The Effect of the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami on Transportation Systems in India's Andaman and Nicobar Islands

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Boats and ships are the major modes of transportation among the Andaman and Nicobar group of islands. The Andaman Trunk Road also forms an important part of the transportation system in the Andaman Islands north of Port Blair. The harbor structures in the islands were the most affected during the ground shaking; the result heavily disrupted the lives of the island residents. These transportation systems are expected to be in working condition after a major disaster, to facilitate the search and rescue operations and the relief work in the affected areas. A reconnaissance team surveyed the damage that the 2004 earthquake and tsunami caused to the transportation structures in the islands. Damage was observed in all transportation systems, including harbors, highways, airports, and hangars.
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INTRODUCTION

The major modes of transportation in the Andaman and Nicobar (A&N) islands are—in the order of their importance and usage—sea, road, and air. People use ships to travel among the A&N islands, and also between the islands and mainland India. This makes the harbors the most widely used transportation systems in the islands. In addition, the Andaman Trunk Road (ATR) is also used as the main mode of land transportation among the Andaman Islands. Port Blair, on the eastern side of South Andaman Island, is also connected to Chennai and Kolkata in mainland India by aerial routes, although the traffic volume is rather low. Transportation systems are required and expected to perform better during a natural catastrophe like the 26 December 2004 earthquake. In far-off and isolated places like the A&N islands, where alternate sources of transportation are difficult to generate, good performance of these systems is even more important. If transportation structures fail or sustain severe damage, then the search and rescue op-

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erations and relief work can suffer critically. The performance of the transportation systems in the A&N islands during the 26 December earthquake shaking is discussed below.

Intense ground shaking occurred at about 6:30 A.M. India standard time (IST), and 50 minutes elapsed between the initial earthquake and the first tsunami wave. Port Blair was struck by four waves, with the largest being about 5 m high. The approximate time between waves was 30−35 minutes. The digital strong-motion instrument installed at Port Blair by the India Meteorological Department failed to record the main event. The intensity of ground shaking during the earthquake in Port Blair was VI–VII on the MSK intensity scale (Jain et al. 2005). For shaking intensity VII, the average peak ground acceleration was generally about 0.1 g. Analysis of a collapsed RC bicycle and motor scooter shelter also indicates that the peak ground acceleration in Port Blair during the earthquake was about 0.1 g (Kaushik and Jain 2006).

ROADS

Widespread lateral spreading in the Andaman Islands led to significant damage to pavement and drainage structures of the ATR and other link roads (Figure 1).

The tectonics-induced subsidence of the land has led to submergence of roads in some areas, particularly in the low-lying areas neighboring Port Blair (Figure 2).

BRIDGES

The Andaman Islands have a larger population, and hence more roads and bridges, than the Nicobar Islands. In general, the superstructures of bridges in the A&N islands are of three types: reinforced concrete (RC), steel truss (e.g., Bailey bridge), and wooden sleeper (semipermanent). In general, the substructures are made of either RC or masonry. Under earthquake shaking, the steel truss-type systems performed reasonably better. However, the RC bridges showed varied damage.

The largest bridge in the A&N islands is over the Austen Strait, which connects the North and Middle Andaman islands on the ATR. This is a newly constructed 268-m-long 7.5-m carriageway RC bridge (Figure 3). Two of the authors had visited this region two years ago after an M_w=6.5 earthquake on 14 September 2002 and had expressed the following concerns about this bridge in published reports (Rai and Murty 2003, 2005):

> *"Inadequate seating of bridge deck over piers and abutments is a serious concern for its safety during a stronger earthquake in 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."*

Damage to the bridge during the 26 December earthquake was in line with the above observation and could have been far worse in the event of stronger shaking. The fifth, sixth, and seventh spans from the Diglipur side were displaced by about 700 mm horizontally and by about 220 mm vertically from their original position and fell off the bearings. Other spans, including the third, fourth, eighth, ninth, tenth, and eleventh spans

