Sri Lanka Field Survey after the December 2004 Indian Ocean Tsunami

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An International Tsunami Survey Team (ITST) consisting of scientists from the United States, New Zealand, and Sri Lanka evaluated the impacts of the 26 December 2004 transoceanic tsunami in Sri Lanka two weeks after the event. Tsunami runup height, inundation distance, morphological changes, and sedimentary characteristics of deposits were recorded and analyzed along the southwest and east coasts of the country. Preliminary results show how local topography and bathymetry controlled the limits of inundation and associated damage to the infrastructure. The largest wave height of 8.71 m was recorded at Nonagama, while the greatest inundation distance of 390 m and runup height of 12.50 m was at Yala. At some sites, human alterations to the landscape increased the damage caused by the tsunami; this was particularly evident in areas of coral poaching and of sand dune removal.
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INTRODUCTION

On 26 December 2004, the boundary between the Indo-Australian and Eurasian plates off the coast of northern Sumatra ruptured in a great (M_w=9.3) earthquake at 00:58:53 universal time (UT) (Malik and Murty 2005). Up to 15 m of thrust on the plate interface displaced approximately one trillion tons of seawater, releasing 10^{17} J of energy and propagated a tsunami across the Indian Ocean (Ni et al. 2005, Lay et al. 2005).

In Sri Lanka, the tsunami arrived as a leading elevation wave a little over two hours after the earthquake (2:55 UT, 8:55 A.M. local time) (Table 1). The highest wave was on the east coast around Nonagama with a later and smaller peak wave, inundating the south and west coasts up to at least an hour later (Table 1). One to three recognizable waves inundated Sri Lanka. In most cases, two waves were reported, with the first about

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Table 1. Tsunami runup and inundation (see also Figures 1 and 2)

Location	Longitude (°)	Latitude (°)	Max. elevation (m)	Runup (m)	Max. sed. thickness (cm)	Min. distance inland (m)	Approx. arrival time (local), A.M.
Trincomalee Hotel	81.21845	8.618075	4.4				9.10
Trincomalee town	81.24202	8.561729	2.7				9.10
Stop 2	81.24202	8.561729	5.9	2.4			9.10
Trincomalee military checkpoint Stop 3	81.23478	8.563063	2.5				9.10
Trincomalee Hearing-Impaired Hostel	81.21380	8.579356	3.2				9.10
China Bay Stop 1 —Kinnaya	81.19094	8.503758	2.8				9.00
China Bay Stop 2 —Kinnaya	81.19206	8.492397	3.35				9.00
China Bay Stop 3 —Mutur	81.26444	8.463147	3.25				
N of Batticaloa	81.69267	7.744343	2.7				9.00
Kattativu	81.74025	7.686330	3.7				
Karativu	81.85432	7.364405	4.85				
Ninto	81.86083	7.343535	4.5				
Nalaveli Hotel	81.18847	8.706572	4.1		17.0	80.0	
Pottuvil			6.1	6			8.55
Ibral Nagar Nalalevi-1	81.21794	8.660616	4.65				
Ibral Nagar Nalalevi-3	81.21918	8.660272	4.5				
Ibral Nagar Nalalevi-4	81.21674	8.661204	4.45				
Ibral Nagar Nalalevi-5	81.21650	8.661829	3.8				
2 km SE of Kuchchaveli	81.12103	8.790385	3.35				
Mankeri	81.48953	8.013957	5.5		11.0	134.7	
Kalmunai Kuddi	81.84164	7.405348	6.2		15.0	210.0	
Kulmunai Kuddi 2	81.83044	7.422988	7		12.0	110.0	
Moratuwa	79.88353	6.762450	3.56				9.30
Koralawella	79.88879	6.749667	4.55				
Wadduwa	79.92110	6.673167	3.61				
Hambantota	81.12752	6.128450	6.1	11			9.18
Nonagama	80.98835	6.093750	8.71				
Tangalla	80.79562	6.029367	3.24				
Tangalla 2	80.47717	6.011630	7.9		Boulders	14.8	9.00
Kamburugama	80.49195	5.940050	2.4				
Weligama	80.44682	5.968984	2.73				9.20
Galle	80.24915	6.009734	5.24				9.20
Dodanduwa	80.14692	6.083717	3.6				
Hikkaduwa	80.10413	6.127517	4.2				9.15
Hikkaduwa 2	80.06159	6.077360			23.0	34.0	9.30

