SURVEY OF THE DECEMBER 26TH 2004 INDIAN OCEAN TSUNAMI IN SRI LANKA

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SUMMARY

An International Tsunami Survey Team (ITST) consisting of scientists from the U.S., New Zealand, and Sri Lanka evaluated the impacts of the December 26th 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. At some sites, human alterations to the landscape increased damage caused by the tsunami.

1. INTRODUCTION

General details of the December 26th earthquake and preceding events have been given in Bell *et al* (2005).

In Sri Lanka, the earthquake was felt faintly by some and not by others, and as a result the resulting tsunami was entirely unexpected.

The tsunami arrived as a leading elevation wave a little over two hours after the earthquake (3:10 U.T., 9:10 a.m. local time) (Liu *et al*, 2005). Between one and three waves were reported depending upon the location. In most cases two waves were reported with the first about 1 m high and the second, about 10 minutes later, up to 10 m. high. 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 around noon and was reported to have been several metres high (Liu *et al.*, 2005)(Figure 1).

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

2. SETTING

Sri Lanka (7.00 N, 81.00 E) has a total landmass of about 65,610 sq km (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 (approx. 19 million - 2003 est.) lives along this narrow coastal plain below 30 m elevation. Long barriers and spits with sandy beaches and 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-order morphological features controlled tsunami impacts such that the headlands blocked tsunami inundation and prevented interior damage, whereas the embayments focused the waves and increased the limits of inundation and runup.

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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 nearshore sediments from which they were derived. Beach erosion was a serious problem for many communities even before the tsunami. At some locations, shoreline stabilisation 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. A result there is a perceived safety from earthquake and tsunamis. The most notable natural hazard 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 ruptured along the same section of the plate boundary that failed on December 26th, 2004 (Bell *et al* 2005), so tsunami inundation of the Sri Lankan coast has probably occurred in the past. Perhaps the best recorded is the tsunami associated with the eruption of Krakatau in 1883 which produced a tsunami wave amplitude of about 0.5 m in Colombo (Choi *et al.* 2003).

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 AD1883 Krakatoa (max. 1-2 m waves) and a possible tsunami *c.* AD1650 (another possible event occurred in AD1882). 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 suggests that at least one tsunami may have been comparable to the 2004 event. The *Mahavansa* states that around 150BC "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".

3. FIELD OBSERVATIONS

The post-tsunami field investigations documented the extent of inundation, height and nature of waves, thickness and character of sediments, and collected information on impacts. This was achieved through observation, surveying, collation of pertinent documents, and the interviewing of eyewitnesses and others such as government officials and aid workers. Several Sri Lankan scientists supported the ITST in these endeavours.

The team measured local flow depths based on 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 relative to the sea level at tsunami impact. Numerous eyewitness interviews were recorded on video to estimate the number of waves, their height and period as well as the tsunami arrival time.

Data were collected from both the east and southwest coasts. In general, data were collected from areas with easy access from roads or by short beach walks. Tsunami height was measured at most locations, while 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 defences.

The first signs of the tsunami observed by the public here was a negative wave, although a smaller positive wave had 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 re-opened within three days of the tsunamis, whereas roads on the east coast were still seriously compromised at the time of the ITST visit (Figure 4).

Table 1. Tsunami runup and inundation data (Figures 1 and 2)

Location	Longitude	Latitude	Max. elevation (m)	Runup (m)	Max sed. thickness (cm)	Min. dist. inland (m)
Trinco Hotel	81.21845	8.618075	4.4			
Trinco Town Stop 2	81.24202	8.561729	2.7			
	81.24202	8.561729	5.9	2.4		
Trinco Military Checkpoint	81.23478	8.563063	2.5			
Trinco Hearing-Impaired Ctr	81.21380	8.579356	3.2			
China Bay Stop 1 – Kinnaya	81.19094	8.503758	2.8			
China Bay Stop 2 - Kinnaya	81.19206	8.492397	3.35			
China Bay Stop 3 - Mutur	81.26444	8.463147	3.25			
N of Battilocoa	81.69267	7.744343	2.7			
Kattativu	81.74025	7.686330	3.7			
Kartivu	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		
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 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			
Koralawella	79.88879	6.749667	4.55			
Wadduwa	79.92110	6.673167	3.61			
Hambantota	81.12752	6.128450	6.1	11		
Nonagama	80.98835	6.093750	8.71			
Tangalla	80.79562	6.029367	3.24			
Tangalla	80.47717	6.011630	7.9		Boulders	14.8
Kamburugama	80.49195	5.940050	2.4			
Weligama	80.44682	5.968984	2.73			
Galle	80.24915	6.009734	5.24			
Dodanduwa	80.14692	6.083717	3.6			
Hikkaduwa	80.10413	6.127517	4.2			
Hikkaduwa	80.06159	6.077360			23.0	34.0
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			
Yala	81.25503	6.166390	4.65		22.0	390.0
Boosa	80.09014	6.047760	1.50		5.0	30.0
Boosa			2.50			
Telwatte	80.04268	6.110960			20.5	108.0
Wellawatta	79.51413	6.525880	1.50		7.0	30.7
Katukurunda	79.57682	6.333590			37.0	61.0

