

# Impact of Great December 26, 2004 Sumatra Earthquake and Tsunami on Structures in Port Blair

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**Abstract:** This paper reports on the effects of the great Sumatra earthquake and tsunami of December 26, 2004, in and around Port Blair, the capital city of the Andaman and Nicobar Islands, India. The earthquake shaking and subsequent tsunami caused substantial damage to structures that include buildings, harbors, overhead water tanks, seaport control towers, and so on. Other important structures, for example, dams, bridges, hangars, and so on, also suffered minor damage without disrupting their functioning. Reinforced concrete structures on the islands were the worst performers, while traditionally constructed timber and masonry structures performed well in response to ground shaking. The mandatory Indian Standards were not complied within the design of many recent structures on the islands located in the most severe seismic zone in India.

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## Introduction

The great earthquake and tsunami of December 26, 2004, caused widespread damage in Port Blair, where the maximum intensity of shaking was VII on the Medvedev-Sponheuer-Karnik (MSK) scale (Jain et al. 2005a). This great event should not be treated as a surprise because the Andaman and Nicobar (A&N) islands are known to be one of the most seismically active regions and are placed in seismic zone V, the most severe seismic zone as per the Indian code (IS:1893) (BIS 2002). It has been reported that the plate tectonic activities responsible for the great earthquake, were responsible for uplift of A&N islands on the western side, and subsidence on the eastern side (Malik and Murty 2005). Several parts of Port Blair were found to have submerged into the sea by 0.9–1.2 m as shown in Fig. 1 (Jain et al. 2005b). Soon after the earthquake, the writers conducted a reconnaissance survey of the affected areas in and around Port Blair. The performance of various structures due to ground shaking and the subsequent tsunami is documented in the present paper.

## Historical Construction Practices

In the modern era, the islands were first noticed by the East India Company in 1789 when Lt. Archibald Blair surveyed the islands

and reported them to be suitable for establishment of a British colony. Lt. Blair constructed a few masonry buildings on the islands, but because of the hostile climate and unavailability of potable water, the colony was abandoned in 1796. The first freedom struggle in India began in 1857, when Indians working as soldiers with the East India Company revolted. The islands were reoccupied by the British to create an Indian penal settlement to keep the freedom fighters away from rest of the Indian population to suppress the revolt. Several masonry buildings were constructed on the islands for residences, storage, hospitals, schools, churches, jails, and so on. The high-quality masonry structure of the Cellular Jail was built in Port Blair during 1896 to 1906 using solid clay brick masonry. The Cellular Jail had a 5-story central controlling tower with seven 3-story wings emanating from the tower [Fig. 2(a)]. The jail had 696 cells for confining the people involved in the independence struggle of India.

Masonry was the most widely used construction material on the islands till the earthquake of June 26, 1941, which damaged several masonry buildings, perhaps including part of the Cellular Jail (Jhingran 1952). About 6 months after the earthquake, the Japanese captured the islands in December 1941 during World War II. Japanese soldiers used bricks from existing buildings to construct bunkers and other military establishments on the islands. Around the same time, and as a consequence of poor performance of masonry buildings in the 1941 earthquake, construction of wooden buildings started using locally available timber. British forces reoccupied the islands after the World War II ended in October 1945.

After independence in 1947, the islands became an important base of the Indian navy because of the islands' strategically important location. Later, the picturesque islands developed into a famous tourist destination, which boosted construction activities in a big way. Therefore, the government restricted the use of timber in construction projects for environment reasons. In addition, a few major fire accidents resulted in perceived superiority of reinforced concrete (RC) construction, which was responsible for a sudden leap in RC frame buildings on the islands in the 1990s.

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(a)



(b)

**Fig. 1.** Inundation of low-lying areas in and around Port Blair indicating subsidence of islands: (a) aerial view; (b) inundated houses at Nayashahar near Port Blair

### Performance of Masonry and Timber Structures

Presently, only a few masonry structures are left in Port Blair, and these performed well during the shaking caused by the 2004 event. A temple (*Police Mandir*) at Aberdeen market in Port Blair is a single-story brick masonry structure constructed in the 1930s [Fig. 2(b)] that did not suffer any damage during the 2004 shaking. The mosque at Aberdeen in Port Blair (*Jama Masjid*) is a single-story masonry structure (20 m high and  $22 \times 32$  m in plan) constructed in 1913 with hemispherical domes and minarets.

The mosque was damaged in the June 26, 1941 earthquake (magnitude 7.7), after which it was retrofitted using tie rods across the halls, which tied the walls together. In 2001–2002, while the mosque was being renovated, the tie rods that had corroded over the years were replaced. During the 2004 shaking, the building performed very well, the only damage being the collapse of a few slender minarets [Figs. 2(c and d)]. This mosque provides a good example of how simple retrofitting interventions in time can be critically beneficial to the building in the event of an earthquake.

Traditional timber buildings in Port Blair performed extremely well during the shaking, and several properly maintained timber buildings did not suffer any structural damage [Fig. 2(e)]. A few timber buildings with improper maintenance suffered minor damage in the form of detachment of timber planks from the timber frame [Fig. 2(f)].

### Performance of RC Buildings

Presently, RC buildings are preferred over the traditional timber and masonry construction. At several places, older timber structures are being abandoned for newly constructed and supposedly “strong” RC buildings. An interesting example is of a 50-year-old timber office building in the Marine jetty dry dock campus, which was considered dilapidated and was being vacated at the time of the earthquake shaking [Fig. 3(a)]. The office complex was being shifted to a newly constructed 3-story RC building (*Siddhartha*) situated right across the road [Fig. 3(b)]. The timber building performed well during the shaking, even though the *Siddhartha* building was significantly damaged. Damages were observed in the RC frame and masonry infills in the *Siddhartha* building and severe corrosion was observed in the building due to poor quality of construction. As a result, the *Siddhartha* building had been

vacated while the old timber building was being used as the office complex.