Table 1. (**cont.**)

Location	Longitude (°)	Latitude (°)	Max. elevation (m)	Runup (m)	Max. sed. thickness (cm)	Min. distance inland (m)	Approx. arrival time (local), A.M.
Thiranagama	80.12357	6.110650	4.55	6.81			
Galbokka	80.03091	6.323317	4.26				
Seenigama	80.08908	6.166100	5.05				
Dehiwala	79.85640	6.877667	3.48				
Panadura	79.90334	6.715483	4.24				
Pinnatara	79.91306	6.689667	4.15	3.47			
Kalutara	79.94800	6.608450	3.82	3.87			
Payagala	79.97835	6.521217	5.04				9.30
Yala	81.25503	6.166390	4.65	12.50	22.0	390.0	9.15
Boosa	80.09014	6.047760	1.50		5.0	30.0	9.15
Boosa 2			2.50				9.15
Telwatte	80.04268	6.110960			20.5	108.0	9.10
Wellawatta	79.51413	6.525880	1.50		7.0	30.7	9.20
Katukurunda	79.57682	6.333590			37.0	61.0	9.30

1 m high and the second, larger wave about 10 minutes later. Along the west coast between Galle and Kaluthara, a third wave that is believed to have been reflected off the Maldives and/or India arrived at around noon and was reported to have been several meters high (Liu et al. 2005)(Figure 1).

As soon as the scale of the event was known, a team was organized to document the extent and impact of the tsunami in Sri Lanka. The team was divided into two groups; from 9–15 January 2005, one group visited the east coast, and the other visited the southwest. A preliminary report is posted at http://walrus.wr.usgs.gov/tsunami/srilanka05/.

SETTING

Sri Lanka (7.00° N, 81.00° E) has a total land mass of about 65,610 km^2 (slightly larger than West Virginia). It consists primarily of a Precambrian bedrock core that makes up the Central Highlands surrounded by a fringing coastal plain composed of alluvial deposits (Swan 1985). The majority of the population lives along this narrow coastal plain below 30 m elevation (in 2003, the total population was approximately 19 million). The south coast is dominated by long barriers and spits; interior lagoons and estuaries occupy embayments between headlands and promontories that are bluff outcrops of resistant rock. Wave-cut platforms and other expressions of submerged outcrops extend offshore along much of the west and southwest coast between Colombo and Matara (Swan 1985). The lengths of sandy beach are greatest on the east and southeast coast but diminish to the west, where cliff headlands are more common. These first-