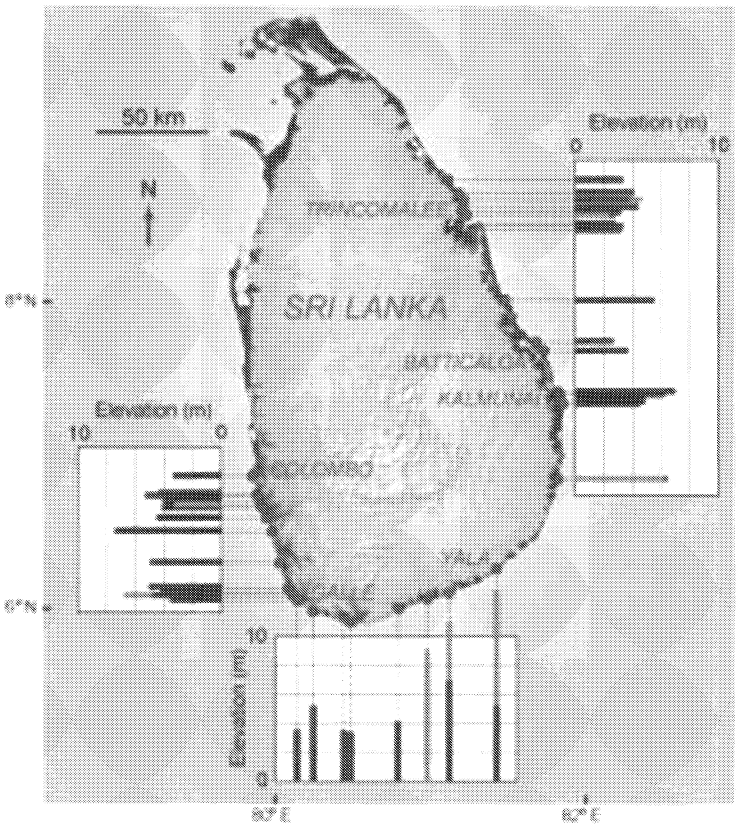

Figure 1. ***Measured tsunami runup (blue) and maximum tsunami heights (black). Red filled dots show sites of elevation measurement; areas shaded in black are less than 10 m above sea level. The map is modified from one by NASA/GSFC/METI/ERSDAC/JAROS and ASTER (after Liu et al., 2005).***

In most cases the emergency clearance of roads and land saw haphazard disposal of debris along the roadside (Figure 5), into open fields, drainage ditches, and where the road ran adjacent to the sea, material was pushed onto the beaches into the intertidal zone (Figure 4).

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).

