Learning from Earthquakes

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

Editor’s Note: Beginning with March issue, and in each one subsequently, we have presented five reports by the many teams that observed the effects of the earthquake and tsunami in countries around the Indian Ocean. In this issue, we focus on lifelines and buildings in Sri Lanka. Publication of this report is supported by funds from the National Science Foundation through the Earthquake Engineering Research Institute’s (EERI) Learning from Earthquakes (LFE) Program under grant # CMS-0131895.

Report #6

Sri Lanka Lifelines and Buildings

The Post-Earthquake Investigation Committee of the Technical Council on Lifeline Earthquake Engineering (TCLEE), a technical council of the American Society for Civil Engineers (ASCE), in conjunction with EERI’s LFE Program, organized a reconnaissance team to assess lifeline damage in areas affected by the tsunami.

The Sri Lanka team was made up of the following: Donald Ballantyne, leader, ABS Consulting, Seattle; Hiran deMel, CH2M Hill, Gainesville, Florida; Suresh de Mel, Lanka Fishing Flies, Sri Lanka; Mary Goodson, CH2M Hill, Oakland, California; John Headland, Moffatt & Nichol, New York, New York; Adam Ludwig, ABS Consulting, Seattle; Gordon Masterton, Jacobs Babbie, Edinburgh, Scotland; Jane Preuss, Planwest Partners, Seattle; Peter Yin, Port of Los Angeles.

Members of the team also represented the ASCE Coastal, Ocean, Port and River Institute (COPRI); the American Planning Association (APA); the Natural Hazards Center (NHC) at the University of Colorado-Boulder; and the Institution of Civil Engineers (ICE), based in the United Kingdom. The team started the reconnaissance effort on January 31, 2005, five weeks after the earthquake and tsunami. Departing from Colombo, the team traveled around the southern and eastern periphery of the country.

Introduction

On December 26, 2004, the Mw 9.0 earthquake struck at 6:28 a.m. local time in Sri Lanka, and the first tsunami wave hit approximately 2.5 hours later, a little after 9:00 a.m. In many locations, three waves were documented, with the highest waves reported in the Hambantota and Ampara districts on the southeast and east coasts of the island (see Figure 1). Wave heights were as high as 5 m in some locations, and inundation spread 3-4 km inland in the Ampara District.

About 43,000 people died or are missing, and 500,000 people were left homeless. The fishing and tourist industries were devastated.

The water supply and transportation systems were the most heavily affected. As many as 60,000 wells were inundated with saltwater. There was an unprecedented outpouring of membrane and reverse osmosis water treatment plant materials that required actions to control potential epidemics.

Surface water supplies from the interior serve the larger cities and were not affected, with the exception of a few distribution lines crossing inlets along the coast.

Dozens of bridges on the highway and railroad system were damaged. Few communities were isolated, but recovery was dependent on replacement of bridges and track.

Power and communications infrastructure was damaged within the inundated area along the coast, but no major nodes were affected. Restoration is hampered by shortages of equipment, labor, and supplies. For example, sand for concrete is in very limited supply.

Lifelines

Highways and Railways: Sri Lanka has a highway system serving most areas, including a coastal road most of the way around its circumference. Major roads close to Colombo are four lanes wide, while
Buses are an important mode of transportation, and the service was hampered by damage to bus stations and buses in several communities. The bus terminal in Galle was flooded, killing many people and floating buses around the downtown (Figure 4). Sri Lanka Railway operates corridors from Colombo south to Matara, and to several points on the east and northeast of the island. There was damage to bridges and track along coastal segments (Figure 5), and to stations in flooded communities. The most severe damage was to the southern segment serving Matara.

Twelve bridges were damaged or collapsed, mostly by scour and erosion. It appeared as though there was inadequate allowance made for flow capacity beneath the bridges, and approaches and/or abutments were washed out. The Arugam Bay Bridge in Pottuvil was the longest bridge damaged, with the southern approach washed out and two of the pile bents settled (Figure 2). Most bridges were temporarily restored with Bailey Bridges (Figure 3).

The tsunami waves swept a passenger train off its track in Telwatta, drowning more than 1,000 riders and the local inhabitants who had jumped on the train after the first wave (Figure 6).

After bridge and road damage isolated several communities, temporary ferry service was provided in Trincomalee (Figure 7) and Pottuvil (by the Canadian military using rubber pontoon boats).

Harbors and Ports: Fishing harbors were heavily damaged at numerous locations, resulting in the loss of 2,000 fishing boats, and 60% of Sri Lanka’s protein comes from the sea. In Tangalla, 60 boats were lost, and the fish processing/cold storage facilities were heavily damaged.

The fishing harbor was also heavily damaged in Hambantota, where 90% of the city was destroyed. A new town was being constructed by an NGO several km inland to protect the population from future tsunamis, but the ramifications of this move are as yet unknown.