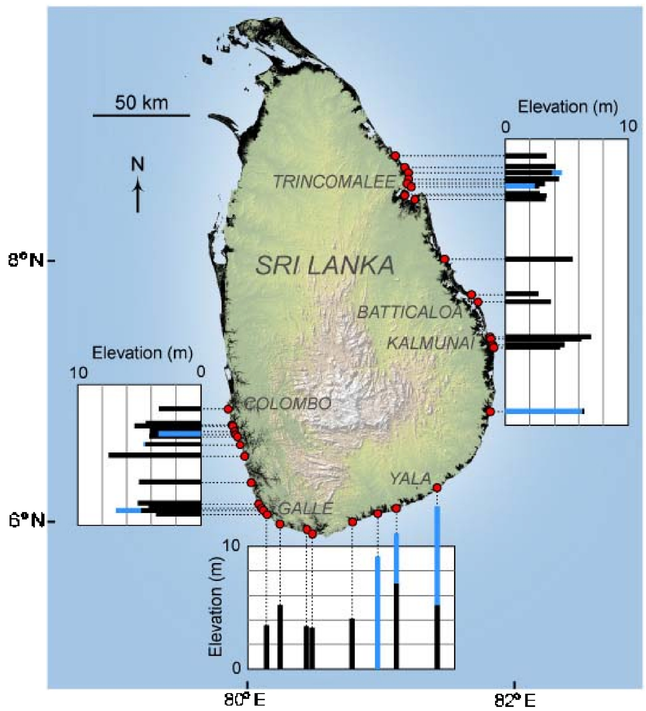


Figure 1. Measured tsunami runup (in blue) (in grayscale: gray) and maximum tsunami heights (in black). Red-filled dots (in grayscale: gray) show the sites of elevation measurement; areas shaded in black are less than 10 m above sea level. The map is modified from one by ASTER (after Liu et al. 2005). In the online version of this figure, the measured runup is in blue, and the maximum tsunami heights are in red.

order morphological features controlled tsunami impacts so that the headlands blocked tsunami inundation and prevented interior damage, whereas the embayments focused the waves and increased the limits of inundation and runup.[1]

Sand dunes are locally well developed on the southeastern beaches of Sri Lanka, where sand supply is abundant and the climate is relatively dry. Sand dunes are largely absent on beaches of the south and southwest coast as a result of higher rainfall in the region. Beach sands are composed predominantly of fine-to-coarse quartz sand with variable amounts of carbonate material consisting of shell and fragments of coral reef. The tsunami deposits have compositions similar to the adjacent beaches and near-shore sediments from which they were derived. Beach erosion was a serious problem for many

[1] Tsunami runup is the vertical distance between n, the maximum height reached by the water on shore, and the mean sea-level surface.

communities even before the tsunami. At some locations, shoreline stabilization structures such as riprap revetments and gabions were damaged or rendered ineffective by the tsunami.

The country experiences few earthquakes, because it is in an intraplate setting away from major tectonic zones. As a result, there is a perceived safety from earthquakes and tsunamis. The most notable natural hazard in Sri Lanka is the occasional large cyclone. The effect of these cyclones has been exacerbated in recent years as a result of coastal erosion caused by sand mining activities and coral poaching (Fernando et al. 2005).

Large earthquakes, however, are known to have occurred along the same section of the plate boundary that failed on 26 December 2004, so tsunami inundation of the Sri Lanka coast has probably occurred in the past. Historically, large earthquakes occurred along this plate boundary in 1847 (M_w=7.5), 1881 (M_w=7.9), 1941 (M_w=7.7), and in 1930 a different section failed in the northern Andaman Sea near the coast of Myanmar (Nutalaya et al. 1985, Ortiz and Bilham 2003, Bilham et al. 2005). Those earlier Andaman events produced tsunamis that, while locally destructive in the islands, had limited regional impact, probably because they involved slip on deeper parts on the plate interface than occurred on 26 December 2004 (Bell et al. 2006). The earthquakes of 1930, centered in the far north of the Andaman Sea on a section of the plate boundary characterized by right-lateral strike-slip faulting, destroyed the ancient seaport of Pegu, in southern Myanmar. The associated tsunami caused severe flooding and numerous fatalities in Myanmar (Nutalaya et al. 1985) but no historically documented tsunami damage in Sri Lanka. Perhaps the best recorded is the tsunami associated with the eruption of Krakatoa in 1883, which produced a tsunami wave amplitude of about 0.5 m in Colombo (Choi et al. 2003).

Farther south, off the shore of Sumatra, the potential for great earthquakes has long been recognized from historical events with estimated magnitudes even larger than those mentioned above (Newcomb and McCann 1987). Earthquakes there, in 1797 (M_w =8.4), 1833 (M_w=9), and 1861 (M_w=8.5) generated large tsunamis. The waves of the 1833 event probably made landfall in Indonesia with heights in the range of 5–10 m (Cummins and Leonard 2004). A smaller event (M_w=7.8) in 1907 just south of the 26 December 2004 rupture zone also produced a locally destructive tsunami in northern Sumatra (Newcomb and McCann 1987). The inferred rupture area of that and the adjoining 1861 event were broken again by the recent (28 March 2005) Nias earthquake.

