Lifeline Systems in the Andaman and Nicobar Islands (India) after the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami

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Lifeline systems in the Andaman and Nicobar islands performed poorly during the December 2004 Great Sumatra earthquake and tsunami. Several power stations and transmission lines were damaged by the ground shaking, affecting the electric power supply to parts of the islands. Telecommunication services were severely affected because of destruction of several telephone exchanges. These services were restored quickly by government agencies. The dams and reservoirs, which supply potable water, sustained minor damage from ground shaking. However, segmented pipelines connecting the dams and reservoirs to various storage sites broke at several places, which significantly affected the water supply for a few days. Ground shaking damaged several elevated as well as ground-supported storage tanks. Damage related to tsunami waves was substantial in the 500–1,000-m strip immediately next to the coastline. [DOI: 10.1193/1.2205874]

INTRODUCTION

Within two weeks of the Great Sumatra earthquake of 2004, the Earthquake Investigation Committee of the Technical Council on Lifeline Earthquake Engineering (TCLEE), which is a technical council of the American Society of Civil Engineers (ASCE), organized a team composed of members of TCLEE, ASCE, the Coastal, Ocean, Ports and Rivers Institute (COPRI), and the Institution of Civil Engineers (ICE) to perform a reconnaissance of the lifelines in areas affected by the earthquake or tsunami.

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This group is referred to herein as the investigation team. The investigation team started its reconnaissance on 1 February 2005. Most members departed the United States, UK, or Canada on 30 or 31 January and returned on 5 or 6 February.

The Indian Institute of Technology, Kanpur organized a reconnaissance study of the affected areas to document the scientific, engineering, and disaster management lessons from this tragedy. The reconnaissance study was sponsored by the Department of Science and Technology, Government of India, New Delhi. Thirteen investigators were divided into six groups having independent responsibilities; each of the groups spent about eight days in the field between 1 January 2005 and 13 January 2005

ELECTRIC POWER SYSTEM

DESCRIPTION OF SYSTEM

A variety of power-generating systems are in operation in the Andaman and Nicobar (A&N) islands. Due to the physical separation of the islands across the Indian Ocean, most of the power-generating facilities operate independently. Because of the rural nature of the islands, solar, biomass, ocean, wind, and other renewable energy systems play a role in providing power to remote villages.

There are 34 diesel-generator powerhouses scattered across the islands, providing a total capacity of about 40 MW. The generating stations produce 6 kW to 12.5 MW of power. There is also a 20-MW privately operated diesel power plant operating at Bamboo Flat, South Andaman Island.

Since September 2001, the Kalpong Hydroelectric Power Project has provided 5.25 MW of additional capacity to the power grid of the North and Middle Andaman region. It also operates as a base load station when the demand for power is at its peak. The project has a 34-m-high concrete dam on the left fork of the Kalpong River and a 25-m-high rockfill dam on the right fork.

Diesel generator (DG) sets provided power to up to 92.5% of the population in the islands at South Andaman, Middle Andaman, Long Island, Neil Island, Havelock, Little Andaman, Car Nicobar, Katchal, Kamorta, and Campbell Bay. At other locations, electric power is available for 5–16 hours per day through small DG powerhouses and solar PV power plants. Of 547 villages, 479 villages have electric power.

OVERVIEW OF SYSTEM PERFORMANCE

In the areas affected by the tsunami, power plants on hills and elevations were spared, while those in low-lying areas were severely damaged. There are a number of reasons for the delay in restoring power from the latter plants, including (a) damage to the structure in which the DG sets were placed—for example, in a reinforced concrete (RC) frame building in Little Andaman Island, the infills in the upper elevations had partially collapsed, and the rest of the infills were precariously balanced; (b) contamination of the high-strength diesel oil and waste oil tanks by saltwater; (c) inundation of the generators in saltwater; (d) damage to the control panel boards of the DG sets; (e) loss of the main fuel tanks when they were rendered buoyant and carried far away, sometimes up to a couple of kilometers; and (f) damage to battery units, battery chargers, tools, and instruments. Also, the plants had lost the official operating and revenue records.

There was substantial loss of electric power in the A&N islands due to damaged power stations and transmission lines. The A&N Administration requested 200 portable generator sets, as well as experts, from the central government. The Electricity Department restored electricity to more areas, with the cooperation of the general public. The department has cautioned the general public about the possibility of electrocution due to broken power lines. The information about broken electric lines was provided to the nearest site office or police station. The Electricity Department also advised consumers living in waterlogged areas to thoroughly check internal wiring, cables, and equipment before turning power on.

In almost all locations, the generator sets had been adversely affected. A team of 17 engineers from the National Thermal Power Corporation (NTPC), the Central Electricity Authority (CEA), and POWERGRID were sent to the islands on 29 December 2004. With the efforts of these engineers and the local officers and staff of the Electricity Department, the Air Force, and paramilitary personnel, the power supply in most locations was restored. To augment the power supply, 300 DG sets in the 2–3 kW range and 21 DG sets in the 7.5–15 kVA range were distributed to different locations. Except for Nankouri, Kachal, and Teressa, electric power in all the other islands was provided by DG sets as of 5 January 2005. The long-term approach consists of a plan for generation facilities, subtransmission, and distribution systems prepared by CEA, NTPC, and the POWERGRID team.

The distribution network also suffered damage. Tens of kilometers of high-tension and low-tension lines were lost. The transformers on poles were rendered inoperable after the saltwater inundated them (Figure 1). Also, the concrete poles holding the distribution lines also leaned and collapsed in some locations, thus making it difficult to restore power immediately. Several electrical poles were flooded, and several others were washed away, which disrupted the power supply (Figure 2). Since spare poles and backup power generating units were not available, the supply of electric power in many islands almost came to a halt for over four weeks.