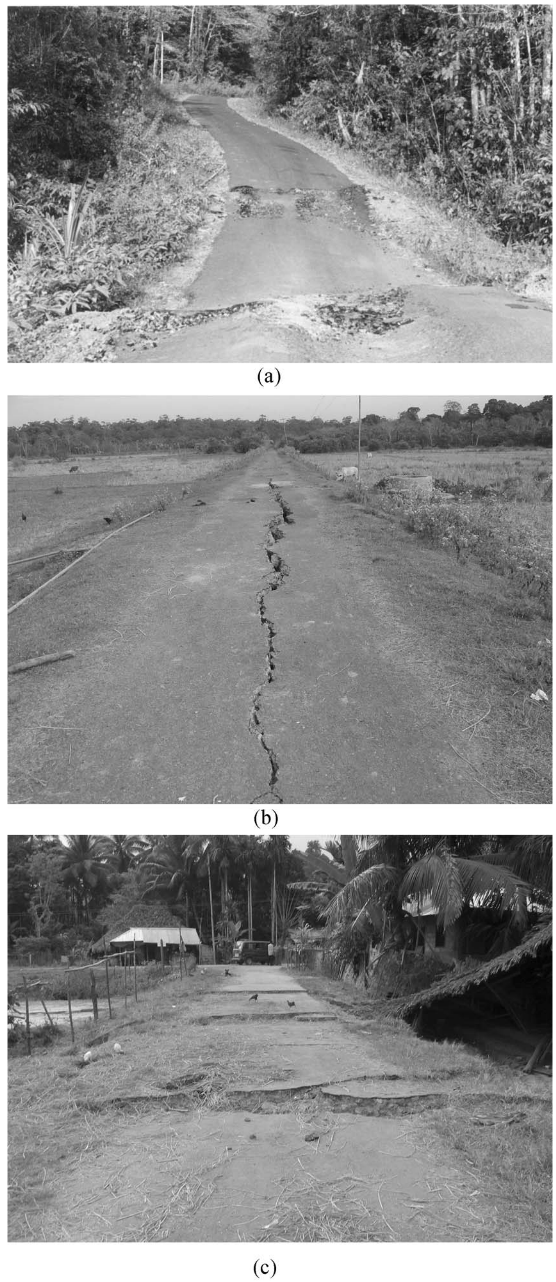


Figure 1. (a) Subsidence of a stretch of road connecting Baratang town to Jarawa Creek on Middle Andaman Island led to the closing of the road to traffic (photo: G. Mondal). (b) and (c) Longitudinal and transverse ground deformation at Mohanpur village in North Andaman Island (photos: D. Rai).

Figure 2. Seawater flooded the ATR in the Sippyghat area near Port Blair during high tide (photo: G. Mondal).

from the Diglipur side, moved by about 20–150 mm horizontally. As a result, the bridge had to be closed even for the light vehicles that were used immediately after the earthquake, particularly when the bridge was needed for facilitating postearthquake emergency services across the islands. Fortunately, the shaking at the site was rather low (VI–VII on the MSK intensity scale), and the span did not fall off the piers. Hence, in the present instance, it was relatively easy to restore the bridge. Because of the remote location of the bridge and the absence of large contracting firms in the islands, the bridge remained out of operation for more than six months.

Wing walls of a small bridge near Port Blair were cracked and displaced by several centimeters. The CD Nala/BD Nala Bridge along the ATR, about 88 km north of Port Blair and 19 km south of Baratang, sustained minor damage. It is a three-span bridge consisting of a 31.5-m-long steel Bailey bridge span in the middle and 3-m-long concrete spans at each side (Figure 4). Separation took place at the joint of the concrete wing wall and the abutment at both sides of the bridge, while the Bailey bridge portion performed well. Cracks in the floor slab were noticed in a box culvert 8 km south of Gandhighat.

Bridges and culverts on the ATR between the Uttara jetty and Rangat in Middle Andaman Island suffered minor or no damage. Dislocation of wing walls was observed in the Kalunala Bridge (Kalunala is 19 km north of Kadamtala), the Mithanala Bridge, the Dhaninala Bridge, and a Kunjunala culvert. No damage was observed in the bridges at Rangat Bay and surrounding areas (e.g., Bakultala, Shyamkundu, and Urmilapur). Hairline cracks were observed in the pier of a 47.4-m-long bridge over the Panchabati River in Middle Andaman Island; the bridge was constructed in 2002.