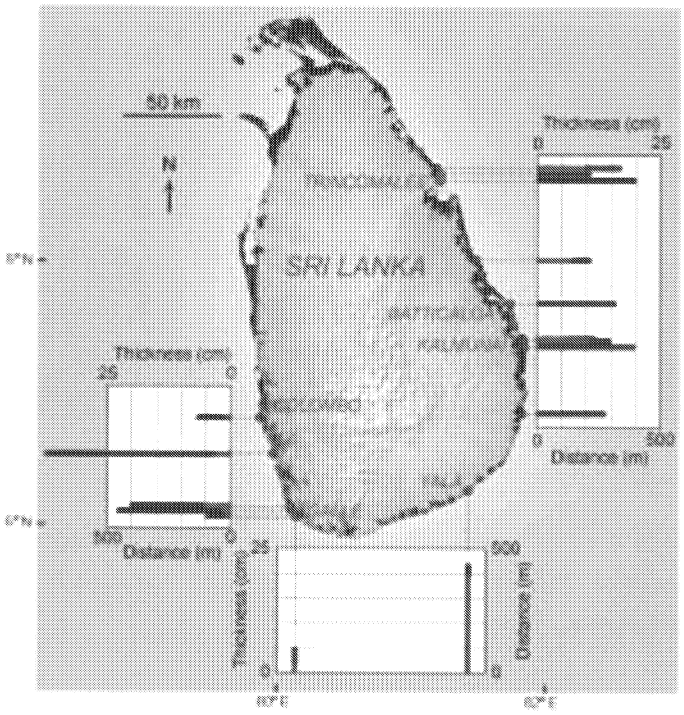

Figure 2. Measured maximum thicknesses of tsunami deposits (black) and minimum inland extent of tsunami sediments (blue). Red filled dots show sites of geological measurement. Other details as listed in Figure 1.

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

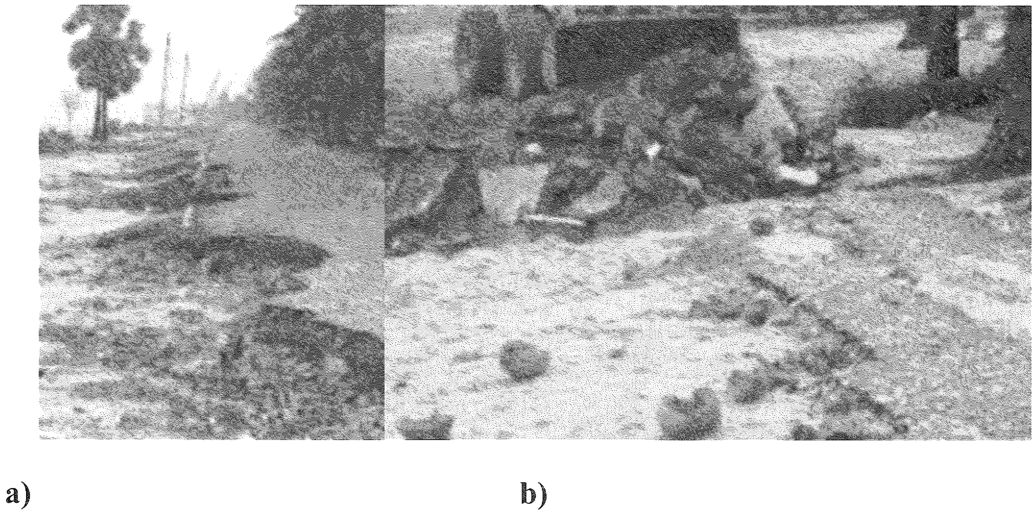

Figure 4. a) Kattankudi: Coastal roads in this area were notched and in some places completely removed. At this location surveyed inundation was about 700 m, with maximum elevations of less than 4 metres. b) Karativu: Here house rubble is used to rebuild a completely eroded coastal road.

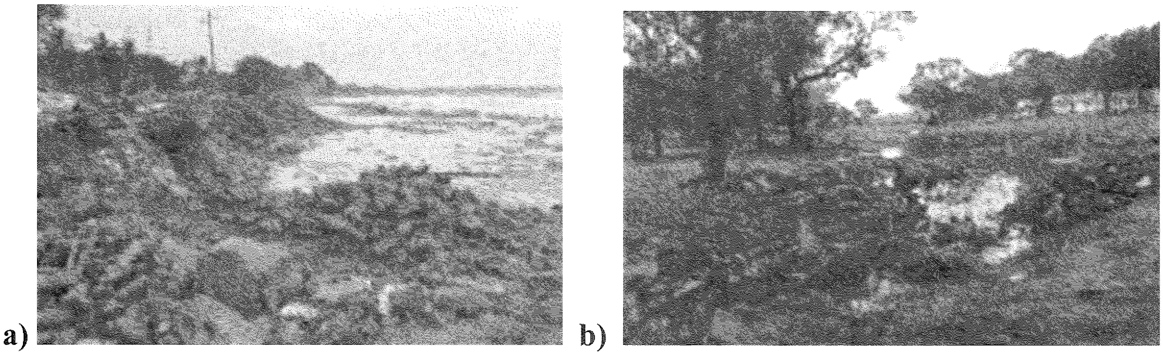

Figure 5. a) Matara: Debris pushed into the intertidal zone to clear roads and streets. b) Hambantota: Debris pushed into rivers and wetlands has implications for contamination of surface and groundwater resources.