LOCATIONS OF DAMAGE AND RECOVERY ACTION

Transmission Line Failure at New Haddo Wharf in Port Blair, South Andaman Island

The transmission tower that carries 440 kV from Port Blair to Namunaghar was damaged and might have collapsed if the transmission line had not snapped first.

Bamboo Flat (Phoenix Bay) 20-MW Power Plant Failure in South Andaman Island

The earthquake and tsunami damaged the power infrastructure, including transmission and distribution lines in many areas. The Electricity Department of the A&N Administration could provide only 30% of the required electricity from its powerhouses at Chatham and Bamboo Flat because of the complete shutdown of the 20-MW fossil-fuel-based power plant of the Suryachakra Power Corporation Ltd. The shutdown was due to

Figure 1. General wreck of the power distribution system at Hut Bay in Little Andaman Island (photo: S. Dash).

Figure 2. High-pressure tsunami waves damaged electrical poles near Haddo Wharf in Port Blair in South Andaman Island (photo: S. Jain).

Figure 3. Collapse of the Suryachakra Power Plant masonry boundary walls at Bamboo Flat in South Andaman Island (photo: G. Mondal).

the ingress of seawater and mud in the control room of the power plant; damage included the collapse of boundary walls (Figure 3) and severe damage to mechanical and electrical equipment. Several weeks were required for restoration.

One 5-MW Cummins generator set (5×1.2 MW) was transferred from Rangat to Port Blair. Caterpillar, Sahibabad offered 2×500 kVA (1-MW) sets on a lease basis, free of charge. Cummins also offered a 1,000-kVA (1-MW) set free of charge. Cummins had sent one unit of 2.5 MW to Norway for repair by Rolls Royce. All generators were operational within one month. An arrangement was made for a few more 250–500 kVA sets to augment the supply at Port Blair. The NTPC and CEA team made all of these generators operational. At the same time, POWERGRID was repairing its subtransmission and distribution systems. Wherever required, cables and related elements were being supplied from Chennai and adjoining areas. Power was restored to 40% of normal supply in one week, 70% of normal supply in two weeks, and 80% of normal supply in three weeks.

Kalpong Hydroelectric Power Plant Failure near Dilgipur, North Andaman Island

National Hydroelectric Power Corporation (NHPC) has a small hydroelectric station (5.5 MW) at Kalpong, North Andaman Island. The generator was in working order, but there were misalignments at the foundations. NHPC engineers were sent, and the plant was made operational in about 15 days. While the repairs were being made, a 500 -kVA DG set, which was for startup power, was made operational in Diglipur and the adjoining area. Also, one 1.75-MW unit at the NHPC station in Kalpong was repaired and was operational as of 4 January 2005. There was some cracking in the 25-m-high rock-filled dam. The collapse of an electrical transmission tower at Middle Strait (between South and Middle Andaman islands) disrupted the power supply from the Kalpong Hydroelectric Project to Baratang Island.

Middle Andaman Islands

At Rangat, there is a 6-MW power station (1.2 MW × 5). There was some damage to this station, which was repaired. Subtransmission and distribution systems also had major problems, which were repaired. The power station is now operational, and the power supply is being maintained.

Southern Islands

Twenty-seven small- and medium-size DG sets with an aggregate capacity of 12 MW serviced the southern islands. Of 27 stations, 20 have been washed away, aggregating to 7 MW of capacity. The remaining 7 stations, aggregating to 5 MW of capacity, are operational and are supplying power to Car Nicobar, Kamorda, and Campbell Bay.

In Car Nicobar Island, diesel-based power generation was halted due to flooding of the generators with saline water and displacement of these generators from their position. They were displaced because the large pressures imposed by the giant tsunami waves had caused anchor bolts to snap (Figure 4). Also, the oil tanks of the DG sets were carried about 2 km away by the tsunami waves to the end of the military airport runway (Figure 5).

To further augment supply in Car Nicobar, a 15-kW set was sent from Port Blair on 31 December 2004 and was operational at Car Nicobar as of 2 January 2005. As many as 300 DG sets in the 2–3 kW range have been sent to Car Nicobar. The priority of power supply was given to the telephone exchange, hospitals, dispensaries, and relief camps. To further augment the power supply in the Car Nicobar area, Hut Bay, Kamorda, and Campbell Bay Islands, 21 DG sets of 7.5–15 kW were sent via special IL-76 Air Force aircraft on 3 January 2005.

As of 18 January 2005, normal power supply was restored at Great Nicobar, Kamorta, Neil, Havelock, Long, Middle Andaman, North Andaman, and Champin islands. Power was still supplied through portable DG sets in Car Nicobar, Teressa, Katchal, Little Andaman, and a few other islands. All relief camps had been electrified by portable DG sets. A hydroelectric power station run by the NHPC was made operational, and that improved the power supply on North Andaman Island. The estimated cost of permanent restoration/reconstruction of the power infrastructure was estimated at about Rs. 150 crores (US $33.3 million).

Major Observations

Although there was substantial damage to the power system from the earthquake, the government response appeared to be quick and well organized. Manpower and equip-