The Sri Lanka Ports Authority (SLPA) manages ports throughout the country. The Port of Colombo is a major international container port, where containers are redistributed to smaller ships that carry them to near the southern tip of Sri Lanka. The line carries 78,000 passengers a day (mostly commuters) as well as petroleum products to and from the Port of Galle. Restoration along that segment includes relaying 20 km of track; reconstructing 15 bridges, 20 railway stations, and signaling and control equipment; and replacement of rolling stock.
their final destination. In Colombo, a 2-3 m tsunami wave overtopped a few of the wharves and the 150-year-old breakwater. Some minor damage was experienced at a few buildings, including the SLPA administration building, where the ground floor was flooded with 0.5 m of water.

A relatively small container ship lost navigational control in the harbor entrance as the receding tsunami wave created large currents. The ship struck the tip of one of the breakwaters and ran aground. The port was closed for two days. At Galle, a 4-5 m wave picked up a dredge and placed it on top of one of the wharves, but the damage was not widespread.

**Water:** Surface water supplies from higher inland elevations serve the larger communities. Reservoirs gather water that is then treated and distributed. Most of the components of these systems were not damaged by the tsunami, but some pipelines (about ten) were damaged at river crossings near the ocean. This was the case at Matara, where a 10-inch line was lost and a temporary polyethylene pipe was installed to restore service (Figure 8).

Smaller communities rely on groundwater from dug wells or, in a few places, drilled or driven wells. In many cases, the dug wells are less than 20 feet deep. Water is either withdrawn manually or pumped to tanks situated on roofs or elevated structures (Figure 9). One estimate put the number of inundated wells at about 60,000, of which 12,000 required cleaning.

When the wells are flooded with turbid salt water and debris, this also allows the saltwater and contaminant to have direct access to the shallow freshwater aquifer in which the well is dug. Wells were being restored by pumping out the salt water, but by early February, less than 10% of the wells had been restored.

In addition to well contamination from sea water and debris, another concern was the close proximity of...
Groundwater nor piped surface water was available. Providing potable water in the days following the tsunami was a critical issue. The media reported widespread fear of disease due in part to lack of adequate clean water, but because of effective provision of fresh water, there were only 135 cases of diarrhea and 579 cases of viral fever reported during the week of January 8-14, well below epidemic levels.

Since the large inland water supplies were largely unaffected, emergency water supplies were provided as bottled water and in tank trucks. But within several days, delivering water in reused containers was discouraged because of water quality concerns. Bottling plants in Colombo and other unaffected areas continue to bottle water for distribution to damaged areas. Emergency responders from around the world provided portable (and then permanent) water treatment facilities (Figure 10). Most of these were either reverse osmosis or membrane filter units. The Canadian military set up reverse osmosis units in refugee camps along the east coast. Private suppliers of membrane and reverse osmosis plants included General Electric, Siemens/US Filter/Memcor, ITT Industries, Zenon Environmental, and Pall Corporation. This private provision of state-of-the-art water treatment equipment is unprecedented.

Water was distributed to “bowsers,” mobile or stationary tanks, from onsite sewage disposal systems to the shallow wells used for potable water. In Sri Lanka, only Colombo has a centralized wastewater system, and there only one sewage pump station was damaged, but in rural areas, more than 30,000 latrines, associated septic tanks, and leach fields were damaged.

Water was needed in areas where people remained in their damaged homes and camps where displaced people were living, since neither groundwater nor piped surface water was available. Providing potable water in the days following the tsunami was a critical issue. The media reported widespread fear of disease due in part to lack of adequate clean water, but because of effective provision of fresh water, there were only 135 cases of diarrhea and 579 cases of viral fever reported during the week of January 8-14, well below epidemic levels.

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Figure 10. Water being pumped out of well (right) to treatment unit (left) and then into bladder beyond well (photos: Ballantyne).

Figure 11. Water "bowser" in damaged village (photo: Ballantyne).

these treatment units and from noncontaminated surface and groundwater sources further inland (Figure 11).

**Electrical Power:** Two thirds of Sri Lanka’s power is generated by hydroelectricity, and one-third by thermal plants using imported oil and natural gas. The Ceylon Electricity Board and the Lanka Electricity Company provide service from generation facilities all located inland and not damaged by the tsunami.

However, there was power supply interruption to approximately 63,000 households, as approximately 450 km of medium and low voltage power distribution lines were ripped up along coastal roads (Figure 12), and 88 substations were damaged. The Ceylon Electricity Board complex in Hambantota was damaged.

**Communications:** There was a reported $100M damage to Sri Lanka Telephone’s poles and local switching equipment in inundation areas. One communications tower was toppled when heavy floating objects hit the legs (Figure 13). Transmission equipment was relocated to an adjoining tower within one week.

**Buildings**

Tsunami waves accounted for all reported damage in Sri Lanka; there was no significant ground motion, with a maximum reported MMI of II. The tsunami damaged more than 99,800 building structures, of which about 90% were modest single-family residential structures. Approximately 170 schools and 26 hospitals were completely or partially damaged. The level of damage to structures within inundation zones was observed to be linked to type of construction, tsunami wave height, receding wave flows, the structure’s proximity to the shoreline and position with respect to neighboring buildings, and topographical features.