Various types of damage were observed in most of the residential, commercial, and government RC buildings in Port Blair, which are generally two and three stories high. Several deficiencies identified from the damage and collapse of RC frame buildings are discussed in the following.

#### Open First-Story Collapses

In recent years, common construction practice in Port Blair (and in most of urban India, for that matter) is to generate parking space in the first story of multistoried RC buildings by not providing masonry infill walls in that story. This makes the open first story much softer and weaker than the adjacent stories, in which masonry infills are provided. Several such buildings suffered severe damage or complete collapse due to ground shaking (Fig. 4). Most of these buildings were constructed without engineering supervision and lacked proper seismic design and ductile detailing. The provisions in Indian seismic code (IS:1893 2002) require such buildings to be designed for enhanced forces, which were definitely not followed in design of these buildings. The collapsed 3-story building at Naya Gaon [Figs. 4(a and b)] and two recently constructed collapsed buildings at Bamboo Flat [Figs. 4(c and d)] were privately owned. A 2-story Police Barrack building with an open first story collapsed at Haddo wharf [Fig. 4(e)], whereas adjacent buildings with infills in the first story survived the shaking.

#### Deficient Shear Design of Columns

In Port Blair, generally very light lateral shear reinforcement is provided in columns in the form of 6–8 mm diameter bars with  $90^\circ$  hooks at about 200–250 mm spacing. Therefore, open first-story columns and beam-column joints of several buildings suffered extensive damage in brittle shear mode, resulting in complete collapse of some buildings (Fig. 4). In several columns of these buildings, the  $90^\circ$  hooks of the shear reinforcement opened up, leading to buckling of longitudinal bars and subsequent crushing of concrete (Fig. 5). The partially collapsed Passenger Terminal Building at Haddo wharf was recently constructed (around 1999) and formally designed by a structural engineering firm in Chennai and constructed by a contractor with engineering supervision. The building was partly supported on RC piles and partly



**Fig. 2.** Undamaged historical and traditional construction in Port Blair: (a) masonry structure of cellular jail; (b) *Police Mandir* at Aberdeen Market; (c) collapsed minarets mark only damage to *Jama Masjid* at Aberdeen; (d) seismic retrofit of mosque using tie rods; (e) timber house at Marine Hill; and (f) timber building used as office of assistant engineers, Public Health Engineering Division, Andaman Public Works Department

on spread footing on relatively soft soil, which aggravated the damage to the building. Ductile reinforcement detailing was not found in RC members of the building, resulting in extensive damage to columns, beams, and beam-column joints in shear and flexural modes (Fig. 6).

The Indian seismic code for ductile detailing (IS:13920) (BIS 1993) has clear specifications for the design of shear reinforcement in columns and beam-column joints for better confinement of concrete. Noncompliance with these provisions in design resulted in extensive damages to several buildings.

### Short-Column Effect

Because of functional requirements such as ventilation and door and window openings, masonry infills are generally provided in

RC frames only up to partial heights, which creates short columns in the building and significantly increases shear demands in the columns. Several short columns in buildings at Bamboo Flat [Fig. 7(a)] and in the Passenger Terminal Building at Haddo wharf [Fig. 7(b)] suffered damage at the locations where partial height infills were provided. The ductile detailing code (IS:13920) (BIS 1993) requires that such columns be provided with special confining reinforcement throughout their height, which was not followed in the design of these buildings.

### Out-of-Plane Failure of Masonry Infills

Out-of-plane failure of masonry infills confined sufficiently within RC frames generally does not occur, if length or height of unsupported masonry infills is not too long. However, out-of-



(a)



(b)

**Fig. 3.** (a) Undamaged 50-year-old timber building at Marine jetty dry dock; (b) damaged *Siddhartha* building in dry dock complex

plane failure of infills was observed in several RC buildings in Port Blair, primarily due to poor quality of masonry and inadequate and loose joints between RC frame and masonry walls. In the 3-story school building at Mohunpura in Port Blair, long infill walls tilted out of plane [Fig. 8(a)]. Similar damage was observed in the Passenger Terminal Building [Fig. 8(b)] in the second-story infills. In the single-story RC building with flexible timber roof at the office complex of Andaman Lakshadweep Harbour Works (ALHW) at Mohunpura, several masonry partition walls collapsed out of plane [Fig. 8(c)].

### **Pounding Damages**

Buildings are required to be constructed with a sufficient gap between them such that lateral displacement of buildings occurring due to ground shaking during earthquakes can be safely accommodated. Several buildings constructed very close to each other in the Bamboo Flat shopping complex and Passenger Terminal Building at Haddo wharf suffered substantial damages in slabs, columns, and masonry infills because of pounding [Figs. 9(a–c)]. The L-shaped 3-story RC school building at Mohunpura constructed in stages between 1986 and 1989 was damaged at the expansion joints provided between different blocks [Figs. 9(d and e)].

