Pure appl. geophys. 164 (2007) 395–411
0033–4553/07/030395–17
DOI 10.1007/s00024-006-0161-8

Pure and Applied Geophysics

Field Survey of Tsunami Effects in Sri Lanka due to the Sumatra-Andaman Earthquake of December 26, 2004

Shusaku Inoue,[1] Anil C. Wijeyewickrema,[2] Hiroyuki Matsumoto,[3] Hiroyuki Miura,[1] Priyantha Gunaratna,[4] Manoj Madurapperuma,[4,2] and Toru Sekiguchi[5]

Abstract—The December 26, 2004 Sumatra-Andaman earthquake that registered a moment magnitude (M_w) of 9.1 was one of the largest earthquakes in the world since 1900. The devastating tsunami that resulted from this earthquake caused more casualties than any previously reported tsunami. The number of fatalities and missing persons in the most seriously affected countries were Indonesia - 167,736, Sri Lanka - 35,322, India - 18,045 and Thailand - 8,212. This paper describes two field visits to assess tsunami effects in Sri Lanka by a combined team of Japanese and Sri Lankan researchers. The first field visit from December 30, 2004 – January 04, 2005 covered the western and southern coasts of Sri Lanka including the cities of Moratuwa, Beruwala, Bentota, Pereliya, Hikkaduwa, Galle, Talpe, Matara, Tangalla and Hambantota. The objectives of the first field visit were to investigate the damage caused by the tsunami and to obtain eyewitness information about wave arrival times. The second field visit from March 10–18, 2005 covered the eastern and southern coasts of Sri Lanka and included Trincomalee, Batticaloa, Arugam Bay, Yala National Park and Kirinda. The objectives of the second visit were mainly to obtain eyewitness information about wave arrival times and inundation data, and to take relevant measurements using GPS instruments.

Key words: Damage, field survey, inundation, Sri Lanka, Sumatra-Andaman earthquake, tsunami.

1. Introduction

At 07:58:53 December 26, 2004 (00:58:53 UTC) a great earthquake of moment magnitude (M_w) 9.1 struck northern Sumatra. The epicenter was located at 3.3° N, 9.9° E with a focal depth of 33 km (USGS, 2006). This event was one of only four events since 1900 with magnitude greater than or equal to 9.0. The other events are, the 1960 Great Chilean earthquake (9.5), the 1964 Prince William Sound, Alaska earthquake (9.2) and the 1952 Kamchatka earthquake (9.0), (USGS, 2006). The

[1] Department of Built Environment, Tokyo Institute of Technology, Japan.
[2] Department of Civil Engineering, Tokyo Institute of Technology, Japan. E-mail: anil@cv.titech.ac.jp
[3] Japan Agency for Marine-Earth Science and Technology, Japan.
[4] Department of Civil Engineering, University of Moratuwa, Sri Lanka.
[5] Department of Architecture and Building Engineering, Tokyo Institute of Technology, Japan.

tsunami generated by the Sumatra-Andaman earthquake resulted in more casualties than any previous tsunami in recorded history. Due to the earthquake and tsunami 167,736 people lost their lives or were reported missing in Indonesia. The other countries that reported a large number of fatalities or missing persons due to the tsunami were Sri Lanka – 35,322, India – 18,045 and Thailand – 8,212 (Appendix A). The location of the epicenter and the most seriously affected countries are shown in Figure 1.

This paper describes two field visits to assess tsunami effects in Sri Lanka by a combined team of Japanese and Sri Lankan researchers. The field visit routes and main cities covered by the field visits are shown in Figure 2. The first field visit from December 30, 2004 – January 04, 2005 covered the western and southern coasts of Sri Lanka and included the cities of Moratuwa, Beruwala, Bentota, Pereliya, Hikkaduwa, Galle, Talpe, Matara, Tangalla, and Hambantota. The objectives of the first field visit were to investigate the damage caused by the tsunami and to obtain eyewitness information about wave arrival times. One of the most tragic events due to the tsunami occurred at Pereliya on the SW coast, where a train that was stopped between stations was swept off the rail tracks when the tsunami struck, and around 1,000 people are estimated to have lost their lives due to this incident (Fig. 3). Most

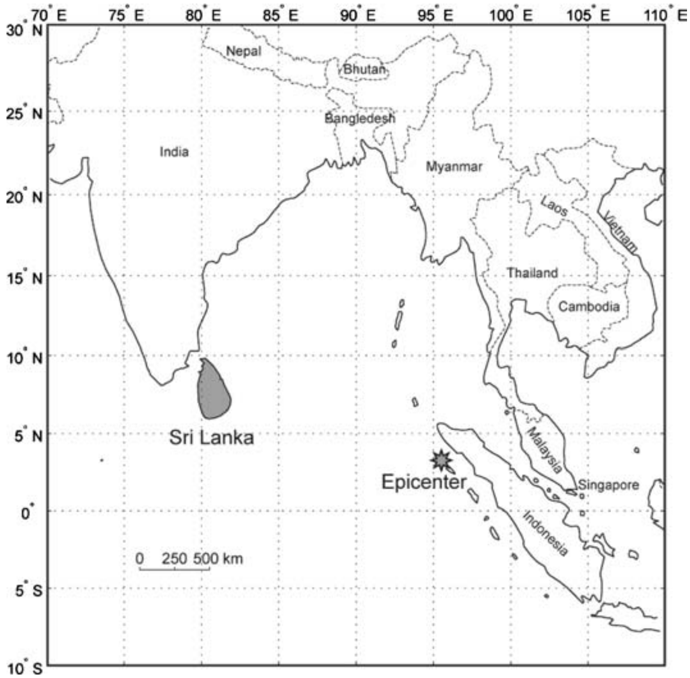

Figure 1
Epicenter of Sumatra-Andaman earthquake and surrounding countries. The most seriously affected countries were Indonesia, Sri Lanka, India and Thailand.