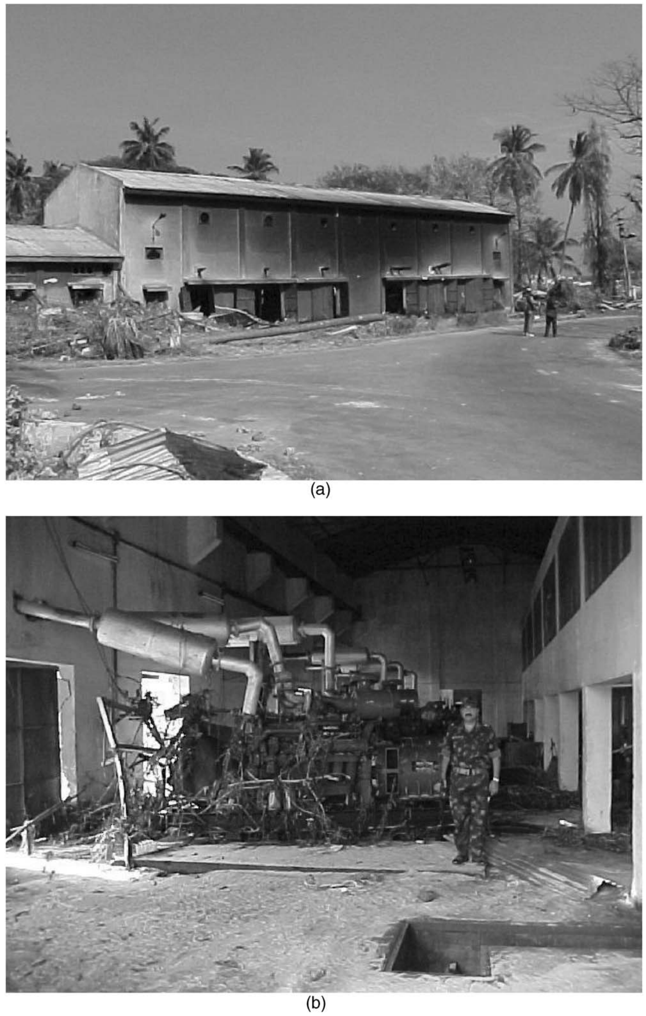


Figure 4. Electrical power generator unit at the Air Force Colony in Car Nicobar Island: (a) outside view of the building (photo: C. Murty). (b) Lateral displacement of generator sets by about 4 m (photo: S. Dash).

ment were obtained quickly, and all repairs were completed in about one month. The logistics of restoration were very efficient, to facilitate a speedy recovery. Fuel and other necessities were brought over by the military.

Figure 5. An oil tank of an electric power generator unit at the Air Force Colony in Car Nicobar Island was displaced by about 2 km to the end of the military airport runway (photo: S. Dash).

COMMUNICATION

DESCRIPTION OF SYSTEM

Port Blair, the capital city of South Andaman Island, is the communications link to the Indian mainland. While the islands are linked via a radio network, the link to the mainland is through the Indian satellite INSAT[1]-3C, from Port Blair to New Delhi. Low-power radio communications connect the smaller islands to Port Blair. Television on the islands is also linked to the INSAT-3C satellite.

The A&N islands at present have 34,500 subscribers using basic fixed-line telephone service and 500 using the wireless-in-local-loop technology. Under the Bharat Sanchar Nigam Limited (BSNL) CellOne brand, the mobile service will allow residents of Port Blair full roaming, according to BSNL chief general manager G. S. Srivastava. The calls will be routed via a satellite link through Kolkata, the main base station. The base station has an emergency DG. The company also launched Internet telephone cards under the brand name "Webfone." The card will allow subscribers to make telephone calls globally by accessing the Internet through a local dial-up connection.

[1] International satellite

BSNL also announced that it would connect six satellite telephones. Each island will be provided with one INMARSAT[2] terminal for this purpose.

Amateur (ham) radio also played a key role in providing emergency communications after the earthquake, especially right after the devastating tsunami waves struck the coastal communities, and especially in the more remote parts of the region.

OVERVIEW OF SYSTEM PERFORMANCE

In general, the A&N islands have land-line phone facilities. Cellular phone service is available only in the Port Blair area. In the immediate aftermath of the earthquake, only the telecommunication network in Port Blair area was operational.

Telephone exchanges across the islands were destroyed. In most cases, damage occurred to the exchange equipment, battery and power plants, and satellite receivers.

BSNL set up public phone booths with satellite phones in the Andaman and Car Nicobar islands as part of its emergency plan to restore connectivity with the outside world. BSNL rushed five INMARSAT phones to Port Blair, and ten more were diverted from the rest of the islands. After consultation with the local administration, the ten phones will be used to set up public call booths at places where the telecommunication infrastructure was washed out.

The move to install satellite phones comes in the wake of heavy damage to the satellite base station on Nicobar Island. This station was, in a way, the telecommunication lifeline for the islands. Operations at five exchanges (Diglipur, Kalighat, Kalera, Kishori Nagar, and Ram Nagar) in the Andaman Islands were restored. Besides, satellite terminals at Diglipur, Campbell Bay, and Kamorta were also up and running. BSNL had rushed technical people in from Kolkata to assist in restoration work.

LOCATIONS OF DAMAGE AND RECOVERY

Commercial power was out, and telecommunications with the mainland were terminated. All India Radio (AIR) switched to DG power and continued to broadcast with 20 KW of power, on HF bands of 40 and 60 m. Telecommunication equipment in most of the other Andaman Islands was damaged by either the earthquake or the tsunami. In one island, Car Nicobar, the police headquarters was washed away, and all communications equipment was totally destroyed by the tsunami. The satellite uplink antenna (for INSAT-3C) in Port Blair lost its alignment during the earthquake, and communication with New Delhi was terminated. This affected all radio, television, and telephone service to the mainland as well as inter-island communications. However, local telephone service within Port Blair was up and operating about two hours after the event. The local telephone service equipment is collocated in the telecommunications building and was not seriously affected by the initial earthquake or aftershocks. By 10:00 A.M., AIR was broadcasting interviews with key people, but transmission to other islands and the mainland was cut off.

[2] International maritime satellite

In order to tie the islands together and reach the mainland, the short-term solution was to utilize 25 satellite phones distributed to government administrators. Additional communications were facilitated via the military.

Within two days after the event, commercial power was restored, and the satellite antenna was aligned and used as an uplink to INSAT-3C. After the antenna was aligned, the local television station hosted live feeds from many national and international news organizations. The television station at Port Blair also shut down due to electric power failure but restarted 10 minutes later, under emergency backup power supply.