### **Other Damages**

In addition, several other types of damages were observed in RC buildings in Port Blair, which disrupted the occupancy of these buildings. Several buildings at Bamboo Flat settled down, possibly due to liquefaction and erosion or settlement of underlying soil due to inundation by tsunami [Fig. 10(a)]. Several buildings at the Marine jetty complex and Haddo wharf also settled due to failure/settlement of foundation piles [Figs. 10(b and c)]. Damage to nonstructural elements in buildings due to earthquake shaking were observed in several buildings; for example, the false ceiling of a fiberglass boatshed in the Marine jetty dry dock complex collapsed completely [Fig. 10(d)]. Laterally unsupported masonry walls in the shell structures used as a storage area in the dry dock complex collapsed due to absence of any confining elements [Figs. 10(e and f)].

### **Performance of Harbor Structures**

Ships and steamers are the major modes of transportation between several islands in the A&N group of islands. Unfortunately, harbor structures in Port Blair were severely damaged due to the shaking and subsequent tsunami, which severely affected the transportation and cargo facilities on the islands and delayed help for the survivors. Most of the jetties suffered extensive damage and some even collapsed. Jetties are long structures constructed perpendicular to the land into the sea and there are sudden changes in their orientation along length, while wharfs are constructed along the land and did not suffer much damage. RC buildings in the wharf complex suffered varying degree of damages depending upon the configuration and quality of construction. Severe damages to the Passenger Terminal building and other buildings at Haddo wharf have already been discussed in the paper.

The Haddo naval jetty has a reentrant plan shape due to the extension of the jetty in 2003. The extension joint between the old and new constructions suffered some damage. An aerial photo of the jetty shows the location of damage concentrated at the reentrant junctions [Fig. 11(a)]. Significant displacement and damage were observed in heavy RC slabs on the jetty near these reentrant junctions [Figs. 11(b and c)], and the crane track was displaced by about 400 mm in the longitudinal direction [Figs. 11(d and e)].

The Jungli Ghat jetty in Port Blair, used primarily as a passenger jetty, was severely damaged and the entire working and operation were closed. Part of the jetty and RC passenger waiting room constructed over the jetty collapsed into the sea because of failure of the piles underneath [Fig. 12(a)]. The electricity supply to the jetty was hampered due to severe damages to electric poles and cables by the high pressure tsunami waves [Fig. 12(b)].

About a 20-m stretch of a jetty in the Marine jetty complex in the Phoenix Bay collapsed because of failure of piles when the tsunami struck [Fig. 13(a)]. Extensive settlement of roads [Fig. 13(b)] took place in the jetty complex, primarily because of failure/settlement of a large number of piles, which disrupted the operation of the jetty. Settlement of an approach road to an RC bridge in the complex forced the authorities to close the bridge to vehicles. The marine jetty dry dock, which is required to remain dry for maintenance work on ships, submerges in water during high tides since the earthquake because of subsidence of land in



(a)



(b)



(c)



(d)



(e)

**Fig. 4.** Collapse of RC buildings on stilts at (a), (b) Naya Gaon; (c), (d) Bamboo Flat; and (e) Haddo wharf

the area. It was reported that the water level in the area has risen by about 1 m. All the structures on the dry dock suffered extensive damage because of shaking and the tsunami. An undated photo obtained from the ALHW shows the maintenance work being done on several ships in the dry dock [Fig. 14(a)], whereas several ships were lying under water after the event [Fig. 14(b)]. A large portion of the RC slab with crane tracks suffered extensive damage due to shaking [Fig. 14(c)], and several steel gates of the machine shops were bent and damaged after the tsunami struck the dock. Temporary masonry walls of about 300 mm height were quickly constructed in front of all the machine shops to prevent seawater from entering them [Fig. 14(d)].

### Performance of Dams

There are two dams near Port Blair: Dhanikari concrete gravity dam at Nayashahar, and Chouldari earthen dam at Chouldari. The former was constructed in 1973 and supplies drinking water to the city of Port Blair, while the latter was recently completed in 2002 and supplies water primarily to the military establishments in Port Blair. Both dams suffered minor damage during the shaking, which did not affect functioning of these dams. However, damages were reported in the pipeline carrying water from the Dhanikari dam to the water treatment plant in Port Blair, which



(a)



(b)



(c)

**Fig. 5.** Poor shear design attributed to several column failures in RC buildings at (a) Naya Gaon; (b), (c) Bamboo Flat

disrupted the water supply in some parts of the city for a few days.

Dhanikari dam is 132 m long and 32.25 m high [Fig. 15(a)], and the ground shaking induced vertical cracks at the spillway section along the full height of the dam on the downstream face [Fig. 15(b)]. Seepage through the dam body collected in the inspection gallery before the earthquake was 25–30 L/min, which

increased to 110–120 L/min after the earthquake because of formation of the crack. However, it was reported that the increased seepage was still within the alarming limit of 160 L/min. Chouldari dam is 95 m long and 19 m high [Fig. 15(c)] and did not suffer any significant structural damage during the earthquake. The unreinforced concrete apron on top of the dam buckled upwards by about 8 cm due to pounding from the adjoining



(a)



(b)

**Fig. 6.** Recently constructed passenger terminal building at Haddo wharf suffered extensive damage due to earthquake shaking: (a) partial collapse of part constructed on reclaimed land on spread footing; (b) shear failure of column at beam-column joint



(a)



(b)

**Fig. 7.** Damage associated with short column effect in buildings at (a) Bamboo Flat; (b) Passenger Terminal Building at Haddo wharf

relatively stiff RC bridge deck over the spillway section of the dam [Fig. 15(d)].

### Performance of Overhead Water Tanks

In Port Blair, elevated water tanks on RC-framed staging are commonly used to distribute water to different parts of the city.