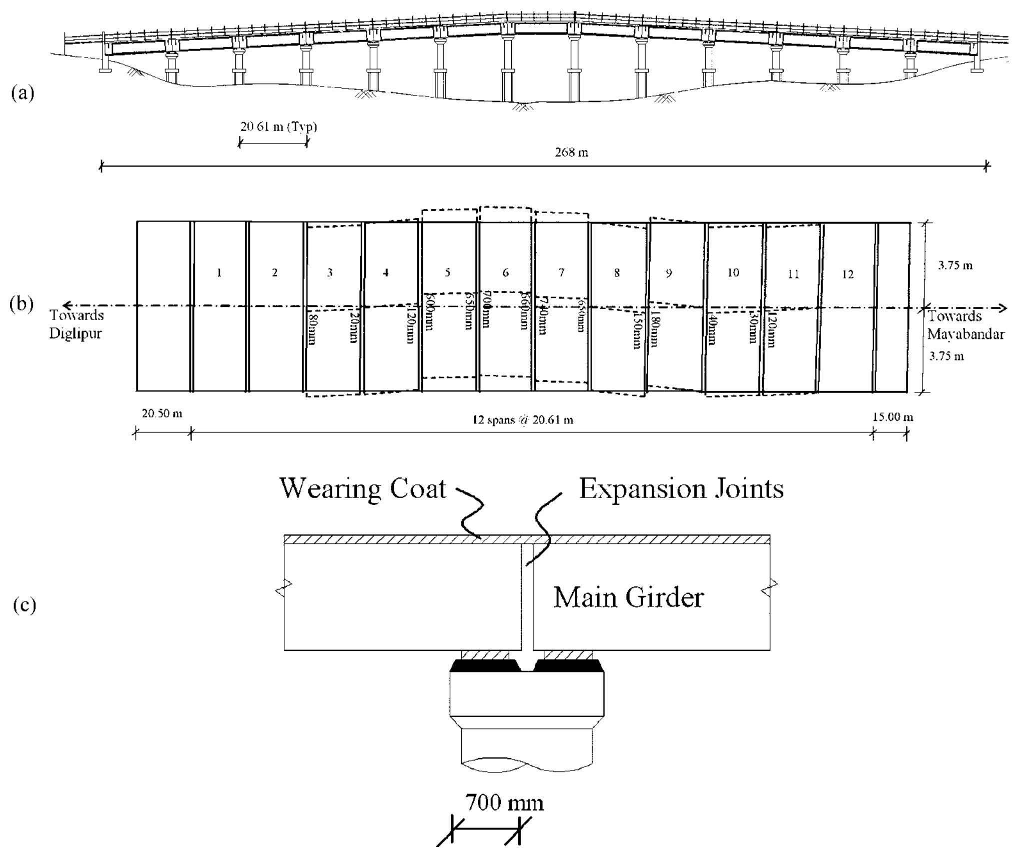
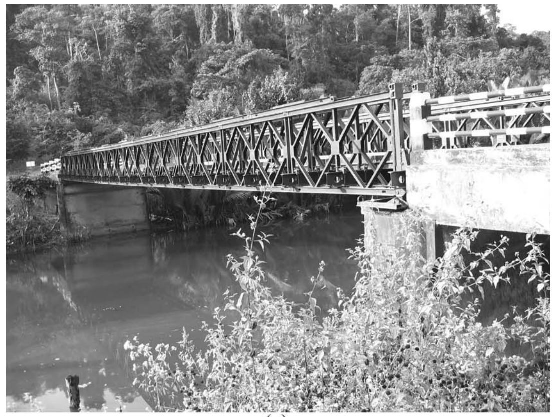


Figure 3. (a) Elevation of the Chengappa Bridge over the Austen Strait at Mayabandar, (b) alignment of the bridge after the 26 December 2004 earthquake, and (c) seating details of the bridge girder.

AIRPORT RUNWAY PAVEMENT

The armed forces and the Coast Guard use air transportation among the A&N islands, particularly to access the islands south of Port Blair. There are only a few airstrips in the A&N islands, 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 alone is of the rigid pavement type, while all the others are of the flexible pavement type. The Car Nicobar runway was built by the Japanese in the 1940s and was recently extended by the Indian Air Force. Locally available light and porous coral aggregates were used as coarse aggregate. The airfield pavement at Car Nicobar Island is made of rectangular panels 6 m wide and 3.75 m long along the runway. Each of these panels is 550 mm thick.