Given the documented tectonic activity of the region, it is surprising that there is a paucity of historical tsunami inundations. Only two historically documented events have currently been identified: the 1883 Krakatoa event (1–2-m waves) and a possible tsunami circa 1650 (another possible event occurred in 1882). This lack of data is somewhat surprising, given the active tectonic margin 1,500 km to the east. One possible addition to this limited database can be found as a mythical account in the *Mahavansa*, Sri Lanka's national Buddhist chronicle. This chronicle suggests that at least one tsunami may have been comparable to the 2004 event. The *Mahavansa* states that, about 150 B.C., "the sea flooded the land, as a wrath of God for the misdeed of the King who ruled the western part of the country at that time."

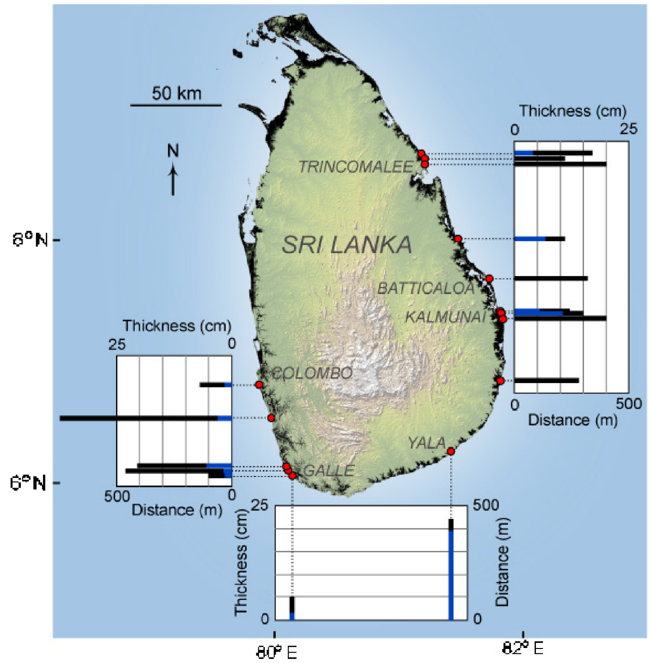


Figure 2. Measured maximum thicknesses of tsunami deposits (in black) and minimum inland extent of tsunami sediments (in blue) (in grayscale: gray). Red-filled (in grayscale: gray) dots show the sites of geological measurement. Other details are as listed in Figure 1. In the online version of the figure, the measured runup is in blue, and the maximum tsunami heights are in red.

FIELD METHODS AND OBSERVATIONS

Dengler et al. (2003) identify the purpose of post-tsunami field investigations. In summary, the nature of the work is to document the extent of inundation, the height and nature of waves, and the thickness and character of sediments, as well as collecting information on impacts. This is achieved through observation, surveying, collation of pertinent documents, and interviewing of eyewitnesses and others such as government officials and aid workers. Several Sri Lankan scientists supported the ITST in these endeavors.

The team measured local flow depths on the basis of the location of debris in trees and watermarks on buildings. The maximum tsunami height on flat terrain and the maximum runup on steep shores were determined in relation to the sea level at the time of the tsunami impact. Numerous eyewitness interviews were recorded on video to estimate the number of waves, their height and period, and the tsunami arrival time.

Data were collected from both the east and southwest coasts. In general, data were

Figure 3. Hikkaduwa: receding ocean. A diver took this photo minutes before a large positive wave arrived. The wreck to the left of the rock outcrop is barely visible on a normal day.