During the shaking, some of these tanks suffered substantial damages in the RC staging. A 50,000 L capacity water tank in the converter room of Haddo naval jetty is supported on 6-m high staging consisting of eight 300-mm square RC columns with intermediate RC beam braces at 3 m height [Fig. 16(a)]. Plastic hinges developed at the bottom of all the columns and at the top of a few columns [Figs. 16(b and c)], while the container sustained no damage. An RC staircase was provided in the tank



(a)

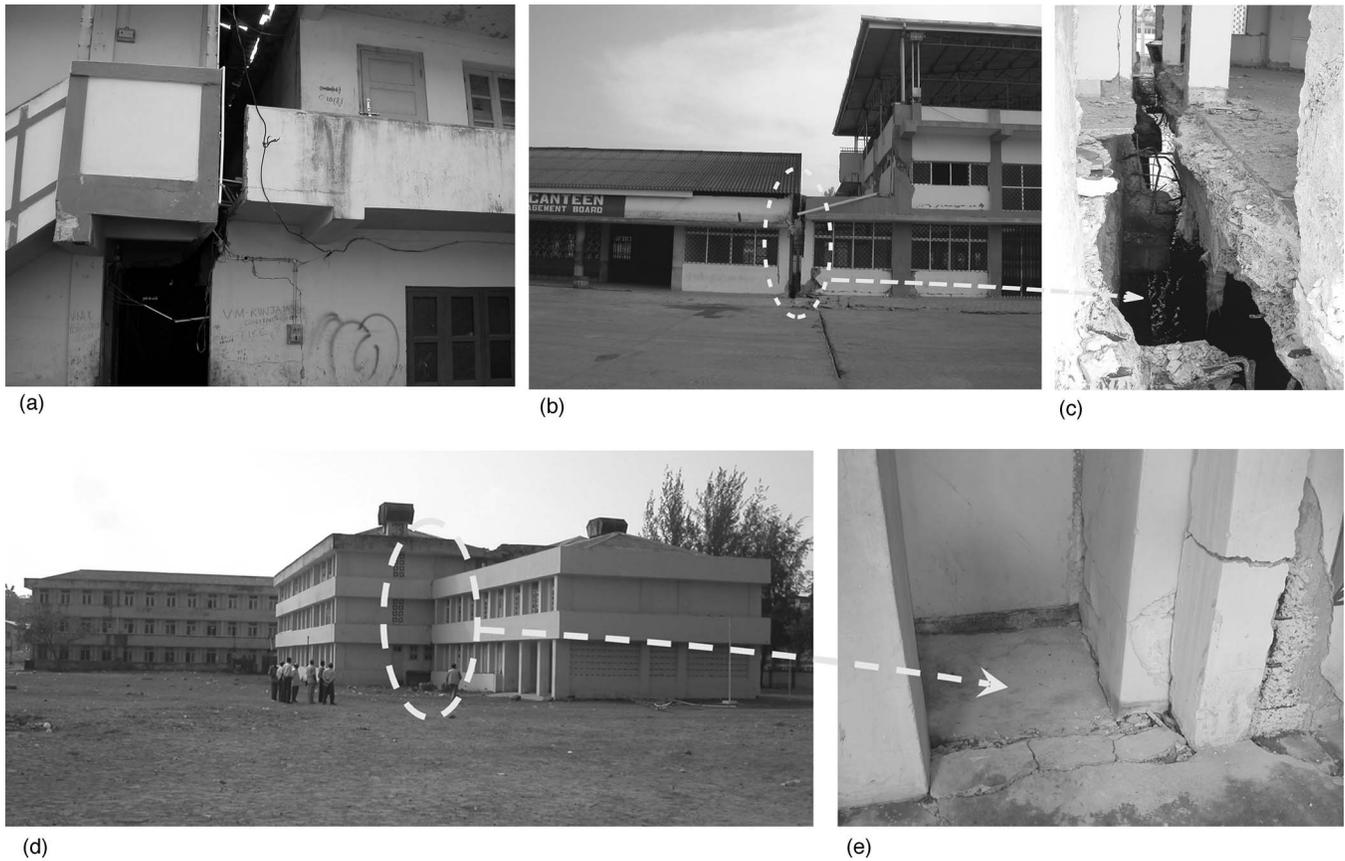


(b)



(c)

**Fig. 8.** Out-of-plane failure of masonry infills in buildings at (a) Mohanpura (school building); (b) Passenger Terminal Building at Haddo wharf; and (c) ALHW office complex



**Fig. 9.** Pounding damage in buildings at (a) Bamboo Flat shopping complex; (b), (c) Passenger Terminal Building at Haddo wharf; and (d), (e) school building at Mohanpura

going around the staging, which seems to have made the tank geometry unsymmetrical, and the tank sustained a torsional response. An overhead water tank at MES headquarters, Birchgunj Military Station in Port Blair, was damaged by severe corrosion of reinforcement in the RC-framed staging and tank, but structural damage was not observed in the tank and it was still under use.

## Performance of Other Structures

### Hangar at Port Blair Airport

The hangar (*INS Utkarsh Complex*) at the Port Blair airport was constructed in 1986 and suffered slight damage due to the ground shaking, but was fully operational. The steel frame structure is  $50 \times 50$  m in plan with roof truss 10 m tall at eave level and 14 m tall at the crown [Fig. 17(a)]. Several braces in the steel columns, which were made of 15 mm square bars, were found to be buckled [Fig. 17(b)]. Several gusset plates connecting inclined brace members between adjacent columns buckled because of nonconcurrent members meeting at the plate [Fig. 17(c)]. Severe corrosion was observed at the junction of several base plates with columns at ground level [Fig. 17(d)].