Ground shaking during the 2004 event damaged this pavement at the junctions of the panels. This damage was accentuated by the numerous landings made by the large trans-



(a)

(b)

Figure 4. (a) CD Nala/BD Nala Bridge on the ATR in South Andaman Island, and (b) cracks and separation at the joint of the wing wall and the abutment (photos: D. Rai).

port aircraft (IL76) that were providing relief in the aftermath of the earthquake. The situation became alarming when spalling of the plain concrete went as deep as 300 mm along the runway at the junctions; landings of IL76 aircraft had to be discontinued, and repair work was begun on this airstrip. The flexible pavement at Port Blair and Diglipur also suffered cracks, although relatively minor in nature. The runway at Campbell Bay did not suffer any damage, even though it was closest to the epicenter.

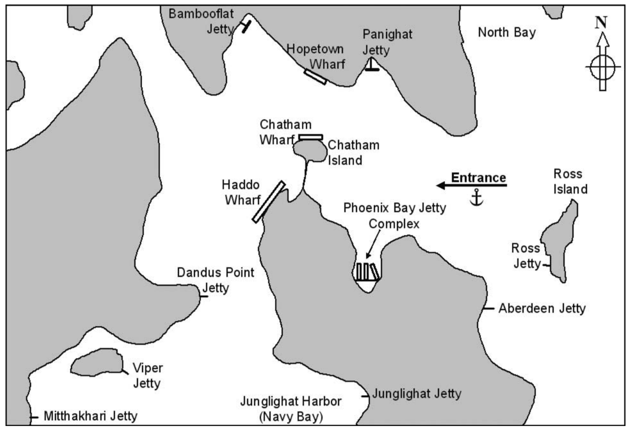


Figure 5. General Layout of Port Blair Harbor. (source: IIT Kanpur).

HARBOR STRUCTURES

The capital city of Port Blair serves as the government center for the islands and is the primary commercial center. The port complex serves as the major throughput for goods and passengers to the islands, handling about 97% of all commerce. Some 275,000 passengers come through Port Blair from the mainland each year, and as many as 375,000 for inter-island passage. The port handles about 800,000 metric tonnes (MT) of cargo and 15,000 20 equivalent units (TEUs) per year. The main port has multiple wharves, including Chatham Wharf, which is a concrete pile structure 150 m long and 9–14 m wide. The Haddo Wharf, a concrete pile structure, is approximately 180 m long. The Junglighat small-craft pier is used for fishing and small craft. The Phoenix Bay pier is near the main ferry terminal building. The main port also has a dry dock. Container wharves, general cargo wharves, and an oil terminal are all within the port area. The major product of the islands is coconuts. The natural harbor area has a large mouth facing east and was partially shielded from the tsunami by Ross Island. The harbor at Port Blair is about 1,000 km north and slightly west of the 26 December earthquake epicenter. Figure 5 shows the general layout of the natural harbor of Port Blair.

Reportedly, there were 20 vessels in the port at the time of the earthquake. All mooring lines were immediately cut (primarily by fire axes on the vessels, because there were no steel mooring lines), and captains of the vessels were told that their vessels must depart immediately. This was the established procedure for seismic events at Port Blair, and it was done in the absence of any knowledge of the impending tsunami.

After the earthquake and tsunami, the main port area of Port Blair had an increase in water depth of approximately 1 m. The probable cause was a tectonic uplift after the earthquake. On the western side of the island, a similar decrease in water depth has been noted. The maximum increase in water depth on the island was reported to be over 2 m. In Port Blair City, structures were damaged by ground shaking, liquefaction, surface faulting, tectonic subsidence, and the tsunami on South Andaman Island. At the ports, the concrete pile wharf/pier structures performed quite well, and in some cases even carried vessels as they were dropped onto the deck by the tsunami. Structures that had prior deterioration due to age, poor construction quality, or prior damage did fail during the earthquake, and in some cases entire sections of piers disappeared, and only light poles remained above the water line.