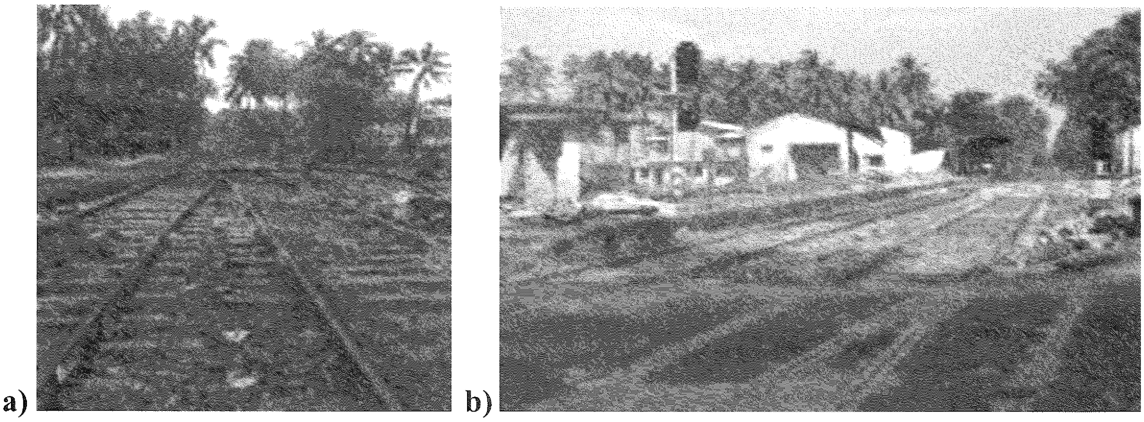

Figure 6. Paiyagala: a) Tracks bent inland (from right to left) by the tsunami; b) Damage to the railway station.

At a number of coastal sites tsunami runup and backwash created extensive and deep scour channels that favoured topographic lows or places where structures concentrated flow. In many cases this led to scouring around and under buildings or the complete removal of storm water 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 (Figure 8), illegal coral mining has been shown to have created "low resistance" pathways that allowed focussed flow and intensified destruction (Fernando *et al.*, 2005).

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

The tsunami surge completely destroyed around 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 unaffected 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 the railway or road) where damage was less severe (Figure 10).

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 foundation levels.

A considerable number of partially damaged buildings survived tsunami inundation but were subject to structural damage caused by 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 backwash (Figure 12).