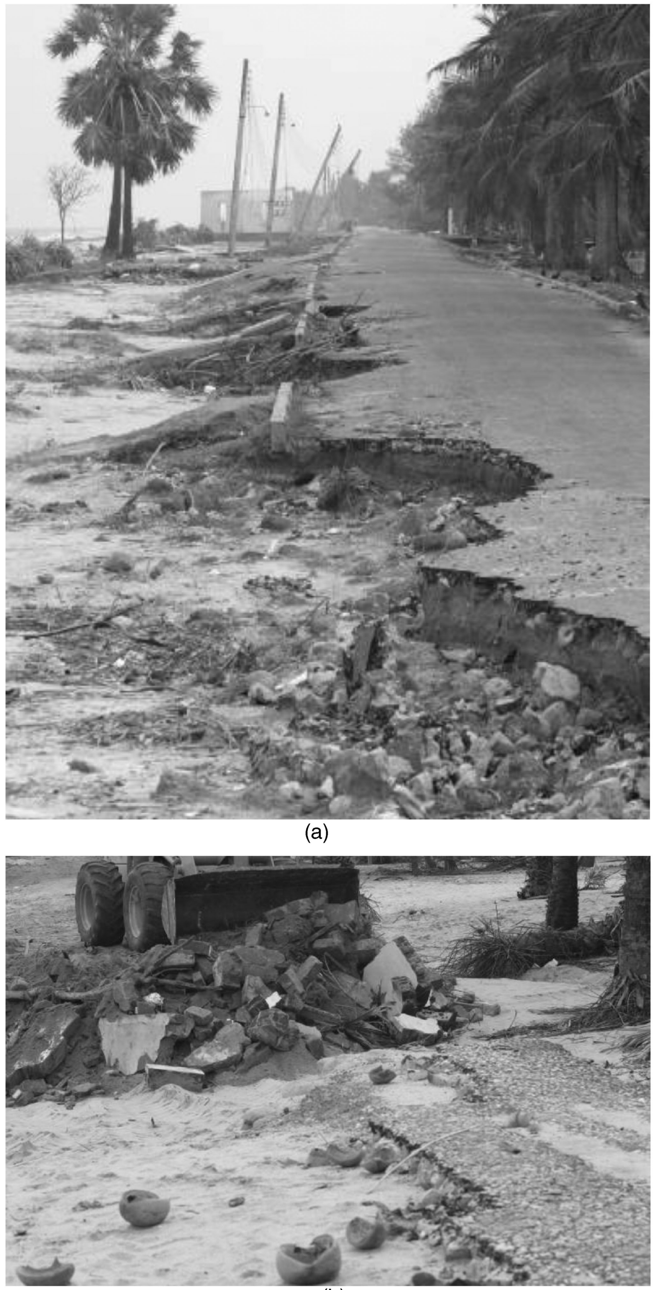
collected from areas easily accessible from roads or from short beach walks. The tsunami height was measured at most locations, whereas runup, inundation, and sediment data are more sparse (Table 1, Figures 1 and 2).

TSUNAMI IMPACTS

The tsunami first arrived on the eastern coast and subsequently refracted around the southern tip of Sri Lanka (Dondra Head). Refracted waves inundated the southwestern part of Sri Lanka with varying intensity, depending upon local topography and beach defenses. The first signs of the tsunami observed by the Sri Lankan public was a negative wave, although a smaller positive wave arrived first. The ocean receded by as much as 1 km in some areas (Figure 3). This was followed by a large positive wave.

Damage to engineering lifelines in the inundation zones was catastrophic. Reconstruction in the immediate aftermath has been variable. About 690 km of the national road network was damaged, in addition to 1,100 km of provincial roads. The main road south from Colombo reopened within three days of the tsunami, whereas roads on the east coast were still seriously compromised at the time of the ITST visit (Figure 4).