The tsunami damage to port and harbor structures was limited. In some cases, barges or vessels were left on the top decks of wharves, but there was no apparent structural damage.

Part of the reason for the light damage was that, at Port Blair, the rules mandated that all vessels must depart after an earthquake. This saved many lives, because a ferry terminal was loading passengers at the time of the 26 December event. About 50 minutes elapsed before the first wave arrived. Port personnel did an excellent job of vacating the port and making sure that all personnel had left the area. The main ferry terminal was severely damaged by the earthquake and was shut down.

The water level at Port Blair was permanently raised by about 1 m due to tectonic subsidence of the eastern side of the island. This apparent rise in the mean sea level created potential problems, because it is almost as high as the underside of some wharf

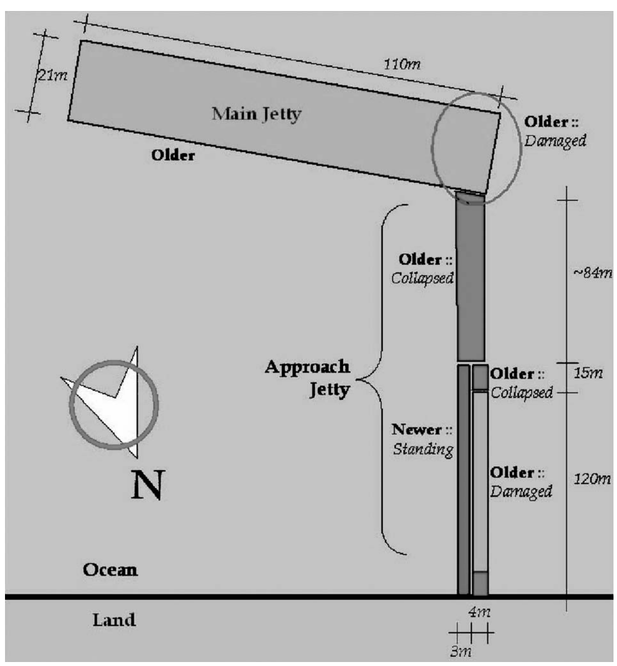


Figure 6. The layout of the inter-island passenger ship jetty at Campbell Bay consists of older and newer segments; the former were severely damaged, and some of them collapsed.

Figure 7. An 80-m segment of the RC approach jetty at the inter-island passenger ship jetty at Campbell Bay was washed away (photo: C. Murty).

structures. It also modified the mooring line angles, making them steeper, thus transferring more vertical load to bitts, bollards, and hooks, and it changed the vertical location of berthing contact points.

Civilians use ships and steamers as the main means of transportation between Port Blair and the islands south of Port Blair (the Nicobar Islands and Little Andaman Island). The $Mw=9.3$ earthquake and subsequent tsunami caused severe damage to harbor structures in the Andaman Islands. A number of major harbors and several small jetties in the A&N islands are managed by Andaman Lakshadweep Harbor Works (ALHW); these facilities include jetties used for inter-island shipping, local ferries, and vehicle ferries.

A number of shorefront structures and jetties suffered damage or collapse during the earthquake shaking and the tsunami waves that followed. For example, collapse of the inter-island passenger ship jetty at Campbell Bay in Great Nicobar Island collapsed, thereby hampering relief efforts. This jetty originally consisted of a 220-m-long approach jetty and a main jetty about 110 m long in a re-entrant corner configuration. The jetties were all supported on 300-m square piles (Figure 6). The approach jetty was later widened to 7 m for a distance of ~115 m on the landward side. During the earthquake, the 80-m segment of the approach jetty connecting the two re-entrant arms collapsed (Figure 7). The existing segments of the jetty show shear failure at the top of the piles underneath.