### RC Culvert at Haddo Navy Area

The 6-m-long RC culvert [Fig. 18(a)] in the Haddo navy area in Port Blair sustained cracks due to shaking at the junctions of the

abutment and girder-slab system at both ends [Fig. 18(b)], but the culvert remained open for traffic because the deck of the RC culvert sustained no damage.

### Seaport Control Towers

The 3-story RC structure of the Atlanta Control Tower at Atlanta Point in Port Blair was constructed in 1997 and used as a port communication center for long range [Fig. 19(a)]. The structure suffered slight damage to its columns, and corrosion cracks, which were in existence in several columns before the earthquake, widened after the shaking [Fig. 19(b)]. The control tower was fully functional after the shaking.

The Chatham Port Control Tower at Chatham in Port Blair is a 4-story RC building [Fig. 20(a)] and suffered severe damage because of ground shaking. Originally the building had 3 stories constructed in 1970–1971. Eventually one story was added in 1984 to enable better communication, and the tower was shifted at the top of the 4th story. After the earthquake, most of the damage was found to be concentrated in the additional 4th story. All the RC beams of the 4th story below the tower were damaged by the shaking [Fig. 20(b)]. The columns in the top story did not suffer any substantial damage, but corrosion cracks developed in two RC columns in the 3rd story, which widened after the earthquake.

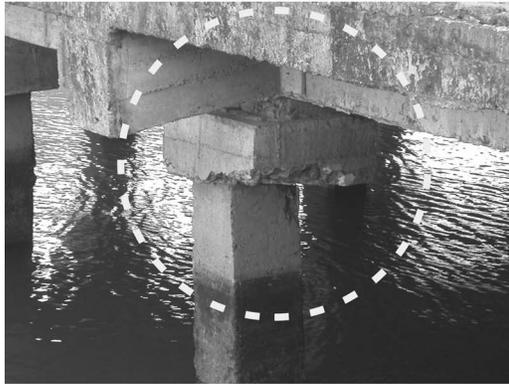
In the first and second stories, RC shear walls were provided, whereas very limited masonry walls were provided on the top two stories because of the requirement of big window openings for



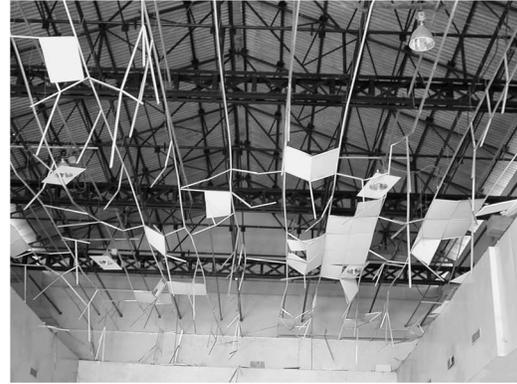
(a)



(b)



(c)



(d)



(e)



(f)

**Fig. 10.** (a) Settlement of buildings at Bamboo Flat shopping complex; (b) settlement of Operation Wing building by about 200 mm at one end along its length at Marine jetty complex; (c) failure of RC pile supporting godown building at Haddo wharf; (d) collapse of false ceiling of fiberglass boat shed at marine jetty dry dock; and (e), (f) out-of-plane collapse of nonstructural masonry walls in storage structure at marine jetty dry dock

inspection. The upper two stories did not perform well during the earthquake shaking because of their higher flexibility compared to the lower two stories. During the construction of the additional floor, the RC staircase from the bottom stories was not continued in the upper stories. Instead, a narrow and steep steel staircase was provided between the third and fourth stories by cutting a portion of the third story RC slab [Fig. 20(c)]. A similar staircase was provided between the fourth story and the terrace to reach the tower. After the earthquake, workers were reluctant to work in the upper stories because of such staircases.

### Concluding Remarks

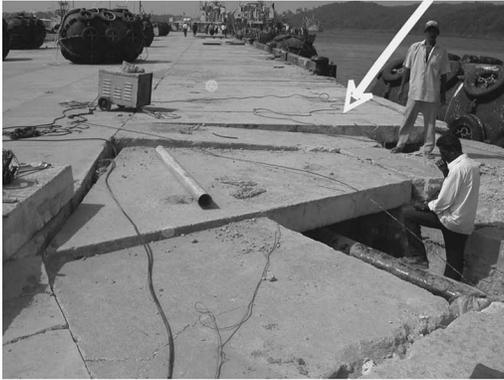
The shaking intensity in Port Blair during the 2004 earthquake was only about VII on the MSK scale. On the other hand, structures built in regions covered under Indian seismic zone V are required to withstand an earthquake shaking corresponding to intensity of IX and above. Considering this, the performance of structures in Port Blair during the 2004 earthquake was really poor, which is consistent with similar observations made after the September 14, 2002, Diglipur earthquake of magnitude 6.5 (Rai and Murty 2005).