Varying inundating flow heights—up to 5 m in some places—resulted in a range of damage to buildings. Construction type had a pronounced effect on building survivability throughout the damage area. Structures of two or more stories, typically of reinforced concrete frame and masonry infill wall, per-
Foundation scarring, and resulting partial and progressive collapse, accounted for a substantial number of structural failures, particularly in areas experiencing modest wave heights (less than 3 m). Receding flows accounted for a large volume of observed scarring damage. Structures in the path of natural drainage were noticeably scarred from the high-volume, high-velocity receding flows.

Building Type and Performance:
The Sri Lankan building stock comprises four basic building types: unreinforced masonry (URM); reinforced concrete (R/C) frame with URM infill; R/C frame and shear-wall; and wood-framed structures.

1) URM: Single-family residential structures in Sri Lanka are typically made of URM (usually clay brick) walls supported on concrete slabs on grade. Perimeter foundations are made of thickened concrete slab edges or shallow brick stem walls if required to adjust for variations in grade. Roof construction typically involves wood beams and light wood rafters supporting either corrugated steel, clay tile, or thatch roof systems. Cross ventilation is an important feature in the tropical climate, and it is commonly provided by continuous air gaps between the roof and walls along the eaves and gables (Figure 14). Generally, no positive means of wall-to-roof anchorage is employed, so exterior masonry walls, sometimes of single-wythe construction, achieve out-of-plane support by spanning laterally to adjacent wall corners or interior partitions. Covered porches,

Figure 12. Remnants of power poles along the road (photo: Ballantyne).

Figure 13. Collapsed communications tower in Hambantota (photo: Ballantyne).

Figure 14. Typical Sri Lankan single-family URM, located 100 m inland from the site of the train disaster at Telwatta (photo: Adam Ludwig).
supported by slender masonry piers, are also common. In some instances, lightly R/C bond beams are cast along the tops of walls to tie the construction together.

Damage to URM buildings was extensive in areas sustaining inundation flows in excess of 2 m. In areas where flows exceeded 4 m, the damage was often total. The structures’ weak out-of-plane wall strength made them vulnerable to the hydrostatic and hydrodynamic forces at higher flow levels. At lower flow levels, foundation scarring often led to progressive damage and partial or total collapse (Figure 15). The impact from floating debris in incoming and outgoing flows was also attributed to many wall and column failures.

2) R/C frame with URM infill: R/C frame with URM infill buildings are the predominant structure type for residential and commercial buildings of two or more stories throughout Sri Lanka. The concrete frames are minimally reinforced with widely spaced ties. Floors are typically one-way cast-in-place concrete slab and beam systems. In two-story structures, some of the URM may be load-bearing, with second-floor bond beams cast integrally over the wall below.

The typical mode of failure in this type of structure was related to collapse of nonload bearing infill walls. Most often, these were walls fronting the incoming waves or receding flows (see Figure 16). However, because the upper floor level bond beams provided increased out-of-plane wall strength and interconnectivity, R/C frame buildings substantially outperformed the more common URM structures (Figure 17).

3) Reinforced concrete: There were few examples of R/C moment frame and/or concrete shear wall structures observed within Sri Lanka inundation zones. Such structures are more prevalent in modern Thailand resort construction, and there they performed very well in many areas where inundation flows exceeded 5 m. Structural damage was generally found to be minimal, though there was significant nonstructural damage at the lower floor levels.

4) Wood: Wood structures found throughout the regions affected by the tsunami are typically lightly constructed nonengineered structures. Few wood structures were observed in Sri Lanka—masonry and concrete construction are preferred to provide protection against heat and humidity—but in Thailand, Indonesia, and India, performance of wood structures was very poor. Extensive damage was noted in areas where
Beyond building type, there are many conditions that enhance or detract from a structure’s survivability. Mortar quality, wall slenderness, masonry type, foundation construction, and porch pilaster construction are just a few examples.

**Other Damage Factors:** Beyond building type and the number and magnitude of inundating waves, several other factors affected the extent of damage to building structures.

1) **Impact from floating debris:** Tsunami damage is related to the effects of multiple waves. Frequently, the receding first wave carried land-born debris out to sea, from where it was carried back to shore in following waves to devastating effect. Floating tree trunks and building materials contributed to much of the observed damage.

2) **Proximity to shoreline:** Structures were particularly vulnerable when located close to the shoreline for two reasons: limited damping prior to impact, and the amplification of impact loads due to the runup on sloped shorelines.

3) **Density of the built environment:** Where structures were densely spaced, significant damage was sustained in the buildings adjacent to shore, but this apparently dampened the wave energy, sparing structures inland (Figure 18).

4) **On-shore topography:** Once the waves were on shore, the natural terrain affected the rate and direction of the flow. In some cases, it acted like a broad-crested weir, causing waves to speed up on the down-sloped side. Where incoming flows naturally collected in interior low lands or lagoons, they would recede through a natural drainage path at a much higher volume and velocity than the incoming wave.

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