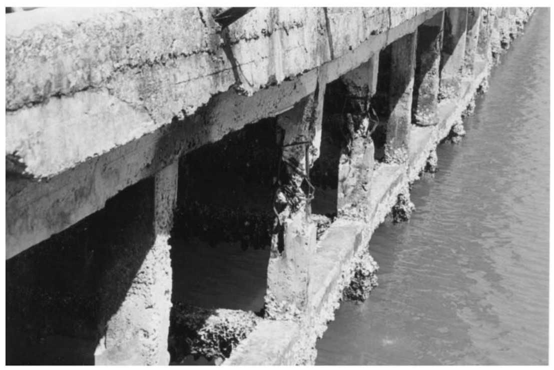
Similarly, the collapsed jetty in Car Nicobar Island, and the breaching of one breakwater-cum-approach jetty and collapse of another approach jetty at Hut Bay in Little Andaman Island (Figure 8), also hampered the relief efforts. At Hut Bay, an RC jetty 32 m wide and 240 m long sustained pounding damage between the old segments (four subsegments of 40 m each) and new segments (two subsegments of 40 m each) of its vierendel-type deck. Furthermore, the 300-mm square RC piles underneath the new

Figure 8. An RC jetty at Hut Bay in Little Andaman Island. The jetty collapsed, which hampered relief work (photo: C. Murty).

segment sustained shear failure at their junction with the deck; this may have led to the 150-mm horizontal separation between the two segments. Jetty structures also collapsed elsewhere in the Nicobar Islands, namely, Kamorta and Katchal islands. In Port Blair, the Janglighat jetty collapsed (Figure 9). In North Andaman Island, jetties at Sagar Dweep and Arial Bay were damaged due to ground shaking (Figure 10). Also, in North Andaman Island, the berthing jetty and a portion of the approach jetty at Gandhinagar

Figure 9. The Janglighat jetty in Port Blair has a sudden change of orientation in its plan geometry. Also, there was additional mass in the form of a passenger verification building at that vulnerable location, and the supporting piles underneath were poorly designed. For these reasons, the jetty partially collapsed due to earthquake shaking (photo: C. Murty).

(a)



(b)

Figure 10. (a) A portion of the berthing jetty at Diglipur Harbor sank due to the failure of piles (photo: D. Rai). (b) Severe corrosion led to damage of the columns of the approach jetty at Rangat Bay Harbor in Middle Andaman Island (photo: G. Mondal).

collapsed. At Mayabandar and Rangat in Middle Andaman Island, several piles supporting the jetty superstructure were damaged (Figure 11). Pounding damage at several sections of jetties was observed.

The Haddo naval jetty suffered severe damage during the earthquake. This jetty has a re-entrant plan shape, due to the extension of the jetty in 2003. The intersection between the old and new construction suffered severe damage. In some harbor structures, the approach to the berthing structures was lost. For example, the breakwater-cum-approach road to the jetty at Hut Bay in Little Andaman Island was breached by the giant waves (Figure 12). This is attributable to the use of light, porous coral stones quarried locally to construct the breakwaters. Such stones became afloat when inundated during the 26 December event. The retrofit of the breakwaters needs good-quality construc-


(a)


(b)

Figure 11. (a) Approach jetty at Mayabandar in Middle Andaman Island. (b) Close-up of the shear failure of short piles close to the shore where the approach jetty begins (photos: D. Rai).

tion material. The reuse of the low-quality material in any future construction needs thorough examination. On this occasion, even the RC jetty structure sustained shear failure of the 300-mm square piles on which it rested.

The Port Blair area has a number of jetties, both old and new. The marine jetty in the Phoenix Bay area of Port Blair suffered severe damage due to the earthquake shaking and tsunami waves. Large numbers of piles over which the jetty was constructed either sustained damaged or settled down, as was evident from the difference in ground level. Before the earthquake, the marine jetty dry dock used to remain dry for maintenance work on ships, but now the dry dock submerges during high tide because of the subsidence of land in the area by about 1 m (Figure 13a). The complex has three major structures: the new dry dock, the old dry dock, and the fiberglass boat shed. All these structures suffered extensive damage from shaking and inundation. This periodic inundation became a menace for the workers in the machine shop, because seawater was entering

Figure 12. A shortage of appropriate construction material led to the use of porous coral stones from local quarries to construct the breakwaters. The stones were easily uplifted by the tsunami waves, and the waves breached over 100 m of a segment of the approach breakwaters of the RC jetty at Hut Bay in Little Andaman Island (photo: C. Murty).

