loss. The cyclone warning system, which is already in place in the country, may be enhanced to address the tsunami issue also. However, such a system can be effective only when scientific infrastructure in terms of quality of manpower and of instrumentation is enhanced.

c) Basic issues of earthquake safety in buildings (like an integral structure with good configuration, good quality of building materials and workmanship) are also helpful in resisting the tsunami effects.

d) Bridges in the coastal areas need to have lateral restraints to prevent the loss of spans during the buoyant conditions developed under high-tide levels.

e) Violations of Coastal Regulation Zone norms led to heavy damage to buildings and structures. The CRZ norms need to be strictly followed and implemented.

f) Buffer zones (raised land masses or forests) helped in curtailing the sea intrusion into the mainland, while the felling of trees, removal of mangrove forests, and construction of water channels invited severe damage. Preventing deforestation and protecting mangrove forests are priorities.

g) Safer mooring should be developed for the fishing boats in towns and villages along the coast that do not have a harbor.

Finally, we must mention that after every earthquake, the country has been putting more and more resources into instrumentation programs and into seismology, ignoring the need to strengthen engineering practice and research. Four years after the Bhuj earthquakes, no major municipal authority has a system in place to ensure that new construction actually complies with seismic code provisions; most cities require a structural engineer to certify that the building complies with the codes, but there are no mechanisms to ensure that such certifications are genuine.

It will be very regrettable if the large number of deaths caused by the 2004 tsunami further diverts attention from the variety of necessary engineering and code programs by focusing attention only on setting up tsunami warning systems.

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