In early December, a ham radio expedition (called DX Expedition) obtained permission from the Indian government to operate a short-term ham radio special event station. No ham radio expedition had been allowed on the islands in 17 years (ham radio communications have been banned in the Andaman Islands, but this policy is now being reviewed). The station (VU2BRI) went on the air, under the direction of Ms. Bharthi Prasad. Ms. Prasad is a housewife and mother of two children who lives in New Delhi. The station made two-way communication with ham operators around the world, but immediately after the earthquake the station reported to AIR, to assist in emergency communications within Port Blair, the Andaman Islands, and the world. For the next few days, it was reported that the ham radio station made hundreds of health and welfare calls between the mainland and the Andaman Islands. Telephone communications to the mainland were restored on 28 December 2004.

The Indian government has taken a major step in providing 2,000 small hand-cranked (battery-free) radios[3] that will be passed out to government employees, and then to the general public, in all of the Andaman Islands for future emergency needs. The cost is 800 Rs. (US $20) per radio. However, it is not clear what the real benefit of these radios will be in a true emergency. Without the users' foreknowledge of when to turn the radio on, it will be difficult to warn them of an impending disaster. After a disaster, clearly the radio would be helpful, perhaps with an hourly check-in time for news updates.

The function of the Swadeshnagar exchange in Mayabandar has been restored, where the fiber optic cable was replaced. The Bamboo Flat exchange was shifted to a new building with new exchange equipment, and the exchange is now fully functional. At Hut Bay, the exchange has started functioning from a satellite building, and the equipment was replaced. At Car Nicobar Island, the fiber optic equipment, engine alternator, and the satellite receivers were damaged. Those units were replaced in the exchange building, and the Car Nicobar exchange is now working properly. At Katchal and Teressa, the exchange equipment, battery and power plant, engine alternator, satellite receiver, and copper cable and pillars were destroyed. They have all been replaced, and the

[3] British inventor Trevor Bayliss developed his original windup radio in 1991, to help educate Third World villagers in regions where the lack of electricity and/or the cost of batteries had discouraged the use of radios. The design won worldwide fame and was successfully used to spread basic health information where it was most needed. Later versions have incorporated a solar panel, giving two "free" ways of powering the integral rechargeable battery—and making it a truly independent travel radio. Just 30 seconds of winding the crank gives 30 minutes of running time, while the solar panel provides a steady trickle charge from the sun.

exchanges are functioning from new buildings. At Kamorta, the satellite receiver was repaired, and the exchange is functioning. At the Campbell Bay exchange, the equipment, battery and power plant, engine alternator, optical fiber cable, and copper cable and pillars were damaged. These components were replaced, and the exchange is working from a satellite building. Efforts are under way to install an INMARSAT satellite phone at the Champin exchange.

The BSNL exchanges on the islands are operated on 48-V DC power delivered from the battery and power plant, which in turn operates on an AC 220 V/415 V commercial power supply. Standby AC supply is generated by the engine alternator.

At a high-level meeting on 3 February 2005, the Minister of Communications and Information Technology, Shri Dayanidhi Maran, reviewed the progress of restoring communication facilities in the A&N islands. The Minister of State for Communications and Information Technology, Dr. Shakeel Ahmad, who reached Port Blair on 2 February 2005 to oversee the relief and restoration work, visited the affected areas and directed the officials to make all-out efforts to restore the telephone exchanges and satellite communications in the tsunami-affected areas of the island.

A new telephone exchange of 256 lines (CDOT[4] 256-port) at Campbell Bay has been commissioned and is working with the telephone network of the A&N islands. One unit of multiple-channel-per-carrier (MCPC) equipment that had been shipped to Car Nicobar Island the day before the team arrived was being installed. One very small antenna terminal (VSAT) was airlifted on 4 February 2005 to Car Nicobar Island, along with engineers.

Three teams with seven INMARSAT terminals left for Kamorta, Katchal, Teressa, and Champin islands, and a separate team with INMARSAT terminals left for Hut Bay Island. They commissioned additional satellite phone service on 5 February 2005.

Efforts were made to provide plant control operations (PCOs) in Bamboo Flat by using Port Blair wireless local loop (WLL) system coverage, because the Bamboo Flat telephone exchange was completely washed out.

In order to reduce congestion at the Port Blair exchange, more than 200 additional circuits have been commissioned from Port Blair to Chennai and Kolkata. Four power plants (25 A), six engine alternators, and ten battery sets were being airlifted to Port Blair, in addition to 8 power plants (25 A) that have already been sent to Port Blair. Seven sets of CDOT 256-port switches, two power plants, and five INMARSAT terminals have been airlifted to Port Blair. In addition, three more 256-port exchanges with main distribution frame (MDF) and 14 optimux (optical fiber equipment) were being airlifted to Port Blair for installation in the affected areas. The entire operation of restoring communication facilities in the A&N islands is being supervised by a team of two senior officers of the Department of Telecommunication, specially sent from New Delhi.

[4] Center for Development of Telematics

OBSERVATIONS

If ham radio (VU4) were authorized from the Andaman Islands, then this would provide an additional means of telecommunication for emergency and recovery response. Ham operators could install a 2-m transceiver repeater at a high point in South Andaman Island. This repeater could be linked to other islands, so that two-way communications could be established in all of the inhabited Andaman Islands. The repeaters should have battery backup power and be properly mounted, so that all systems will remain operational after a moderate earthquake.

The 2-m repeater should be tied into "echolink" so that any ham operator anywhere in the world could communicate with any ham operator in the Andaman Islands. This would require an Internet connection at Port Blair, and if the telephone system were hardened (i.e., if the satellite downlink were seismically retrofitted), then this would be a tremendous step forward and would allow the repeater to tie directly into the Internet.

The satellite antenna (INSAT-3C) could be hardened so that, during the next earthquake, it will not be out of alignment with the Indian mainland's satellite.