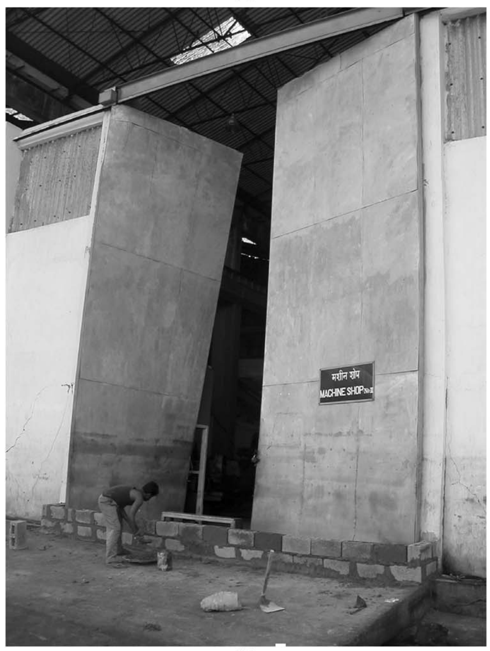
the machine room and damaging the steel equipment and tools. In some instances, masonry walls were raised to prevent the ingress of seawater and protect the contents of the workplace (Figure 13b).

Unserviceable offshore and foreshore harbor structures in the islands delayed the performance of relief work in the earthquake- and tsunami-affected area. Major damage was observed at the expansion joint of two portions of a jetty and at the top of the piles, especially at the top of the short piles; this damage was mainly due to inadequate design, inadequate detailing, and poor maintenance of the structures. Structural damage was also observed that was due to various phenomena related to soil liquefaction. Indian standards do not exist for the design of harbor structures subjected to seismic shaking, particularly for quantifying the effects of liquefiable soils underneath the structures on the design force.

RELIEF AND RESPONSE

The jetties at Car Nicobar, Kamorta, and Champin islands were fit for operations, but the others were severely damaged, hence the prime mode for transporting relief materials to the affected A&N islands was by air. Of 65 inter-island vessels of the A&N Administration, 40 were operational after the earthquake, 18 were undergoing annual repairs, and 7 were damaged. Eighteen vessels were plying between Port Blair and the prominent ports at Mayabandar, Havelock, Baratang, Diglipur, Neil Island, Rangat, Hut Bay, Long Island, and Campbell Bay. Six private vessels were in operation between Port Blair and the ports at Rangat, Havelock, Diglipur, Mayabandar, and Neil islands. Two boats each were provided at Kamotra, Nancowry, and Champin islands for inter-island movement within the Nancowry group of islands, which were the worst affected. Because of the huge relief operation that was required, commercial ships were also used for carrying

(a)



(b)

Figure 13. (a) Inundation of the marine jetty dry dock complex in Port Blair. (b) The steel gates of the machine shops at the marine jetty dry dock complex were bent by the giant tsunami waves; a 300-mm-high masonry wall was constructed in front of the shops to prevent seawater from entering them during high tide (photos: H. Kaushik).

relief supplies from Chennai, Kolkata, Haldia, and Visakhapatnam. Of the 30 lighthouses in the A&N islands, only 2 were functioning. Docks were severely affected. Dry dock 2 at Port Blair was still under restoration as of 18 January 2005. Special teams were sent, along with the necessary materials, to repair a damaged wharf at Hut Bay and

Figure 14. Partial collapse of the upper story of the ATC tower in Car Nicobar Island (photo: C. Murty).

jetties at Campbell Bay and Mus. It is estimated that about Rs. 304 crores (US $67.6 million) is required to restore the shipping sector in these islands.

AIRPORT AND SEAPORT TRAFFIC CONTROL STRUCTURES

Lifeline facilities such as seaport and airport control towers collapsed due to shaking and/or waves. For instance, the airport traffic control (ATC) tower at Car Nicobar collapsed due to earthquake shaking alone (Figure 14). This RC-frame, three-story square-plan structure with masonry infills had only four corner columns, and hence it had limited redundancy. As per functional requirements, the top story had a glass facade all around and was inclined downward to allow the viewing of aircraft in the airspace of the airport without reflecting glare to the aircraft. However, the RC columns were also bent outward along the slope of the glass. During the shaking, the upper story collapsed due to its flexible nature and brittle columns. Such type-designs (i.e., generic designs that are not earthquake-resistant) of the ATC towers are being used elsewhere in the country, particularly in the severe seismic zones; this aspect requires urgent corrective action to strengthen the towers to resist seismic shaking and/or wave loading.