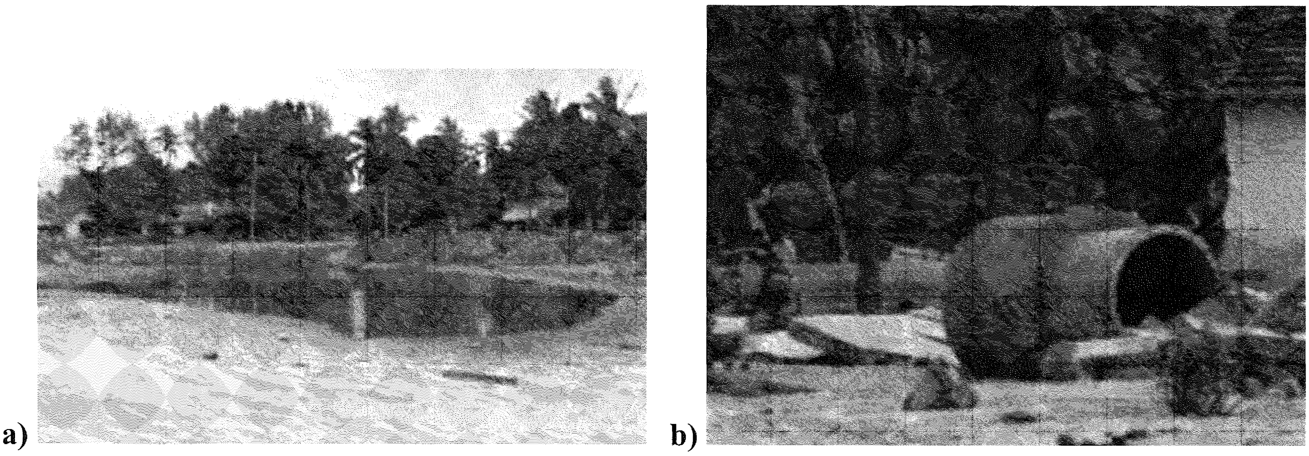

Figure 7. Matara: a) Recently repaired backwash scour of drainage channel and beach. b) Nintavur: The tsunami scoured around and then transported a cement well casing.

Figure 8. Peraliya: "Queen of the Seas" train remains after being placed back onto the tracks (photo from Synolakis et al., 2005).

4. CONCLUSIONS

The December 24th, 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 metres, while deposits averaged about 200 mm in thickness in a range of 50-370 mm. In addition to tsunami height, topographic variability had a strong influence on runup, sediment deposits, and inundation.

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

5. ACKNOWLEDGEMENTS

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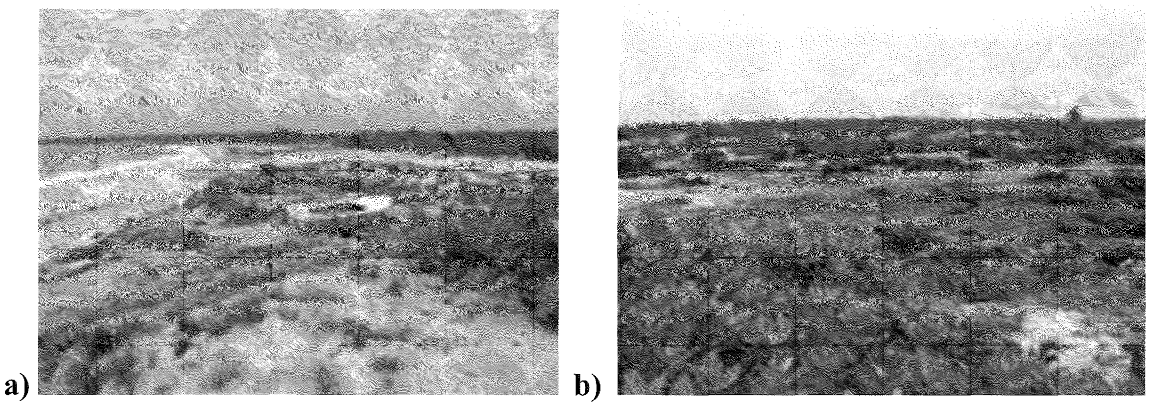

Figure 9. Yala: a) Looking west from the unaltered high dune towards the area previously occupied by the Yala Safari Beach Hotel. Tsunami runup barely overtopped the unaltered dune in the foreground, depositing a boat near the top, but destroyed the hotel and most of the vegetation in the middle distance; b) Live vegetation in the lee of the unaltered dune.

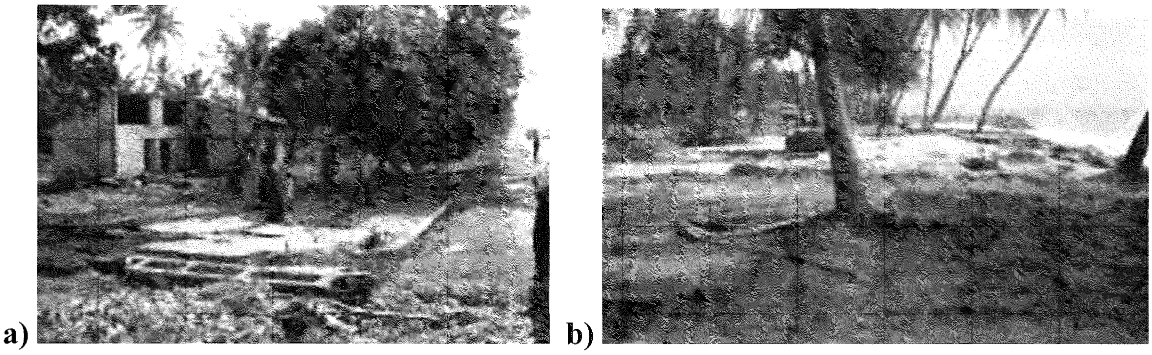

Figure 10. a) Boossa: Partially destroyed house on landward side of road; b) Telwatte: Little remains of poorly constructed houses on the seaward side of the road.