All essential satellite and radio communications equipment and antennas in all the Andaman Islands could be relocated to higher ground, preferably at least 20 m above mean sea level. This will protect against tsunami damage.

WATER AND WASTEWATER SYSTEM

DESCRIPTION OF SYSTEM

Since the average annual precipitation is 3,100 mm, rainwater is the primary source of fresh water for the A&N islands. Reservoirs are used to store the water all through the year. Underground water is another source.

In islands such as Neil, Car Nicobar, Long Island, and others, shallow wells have been dug to supply the water. In most of the other islands, perennial spring water sources, after being treated, are also tapped in order to supply water to the local populace. In Chowra Island, a seawater desalination plant has been installed on an experimental basis. In Port Blair, Havelock, Diglipur, Mayabandar, Rangat, Bakultala, Bamboo Flat, Kamorta, Campbell Bay, and elsewhere, regular water treatment plants were functional.

The Andaman Public Water Department (APWD) provides bulk water supply to the Port Blair Municipal Council (PBMC), which in turn distributes water to the areas under its jurisdiction. For the remaining areas, treatment and the distribution of water is handled by APWD, which taps from a large number of individual small schemes and sources.

URBAN WATER SUPPLY

The main water sources for Port Blair are the Dhanikhari and Jawahar Sarovar reservoirs. In the urban water supply subsector, APWD supplies water to PBMC after treatment at the Lambaline and Dairy Farm treatment plants. The Lambaline treatment plant is basically a rapid sand filtration plant commissioned in 1973 with a capacity of 16,031 metric tons (MT) per day. The other treatment plant with slow sand filter beds is at Dairy Farm, which was commissioned in 1954 and has a treatment capacity of 2,992 MT per day. This plant treats water mainly from the Jawahar Sarovar reservoir. Another slow sand filter plant with an installed capacity of 1,816 MT per day was functioning at the Garacharama suburban area. From 2003 to 2004, the Dilthaman Tank as well as the Nayagaon and Chakkargaon Diggies have also been revived. A slow sand treatment plant has also been constructed to treat water from the Nayagaon and Chakkargaon Diggies. These two schemes contribute about 6,000,000 L per day.

RURAL WATER SUPPLY

Efforts are being made to augment the rural water supply. Of a total 502 villages, 344 have been provided with piped water supply. It is proposed that the remaining villages will be covered during the tenth five-year plan. Improvement of the water supply in Rangat, Nimbutala, Dasarathpur, and other adjoining areas has been undertaken by tapping water from the Panchavati River source. Phase 1 of this scheme has already been completed during 2003–04. Work on the Kamsarat Nallah water supply scheme has been undertaken in the South Andaman Island area. Under schemes recommended by the Central Ground Water Board, augmentation of the water supply has already yielded water—much to the comfort of the people of the Badamash Pahar, Dollygunj, and Austinabad areas.

SANITATION

At present, there is no underground sewage system. Therefore, the human waste disposal is through individual septic tanks, and other domestic effluent is directly discharged into the sea through surface drains or open channels. However, the Government of India has been entrusted to prepare a detailed project report to implement a sewerage scheme.

MINOR IRRIGATION AND FLOOD CONTROL

APWD executes the construction of minor irrigation projects and minor irrigation and flood control schemes. One executive engineer is on deputation to APWD from the Central Water Commission, New Delhi, to fulfill the specific and specialized needs in this sector.

A number of minor irrigation schemes have been identified by APWD, and two of them—the Vishnu Nallah scheme and the RK Pur scheme in Little Andaman Island—have been completed.

ANTI–SEA EROSION MEASURES

The coastline of the A&N islands is about 1,964 km. Under the anti–sea erosion scheme, about 800 m of seawall was constructed during the eighth plan, and 3,950 m of cement concrete seawall was constructed during the ninth plan. In the tenth plan, about 12,250 m of seawall is proposed to be constructed.

Figure 6. Damaged pipeline being attended to near the water treatment plant in Port Blair (photo: S. Dash).

LOCATIONS OF DAMAGE

In general, pipelines were affected by the earthquake shaking. Usually, segmented pipes are used to transport water and sewage in the island region; for transporting oil, continuous pipes are used. During this earthquake, the segmented lines were more affected than the continuous networks were. For instance, about 38 breakages were reported in the long-distance pipeline carrying water from the Dhanikari Dam to the water treatment plant in Port Blair (Figure 6). The damage was primarily caused by the pull of the joints and the rotation between the pipe segments due to ground shaking.

However, important damage occurred at the low-lying Lambaline area (Figure 7). The land subsided, and the seawater rose permanently in the already low-lying area. As

Figure 7. Failure of the bell and spigot joint of the pipeline in the Lambaline area near Port Blair in South Andaman Island: (a) kink in the pipeline, and (b) leakage at the bell and spigot joint (photo: S. Dash).

a consequence, the sloping ground sustained lateral spreading, which in turn caused the pipeline that rested on normal ground to displace laterally. This resulted in the opening of the bell and spigot joints of the cast iron pipe lengths. The leakage of water from these joints hampered the water supply to the city of Port Blair for over ten days.

As of early February 2005, the water supply was 100% restored in Nancowry and Kamorta; 90% in Port Blair, rural South Andaman, and Rangat; 80% in Mayabandar and Wimberlegunj; 60% in Kadamtal and Degreepur; 50% in Campbell Bay; and 40% in Teressa. Nine wells were activated, and 80% of the water supply was restored through springs and wells in Car Nicobar Island. Natural water sources were available at Mildera and Beachdera, and 50% of the water supply was restored in Katchal. Of three wells, one is usable in Great Nicobar Island, and the water supply was partially restored through tankers. Wells and spring water were available in Little Andaman Island, and the water supply there was partially restored.