The two-story, circular RC-frame Courier Point Building at Car Nicobar Airport collapsed due to ground shaking. It had an octagonally shaped roof, and the frame building had no infills in the first story, so it can be classified as a “building on stilts.” The building is situated at an elevation where the tsunami waves did not reach. The building was irregular due to a number of architectural features, including an asymmetric staircase (Figure 15). The columns in the first story were of 330-mm diameter with eight 16-mm-diameter high-yield-strength deformed bars as longitudinal steel and 6-mm mild steel ties at 150-mm centers as transverse steel. The building suffered large asymmetric torsional deformation, causing total crushing of columns in the first story.

Figure 15. Collapsed two-story RC-frame Courier Point Building at Car Nicobar Airport (photo: C. Murty)

In general, port communication towers were RC-frame structures with masonry infill walls. By the time of the earthquake, the RC members of the structures had significant longitudinal cracks due to corrosion of the steel bars. The eyewitness reports indicate that, at best, the crack widths have increased after the earthquake. In at least one tower, namely, the Chatham Port control tower, earthquake damage was noted. This tower was originally a three-story RC tower and was extended to four stories during the 1970–71 war. The damage was concentrated in the fourth story alone—all beams at the roof of the fourth story were cracked during the earthquake shaking.

The seaport traffic control (STC) tower at Hut Bay on the east coast of Little Andaman Island also collapsed due to tsunami-induced damage (Figure 16). This RC-frame, square-plan three-story building with masonry infills had limited redundancy, with only eight perimeter columns. The large positive pressure created by the giant tsunami waves toppled the building. As in the case of the ATC towers, such type-designs of STC towers are also being used elsewhere in the country, particularly in the severe seismic zones; this aspect requires urgent corrective action by the authorities to strengthen and/or modify the towers to resist wave loading.

The airport at Port Blair was relatively less damaged; the main runway sustained cracks but was made fully operational soon after the earthquake. The Ministry of Civil Aviation ran 125 special flights (via Indian Air Lines and Jet Airways), including 24 cargo flights.

CULVERTS

The small culverts along the roads, which allow cross-drainage, were affected by the action of the tsunami waves. Most of these culverts are simply supported slab culverts

Figure 16. Laterally toppled three-story STC tower at Hut Bay in Little Andaman Island (photos: S. Dash).

with no connection with the RC vertical walls or RC pipes on which they rest. When the water rose above the culvert level, the RC slabs became afloat; where RC pipes were used, they were displaced but not completely uplifted, but the bitumen topping over them was washed away (Figure 17).

CONCLUSIONS

Extensive damage occurred to the coastal and harbor structures in the A&N islands, whereas roads and bridges in the area sustained moderate damage. The airport and seaport control towers also suffered extensive damage, which disrupted the air and sea traffic in the islands. The airport runways, hangars, dams, water tanks, pipelines, and electrical distribution systems also suffered various kinds of damage. From an earthquake standpoint, the concerns include the following:

Figure 17. Small culverts along roads were washed away under the tsunami water surge in Little Andaman Island. (a) seven 1.5-m-diameter, 100-mm-thick RC pipe culverts lost bitumen topping. (b) an entire pipe culvert was washed away (photos: C. Murty).

- Specifications need to be developed for the seismic design of harbor structures in the country.
- The control towers at the airports and seaports in moderate-to-severe seismic zones of the country need to be subjected to a strict structural evaluation, and their safety under strong seismic conditions needs to be assessed and increased, if the structures are found deficient.
- The existing harbor structures and other lifeline infrastructure, which are critical and necessary in the aftermath of an earthquake, should be evaluated and strengthened where needed.
- Flexible seismic joints must be provided in long pipelines that supply drinking water and other essential resources to various parts of cities in the higher seismic zones.

- The use of conventional neoprene pad bearings in bridges must be thoroughly reviewed before such bearings are used in new construction. The addition of a few really simple earthquake-resistant features in bridges, such as lateral restrainers for bridge decks, can be critically useful in the event of strong shaking.

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