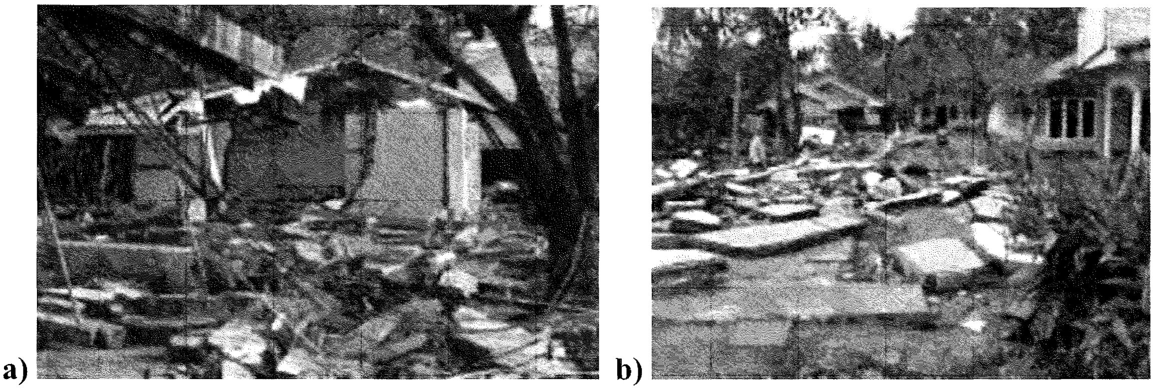

Figure 11. a) Nilavelli: This resort was heavily damaged by the tsunami despite relatively good construction standards. b) Weligama: Houses landward of destruction remained intact while those seaward took the full force of the tsunami.

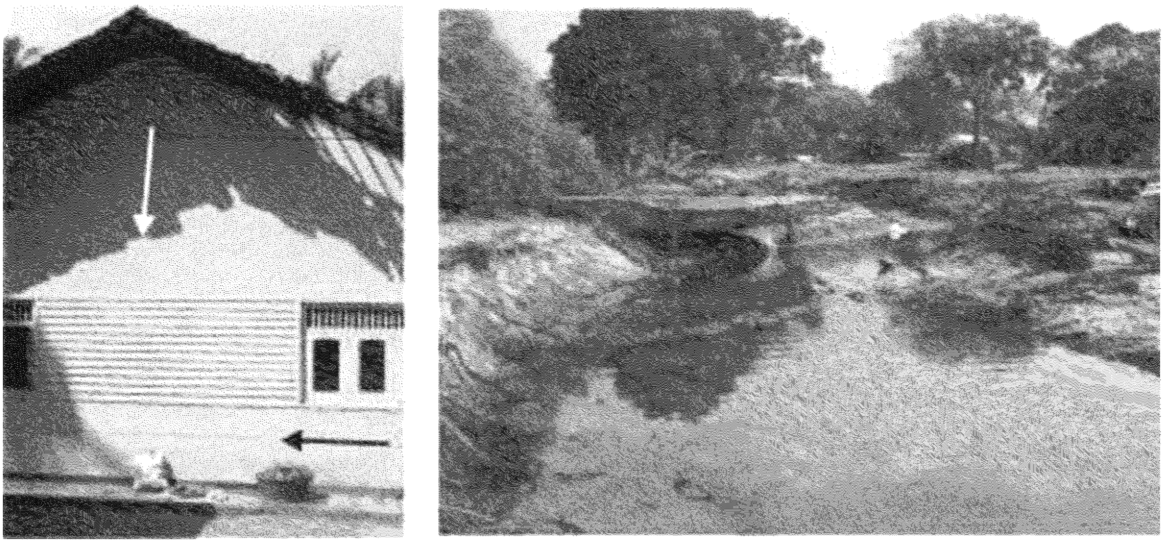

Figure 12. Left photo - Weligama: Partially destroyed building. Note near vertical crack on sea-facing wall (white arrow) and standing water mark (black arrow). Right photo – Yala: Backwash scour of foundations