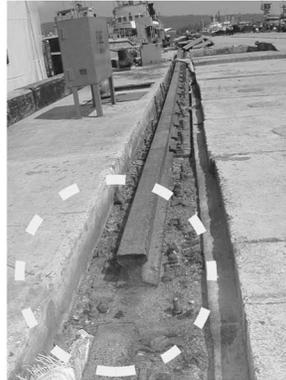
(a)



(b)



(c)



(d)



(e)

**Fig. 11.** (a) Aerial photo showing irregular configuration of Haddo jetty (used with permission of Javed N. Malik); (b), (c) concentration of damage at the location of joint between old and new construction, which are reentrant corners; and (d), (e) damage in steel rails over jetty (which disrupted functioning of jetty—400 mm gap was observed at joints of rails)



(a)



(b)

**Fig. 12.** Severely damaged Jungli Ghat jetty: (a) part of jetty collapsed because of failure of RC piles over which it was constructed; (b) electricity supply on jetty was severely affected because poles were broken and cables washed away by tsunami

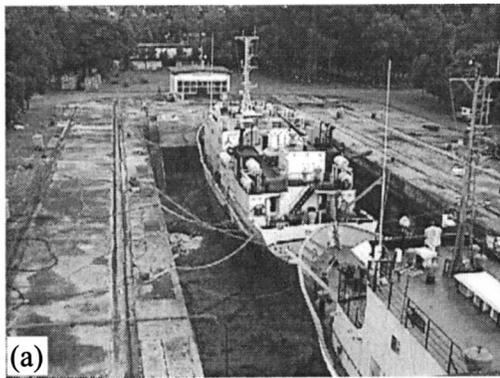


(a)

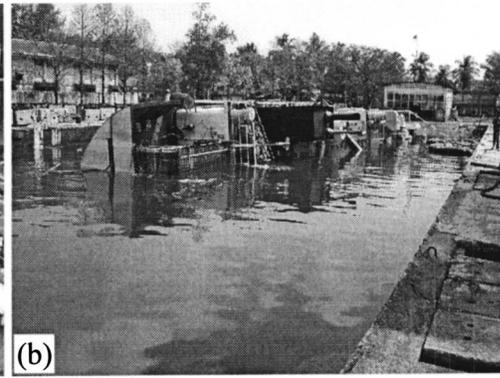


(b)

**Fig. 13.** (a) Collapse of about 20-m length of jetty at Marine jetty complex; (b) settlement of roads in complex because of settlement/failure of piles underneath



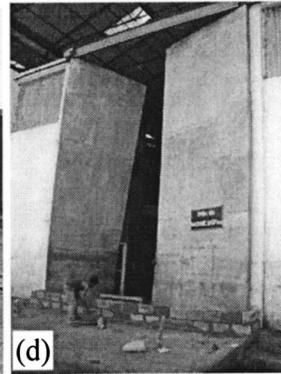
(a)



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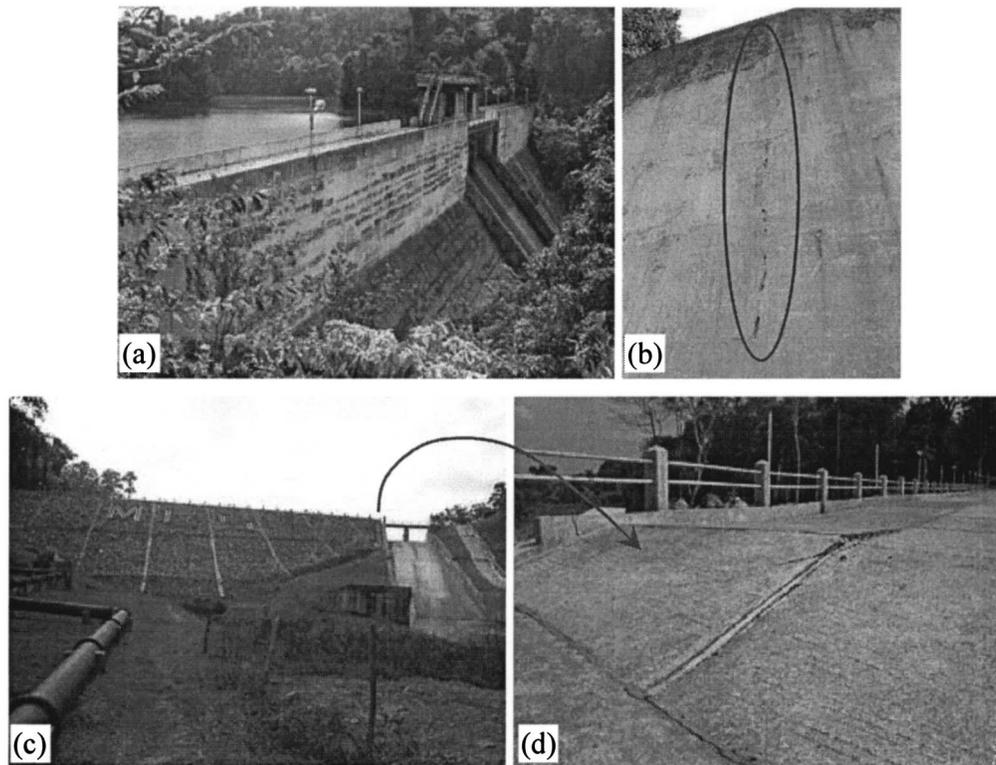


(c)



(d)

**Fig. 14.** (a) Drydock in working condition before tsunami (used with permission of Andaman Lakshadweep Harbour works); (b) damaged ships in inundated drydock after tsunami; (c) damaged RC track below crane; and (d) damaged steel gates of machine shops due to tsunami



**Fig. 15.** (a) Dhanikari concrete gravity dam at Nayashahar; (b) vertical cracks formed in body of Dhanikari dam due to earthquake shaking; (c) Chouldari earthen dam at Chouldari; and (d) buckling of unreinforced concrete slab over top width of Chouldari dam

Harbors are the most widely used transportation systems in the Andaman and Nicobar islands. Boats and ships are most frequently used to travel not only between different islands in the region, but also between Chennai–Port Blair and Kolkata–Port Blair (Chennai and Kolkata are two major port cities in mainland India). Therefore, better performance of harbor structures in Port Blair, which is also one of the biggest ports in the Andaman and Nicobar islands, was expected. Unfortunately, harbors in Port Blair were the most affected structures during the 2004 earthquake and tsunami, which severely hampered the search and rescue operations and relief work on the different islands. Mostly, jetties were affected because of their nonuniform configuration, and wharfs were less affected. Although about 50% of the boundary of Indian territory is along coastline, there is still no seismic code for proper earthquake-resistant design of harbor structures in India, and an urgent need remains for development of seismic codes for such structures in India.