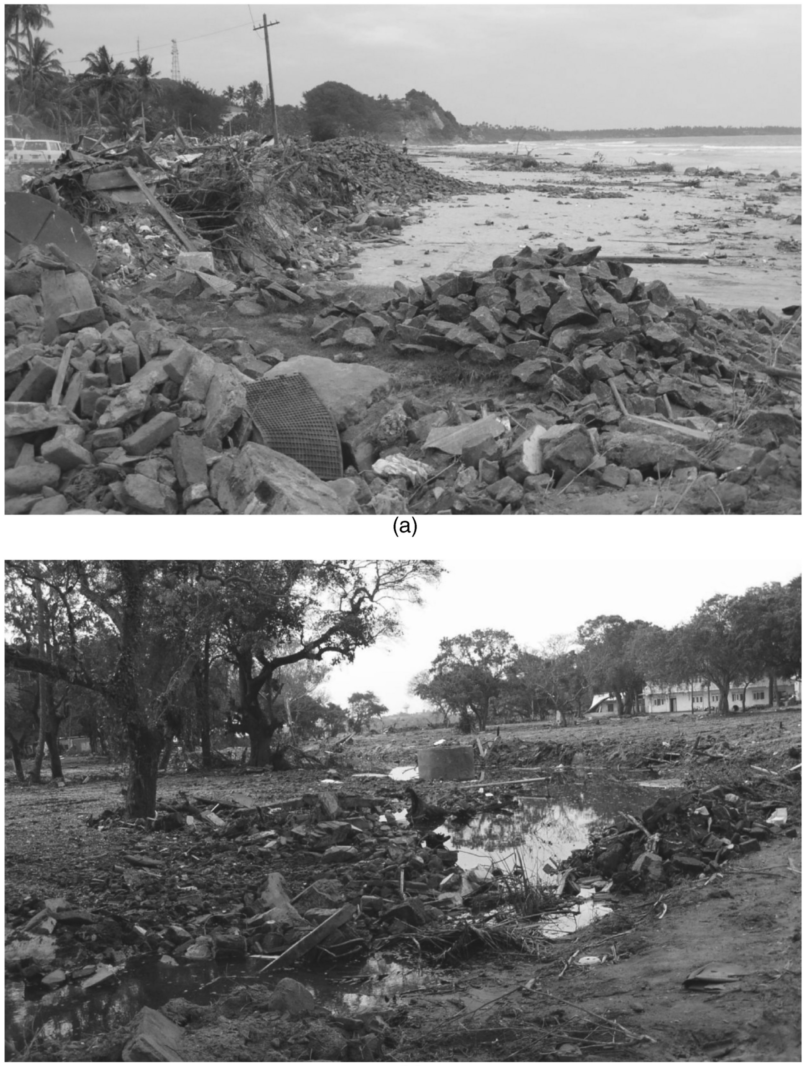
In most cases, the personnel performing emergency clearance of roads and land saw haphazard disposal of debris along the roadside (Figure 5), into open fields, and into drainage ditches; where the road ran adjacent to the sea, material was pushed onto the beaches into the intertidal zone (Figure 5). When pushed onto beaches, much of the debris has been remobilized and incorporated into the near-shore transport zone; in wetlands and ditches, this led to the possibility of groundwater contamination.



(a)

(b)

Figure 4. (a) Kattankudi: coastal roads in this area were notched and in some places completely removed. At this location, the surveyed inundation was about 700 m, with maximum elevations of less than 4 m. (b) Karativu: here, house rubble is used to rebuild a completely eroded coastal road.



(a)

(b)

Figure 5. (a) Matara: debris was pushed into the intertidal zone to clear roads and streets. (b) Hambantota: debris that was pushed into rivers and wetlands has implications for contamination of surface and groundwater resources.

The tsunami caused an estimated US $15 million of damage to the southern rail corridor, with the majority of the damage affecting the track and infrastructure to the south of Kalutara (ADB et al. 2005). Much of the railway was destroyed through bridge or rail damage and scour (Figure 6).

At a number of coastal sites, tsunami runup and backwash created extensive and

(a)

(b)

Figure 6. Payagala: (a) tracks bent inland (from right to left) by the tsunami; (b) damage to the railway station.

(a)

(b)

Figure 7. (a) Matara: recently repaired backwash scour of a drainage channel and beach. (b) Nintavur: the tsunami scoured around and then transported a cement well casing.

Figure 8. Peraliya: the "Queen of the Seas" train after being placed back onto the tracks (photo: Synolakis et al.).

deep scour channels that favored topographic lows or places where structures concentrated the flow. In many cases, this led to scouring around and under buildings or the complete removal of stormwater culverts (Figure 7).

Damage from the tsunami was more marked at sites where there had been some degree of human disturbance of the environment. In the case of Peraliya, illegal coral mining has been shown to have created "low-resistance" pathways that allowed focused flow and intensified destruction, leading to the large loss of life experienced by the derailment of the "Queen of the Seas" train (Fernando et al. 2005) (Figure 8).