The Government of India Central Salt Research Institute has installed a reverse osmosis (RO) unit in Car Nicobar Island, and the unit is treating brackish water with approximately 3,000 ppm total dissolved solids (TDS). Before the tsunami, this well was the source of drinking water, and the tsunami has clearly deteriorated the water quality of this well. Even after two weeks of operation of the RO plant, the TDS level has not decreased.

At Campbell Bay, an RO unit with a capacity of 1,200 L per hour (LPH) has been installed to treat well water with 15,000 ppm salinity—that is, half the salinity of seawater—for a population of 5,000.

WATER MAINS ALONG SOUTH ANDAMAN ISLAND TRUNK ROAD

The 46-cm-diameter RC water pipelines that were laid parallel to the main trunk road in South Andaman Island were damaged as a result of ground shaking, ground settlement, and the tsunami. It is noteworthy that, six weeks after the earthquake, the pipeline was still leaking at the joints (Figure 8).

SLUICE GATES ALONG SOUTH ANDAMAN ISLAND TRUNK ROAD

A number of sluice gates under the South Andaman Island Trunk Road were built to drain the rice fields and control the infiltration of seawater. However, during the earthquake, the tsunami overtopped the roads and broke the sluice gates (Figure 9). Moreover, the eastern part of South Andaman Island suffered tectonic subsidence as a result of the earthquake, and the land is now permanently inundated with saltwater, thus destroying the rice fields that were ready to be harvested (Figure 10).

WATERSHEDS FOR PORT BLAIR IN SOUTH ANDAMAN ISLAND

The main water source for Port Blair is the watershed behind the Dhanikhari Dam. This concrete dam (on the Dhanikhari River) was constructed during 1970–73 to supply water to Port Blair. The dam is 132 m long and 32.23 m high, with a central gated spillway having a capacity of 26,000 cu/sec. The reservoir extends to an area of 0.49 $\times$ 10 mi.^{2}, and the storage capacity is 9,000 lakh L. On 26 December 2004, the reservoir water level was 60.60 m. Inspection of the dam revealed some minor distress to the main structure due to the earthquake (Figures 11a and 11b). Inspection of the foundation gallery showed cracking along the fifth block joint, and seepage was taking place. It was reported that, before the earthquake, the water seepage used to be pumped after every six hours. After the earthquake, this seepage required hourly pumping. After the earthquake, the main supply pipes were dislodged, and therefore the water supply to the town was disrupted. The water supply was eventually restored.

The Chouldari watershed is an earth dam structure 19 m high and 95 m long, with a

Figure 8. Water main leaking along the South Andaman Island Trunk Road (photo: M. Yashinsky).

10-m-wide and 80.58-m-long left bank ungated RC-chute spillway. The earthen section has pitching of basalt blocks, both in the upstream and downstream sides. A concrete apron has been placed over the entire length of the crest. The distress is seen at the junction of the earthen section and spillway concrete. Here, the concrete apron has buckled by as much as 8 cm along the block joint (Figures 11c and 11d). The profile of the earth section otherwise does not show any deformation or distress. It was reported that, on the morning of the earthquake, the level of the reservoir (whose area is 15 ha) was quite low. But, due to the tremors, the waves in the reservoir rose so high that they splashed onto the crest portion that was about 5.6 m above the reservoir level.

Longitudinal cracks developed at the crest of a 27-m-high, 146-m-long rockfill dam of the 5.25-MW Kalpong Hydroelectric Project near Diglipur in North Andaman Island. The cracks developed near the curved end along the axis of the straight portion of the dam (Figure 12). Movements were also noted across the block joints near both ends in the 24-m-high, 138-m-long 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 even after ten days. The collapse of a transmission tower at Middle Strait further restricted its power distribution to North Andaman Island.

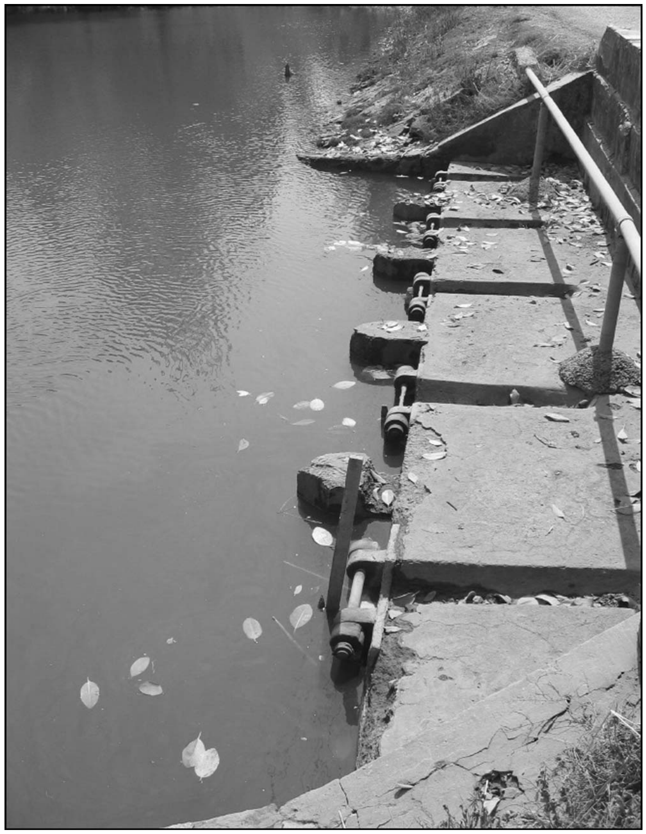


Figure 9. Damaged sluice gates under the South Andaman Island Trunk Road (photo: M. Yashinsky).

ELEVATED WATER TANKS

Elevated water tanks are commonly built in the area, particularly in towns such as Port Blair and Diglipur. These towns are at least 1,000 km from the epicenter and sustained a shaking intensity of VI–VII. Even then, some of these tanks showed substantial damage due to earthquake shaking.