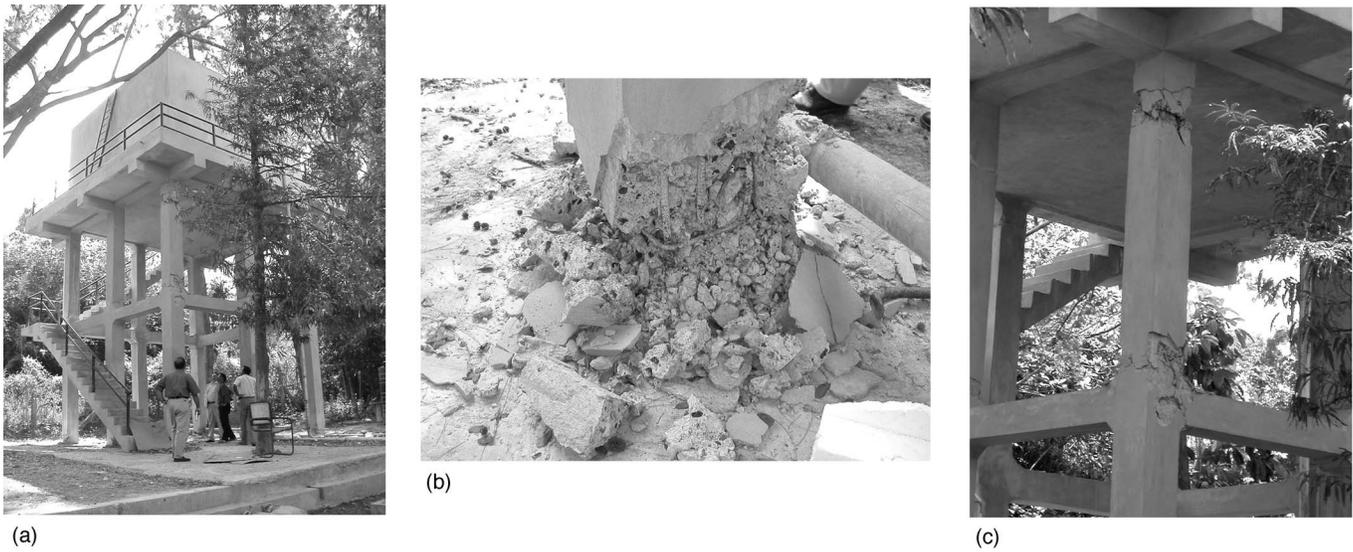
Several RC buildings in Port Blair constructed in recent years suffered severe damage, and some 2- to 3-story RC buildings in and around Port Blair collapsed completely because of moderate ground shaking. Several other buildings suffered variable damage depending on the quality of design and construction. Poor quality control and nonadherence to the basic earthquake resistant features available in the Indian codes were some of the major reasons for unexpectedly poor performance of RC buildings. Insufficient gaps between adjacent buildings resulted in pounding damages in RC buildings during ground shaking. Several masonry infill walls in RC buildings suffered out-of-plane failure, and at several locations, settlement of RC buildings was observed, possibly because of liquefaction or erosion of soil due to inundation of the area by the tsunami waves.