In Yala, removal of dunes seaward of a resort hotel led to complete destruction of the development, with inundation and runup far greater than in areas behind adjacent unaltered dunes (Liu et al. 2005) (Figure 9).

The tsunami surge completely destroyed about 100,000 homes and partially damaged about 45,000, or about 13% of coastal housing (ADB et al. 2005). The majority of coastal settlements are fishing villages comprised primarily of poorly constructed timber-framed houses. Some sections of coastline, however, are occupied by substantial brick-and-stucco houses and reinforced concrete hotels that were less affected by tsunami inundation, except in areas where significant human disturbance of the coast had occurred. In general terms, destruction of poorly constructed buildings at or near the coast was complete. Buildings of better construction tended to be located inland (across

(a)

(b)

Figure 9. (a) Yala: looking west from the unaltered high dune toward the area previously occupied by the Yala Safari Beach Hotel. The tsunami runup barely overtopped the unaltered dune in the foreground, depositing a boat near the top, but destroyed the hotel and most of the vegetation in the middle distance. (b) Yala: live vegetation in the lee of the unaltered dune.

(a)

(b)

Figure 10. (a) Boosa: a partially destroyed house on the landward side of the road. (b) Telwatte: little remains of poorly constructed houses on the seaward side of the road.

(a)

(b)

Figure 11. (a) Nilavelli: this resort was heavily damaged by the tsunami despite relatively good construction standards. (b) Weligama: houses landward of the destruction remained intact, while those seaward took the full force of the tsunami.

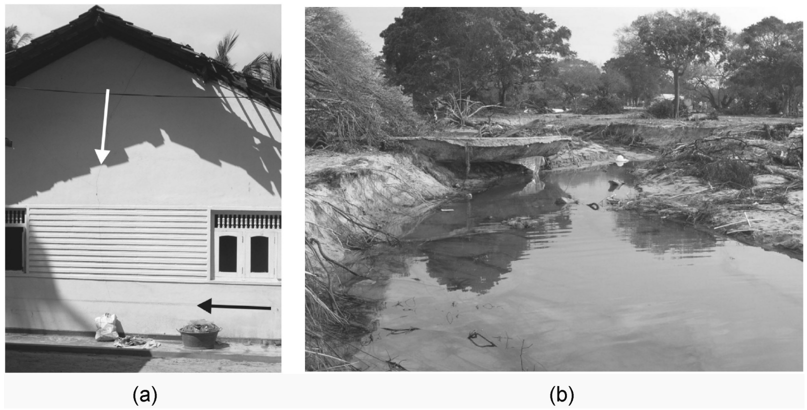


Figure 12. (a) Weligama: a partially destroyed building. Note the nearly vertical crack on the wall that faces the sea (white arrow) and the standing-water mark (black arrow). (b) Yala: backwash scour of foundations.

the railway or road), where damage was less severe (Figure 10), but in areas in which they were located close to the sea and tsunami inundation was severe (the east and south coasts in particular), destruction was also complete or severe.

Extensive areas of debris or cleared land gave an indication of the large number of buildings that had been destroyed (Figure 11). Those that remained standing within the inundation zone appeared to have been either well sheltered by other buildings or were well tied at their foundation levels.

A considerable number of partially damaged buildings survived tsunami inundation but were subject to structural damage caused by the force of the wave or by the effects of standing water (Figure 12). Scour around the side of buildings often caused undermining and structural collapse. This was notable as much in the runup as in the backwash (Figure 12).

CONCLUSIONS

The 24 December 2004 Indian Ocean tsunami produced waves large enough to affect at least 50% of Sri Lanka's coast. Tsunami heights tended to be less than 8 m, while deposits averaged about 20 cm in thickness in a range of 5–37 cm. In addition to tsunami height, topographic variability had a strong influence on runup, sediment deposits, and inundation.

Tsunami damage varied according to the degree to which natural and man-made obstacles either dissipated or concentrated the flow. Reef mining, sand dune removal, and natural channels focused the flow and locally increased damage, while buildings shielded from the beach by other structures had a better chance of surviving.

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