For example, an overhead water tank with a 50,000-L capacity at the converter room of the Haddo naval jetty developed plastic hinges at the bottom of all its columns and at the top in a few columns. The tank is supported on 6-m-high staging consisting of eight 300-mm square RC columns with intermediate RC beam braces at a height of 3 m. The presence of the staircase going around the staging seems to have made the tank geometry unsymmetrical, and the tank sustained torsional response. The container sustained no damage (Figure 13).

In another RC elevated water tank at the Suryachakra powerhouse in the Bamboo Flat area near Port Blair, the beam-column joints of the frame staging sustained damage,

Figure 10. Fields in South Andaman Island were inundated by seawater (photo: M. Yashinsky).

in addition to some concrete spalling on columns at discrete locations along their height where there was very little cover (Figure 14). The space within the frame staging was made into an enclosure by adding infill walls and was being used for storage. The infill walls collapsed out-of-plane under the earthquake shaking. The damage underscores the need to (a) improve the detailing of beam-column joints in RC frames, (b) improve the quality of on-site supervision during construction, and (c) re-examine the out-of-plane stability of the masonry infill walls.

Figure 15 shows a masonry structure with no footing. It would have tipped over without the concrete barrier of the well in front of it.

A very large RC tank with under-reinforced columns and connections had serious damage but somehow avoided collapsing during the earthquake. We also saw several well-designed inverted, cone-shaped elevated water tanks that performed well during both the ground shaking and the tsunami.

A stack-like overhead water tank at the Air Force Colony in Car Nicobar Island (Figure 16a) has cylindrical staging and rests on a pile foundation. This structure withstood the force of tsunami waves without any damage, even though it is right on the shore, owing to its hydrodynamic shape and the use of a pile foundation (Figure 16b).

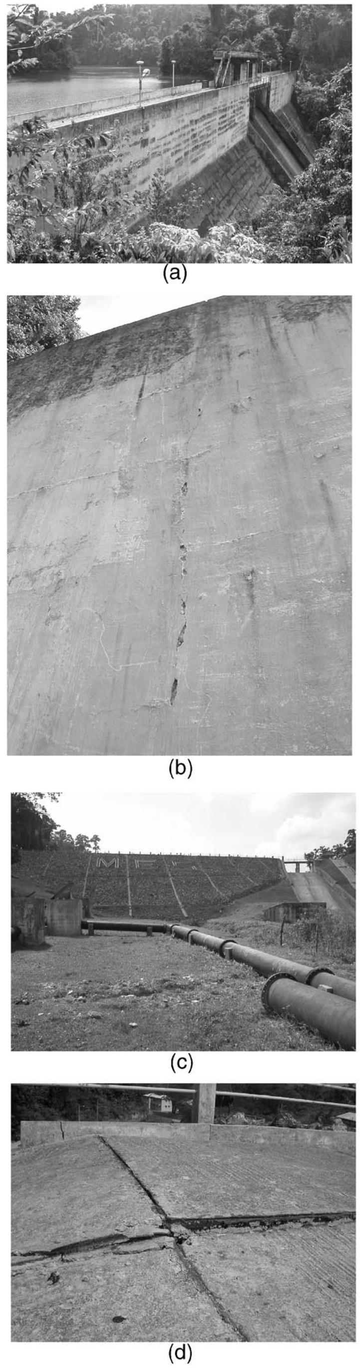
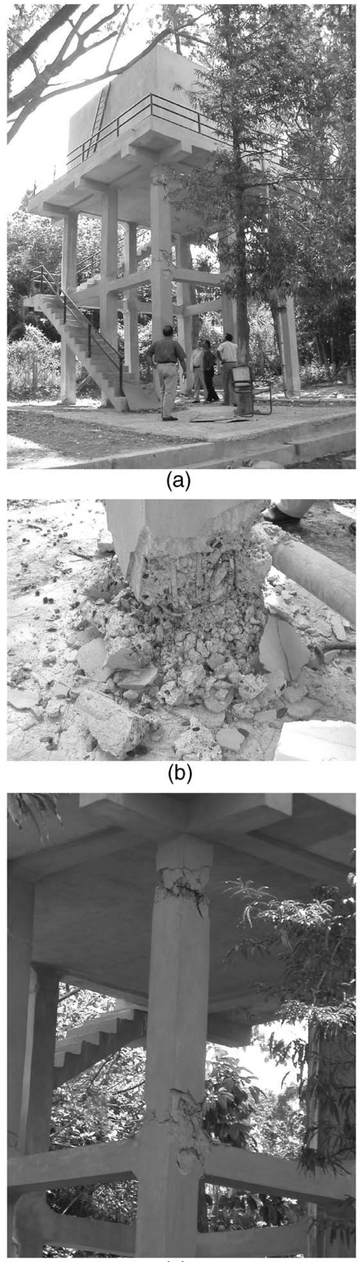


Figure 11. Dams in the Port Blair area in South Andaman Island: (a) and (b) vertical cracks in the body of the Dhanikari Dam on the downstream side; and (c) and (d) buckling of the concrete apron over the crest of the Chouldari Dam at one end (photos: H. Kaushik).

Figure 12. Longitudinal cracks at the crest of the rockfill dam of the Kalpong Hydroelectric Project near Diglipur in North Andaman Island (photos: G. Mondal).

Relief and Response

By 18 January 2005, the water supply system was 100% restored in Nancowry and Kamorta islands; about 90% restored in Port Blair, rural South Andaman Island, and Rangat; 80% in Mayabandar and Wimberlegunj; 60% in Kadamtal and Diglipur; 50% in



(a) (b) (c)

Figure 13. (a) Severely damaged RC overhead water tank at the converter room of the Haddo naval jetty. The tank container was not damaged (photo: H. Kaushik). (b) Close-up of plastic hinge formation at the bottom of one of the columns (photo: H. Kaushik). (c) A few columns also developed plastic hinges at the top level (photo: S. Jain).