On the other hand, traditional timber and old masonry build-

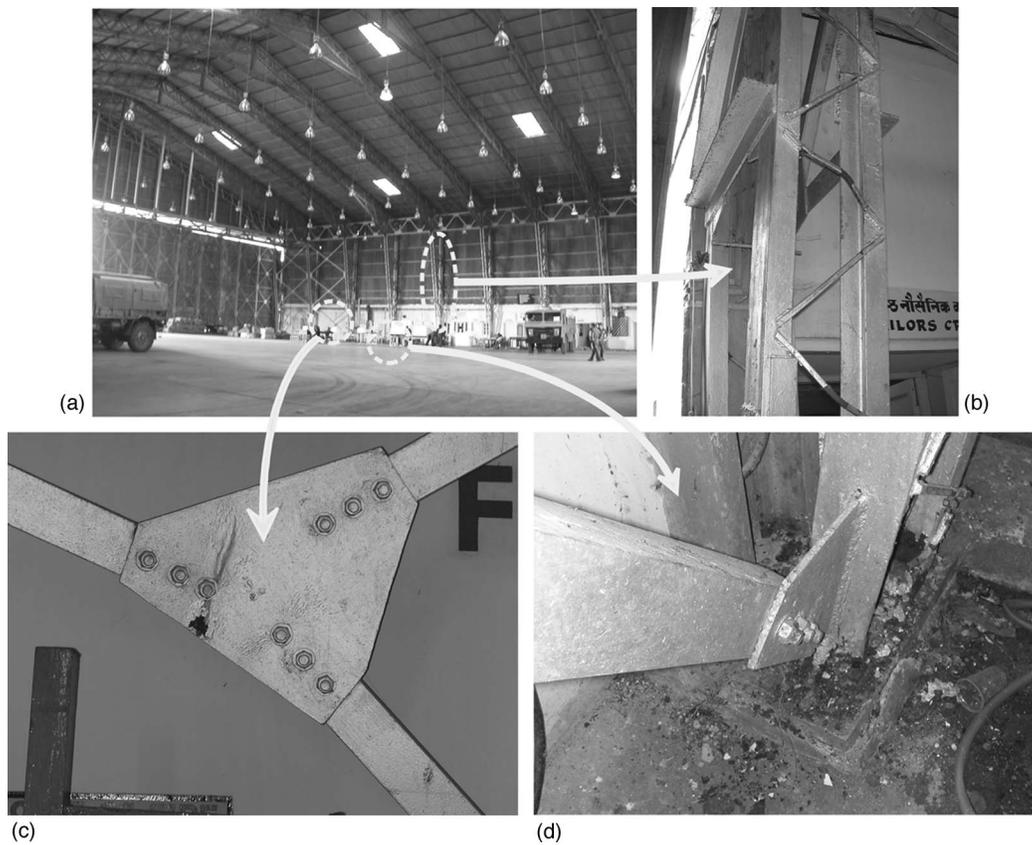
ings performed extremely well during the shaking. In fact, there were no reports of any significant damage to the traditionally constructed timber buildings due to ground shaking. Interestingly, a very effective retrofitting scheme was observed in a masonry mosque structure constructed about 90 years back in Port Blair. The retrofitting strengthened the masonry domes and arches of the structure, and by virtue of this retrofitting the mosque has successfully withstood at least three earthquakes in its lifetime. Elevated water tanks and seaport control structures in Port Blair suffered repairable damages due to earthquake shaking and were under restricted use. Several other important structures, such as dams, hangars, and culverts, performed reasonably well and were continuously operating.

Damage observed in RC buildings at Port Blair indicates serious deficiency in design and construction expertise for RC buildings on the islands at all levels. Basic earthquake-resistant design and construction features such as ductile detailing in columns are generally not followed. This is evident from the disastrous performance of several privately built RC buildings in Port Blair where engineers were not involved, and also from extensive damage and partial collapse suffered by several government buildings constructed by the government departments using consultants. RC-framed buildings require considerable sophistication in the design, detailing, and construction phases in addition to strict quality assurance and engineering inputs.

When government organizations are themselves not able to cope up with the required standards in construction of RC buildings, it would be unfair to expect this from people who construct 1- to 2-story buildings with the help of masons. The situation will not change unless philosophical modifications are made in construction of buildings in higher seismic zones in India. Instead of low-quality RC frame buildings, alternate typologies need to be



**Fig. 16.** (a) Water tank at Converter Room of Haddo naval jetty; (b) formation of plastic hinge at bottom of all RC columns in tank staging; and (c) formation of plastic hinges at top of a few columns in tank staging



**Fig. 17.** INS hangar at Port Blair Airport: (a) overview of hangar structure; (b) buckling of braces in steel columns; (c) buckling of gusset plates connecting nonconcurrent braces between adjacent columns; and (d) severe corrosion at junction of base plate and column at ground level



(a)



(b)

**Fig. 18.** (a) Slightly damaged 6-m long RC culvert at Hadoo navy area in Port Blair; (b) cracks developed in both abutments of culvert

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(a)



(b)

**Fig. 19.** (a) Atlanta Control Tower of Port Management Board did not suffer any substantial damage due to earthquake shaking; (b) corrosion cracks in a few columns, which reportedly existed before shaking, widened after shaking

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(a)



(b)



(c)

**Fig. 20.** (a) Damaged Chatham Port Control Tower; (b) longitudinal cracks formed in all beams of fourth story; and (c) narrow and steep staircases were provided in upper additional stories by cutting portion of RC slab

encouraged that are better suited to the local environment and perform well in earthquakes without requiring much engineering input.

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### References

- Bureau of Indian Standards (BIS). (1993). *Indian standard for ductile detailing of reinforced concrete structures subjected to seismic forces—Code of practice, IS:13920*, New Delhi.
- Bureau of Indian Standards (BIS). (2002). *Indian standard criteria for earthquake resistant design of structures. 1: General provisions and buildings, 5th revision, IS:1893*, New Delhi, India.
- Jain, S. K., et al. (2005a). "The great Sumatra earthquake and Indian ocean tsunami of December 26, 2004." *Special Earthquake Rep. #3, Newsletter of Earthquake Engineering Research Institute*, 39(4).
- Jain, S. K., Murty, C. V. R., Rai, D. C., Malik, J. N., Sheth, A. R., and Jaiswal, A. (2005b). "Effects of M9 Sumatra earthquake and tsunami of 26 December 2004." *Curr. Sci.*, 88(3), 357–359.
- Jhingran, A. G. (1952). "A note on an earthquake in the Andaman Islands (26 June 1941)." *Records of the Geological Survey of India*, 82(2), 300–307.
- Malik, J. N., and Murty, C. V. R. (2005). "Landscape changes in Andaman and Nicobar Islands (India) due to  $M_w$  9.3 tsunamigenic Sumatra earthquake of 26 December 2004." *Curr. Sci.*, Indian Academy of Sciences, Bangalore, 88(9), May 10, 1384–1386.
- Rai, D. C., and Murty, C. V. R. (2005). "Engineering lessons not learnt from 2002 Diglipur earthquake—A review after 2004 Sumatra earthquake." *Curr. Sci.*, 89(10), 1681–1689.