Figure 14. Out-of-plane failure of an infill wall and formation of a plastic hinge at the beam-column joint of a freshwater tank (50 kL capacity) at Suryachakra powerhouse in the Bamboo Flat area in South Andaman Island (photo: D. Rai).

Campbell Bay and Katchal; and 40% in Teressa. On Car Nicobar Island, nine wells were reactivated, and about 80% of the water supply was restored. In Great Nicobar Island, of the three wells used for drinking water and domestic consumption, one was usable, and water supply was partially restored by supplying water from tankers. In Little Andaman Island, the water supply was partially restored through available wells and spring water. Repairs to the rest of the water supply system were in progress.

After the earthquake, liquid petroleum gas (LPG) stocks were replenished according to the priorities in the A&N islands. The Indian Oil Corporation office in Port Blair monitored the stocks and supplies and brought fresh stocks of petrol (MS), diesel (HSD), kerosene (SKO), and aviation turbine fuel (ATF) from Haldia (West Bengal) to Port Blair as required. Petroleum products were regularly transported to other islands from Port Blair in barrels according to the A&N Administration requirement, and there was no reported lack of availability of these petroleum products. The status of petroleum product supplies in the A&N islands as of 12 January 2005 is given in Table 1.

MAJOR OBSERVATIONS

RC water supply storage tanks were relatively unaffected by the tsunami waves. Most of the observed damage came from ground shaking. The main problem was well and soil contamination due to seawater ingress during the tsunami. The tsunami seawater impact on surface soils has yet to be fully investigated, and this task should be com-

Figure 15. Elevated water tank at Port Blair, South Andaman Island (photo: R. Surrampalli).

pleted as soon as possible. This problem was exacerbated by tectonic subsidence that put many islands partially under seawater. It appeared that the government administrators for the union territory of the A&N islands took adequate measures to provide temporary drinking water supplies to the affected villages and towns. A greater understanding is needed of the long-term impacts and effects of the tsunami and tectonic subsidence on the environment and ecology.

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The entire Port Blair telecommunications team should be commended for their fast action and for making the best use of all equipment and tools available to them to continue communications with the mainland, without additional staff.

In terms of ham radio, the Washington Post reported that Ms. Bharthi Prasad became

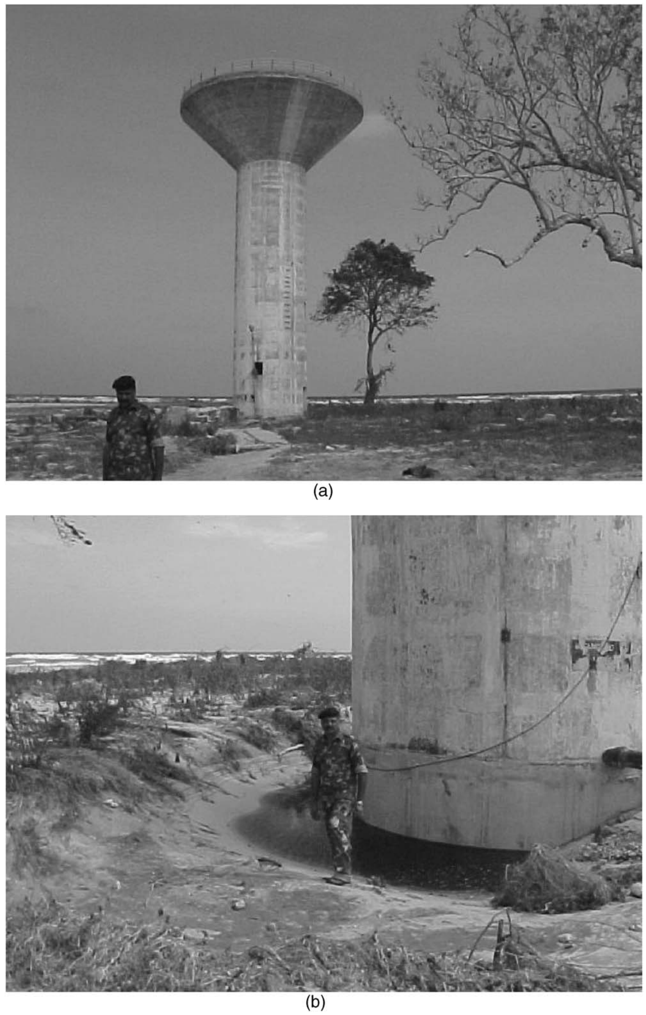

Figure 16. Conical water tank at the Air Force Colony at Car Nicobar Island: (a) no apparent sign of any structural damage; (b) despite some scouring of the soil adjoining the shaft at the ground level, the scouring was not enough to cause instability of the tank (photos: C. Murty).

so popular in the A&N islands that she was nicknamed the "Teresa of the Bay of Bengal," an oblique reference to the late Mother Teresa, a nun who devoted her life to aiding and comforting the poor of Calcutta.

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Table 1. Petroleum products supplied to the A&N islands immediately after the earthquake

Product	Stock (kL)	Number of days for which supply is adequate
MS (petrol)	719	24
SKO (kerosene)	868	35
HSD (diesel)	8,759	25
ATF (aviation turbine fuel):		
Andamans	1,584	13
Car Nicobar	366	18
MT (liquid petroleum gas)	82	4

In addition, there was a local support team, which consisted of the following persons: Professor M. Prasad, Indian Institute of Technology (IIT), Chennai, Tamil Nadu; Ms. Prathibha Gandhi, Ph.D. student, IIT, Chennai, Tamil Nadu; and Mr. M. Ganapathy, chief engineer (retired), Tamil Nadu Public Works Department. We are also grateful for the valuable assistance of P.A.M. Murty, ICE, India.

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