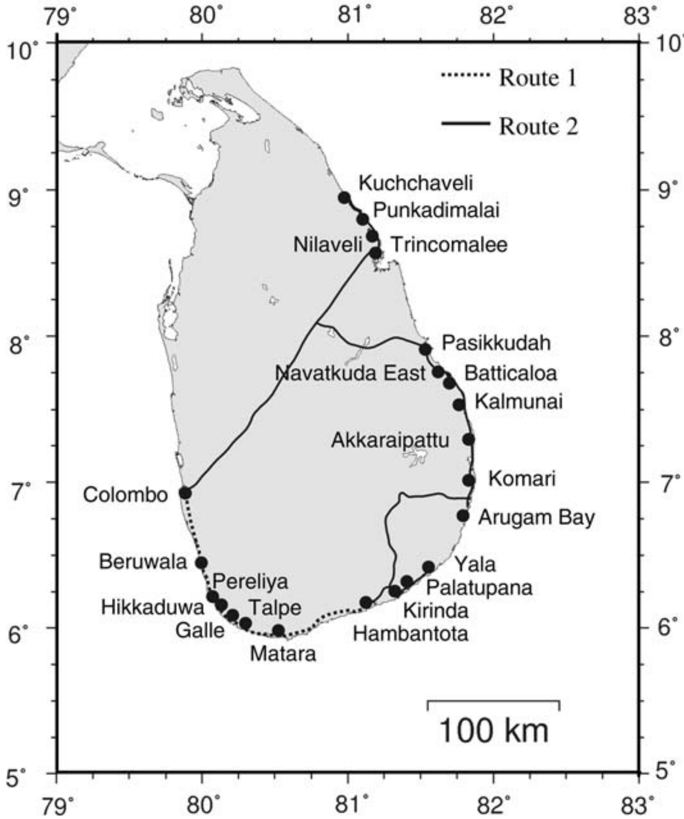

Figure 2
Field visit routes. 1st Route: Colombo, Moratuwa, Beruwala, Bentota, Pereliya, Hikkaduwa, Galle, Talpe, Matara, Tangalla, and Hambantota. 2nd Route: Colombo, Trincomalee, Kuchchaveli, Trincomalee, Polonnaruwa, Batticaloa, Arugam Bay, Yala National Park, and Kirinda.

of the low-cost masonry houses located in the coastal region were completely destroyed, while two story-buildings with concrete columns and beams sustained less damage. Figure 4 shows destroyed masonry houses near the Hambantota coast. More photographs of tsunami damage taken during the first field visit are given in WIJEYEWICKREMA *et al.* (2005). The second field visit from March 10–18, 2005 covered the NE, east, SE and south Sri Lanka and included Trincomalee, Kuchchaveli, Batticaloa, Arugam Bay, Yala National Park, and Kirinda. Some photographs taken during the second field visit are given in WIJEYEWICKREMA *et al.* (2006). The objectives of the second visit were mainly to obtain eyewitness information about wave arrival times and inundation data, and to take relevant measurements using GPS instruments.

In this paper tsunami arrival times are discussed in Section 2 and tsunami inundation heights and depths are discussed in Section 3. Remote sensing techniques,

Figure 3
Pereliya: Though this area is about 200 m from the coast, an express train was washed away by the tsunami and about 1,000 people lost their lives.

Figure 4
Hambantota: Masonry houses located within a few hundred meters from the coast were completely destroyed, a few more recently constructed houses had less damage.

especially the use of high resolution satellite images are quite useful to estimate tsunami damage, since the land surface of vast areas can be examined with high-resolution. In Section 4 inundation distances measured in the Batticaloa district are discussed and compared with the topography observed in IKONOS satellite images.

2. Tsunami Arrival Times

Wave heights and wave arrival times recorded at tidal observation stations are very useful for calibrating numerical models of tsunamis. In the case of Sri Lanka, since there are very few tidal stations, eyewitness accounts of local people were obtained to provide wave arrival times. The tsunami phenomenon is not limited to a single wave but a sequence of two or more main waves, including the maximum wave. Hence, in order to fully understand the tsunami, the wave arrival times of the main tsunami waves are very important.

Several eyewitnesses gave a similar account of the tsunami behavior at Bentota: The first wave came at 09:55 and inundated the land up to about 30 m from the shoreline. Part of the wave crest of this wave broke while approaching the coast and this happened at least four times. A few minutes later at approximately 10:00, the water then receded some 500 m exposing areas that are normally covered by the sea. A second wave arrived at approximately 10:30 with a height of about 3 m and crashed on the shore. Witnesses reported a foul odor when the second wave arrived. The third and largest wave arrived at 11:30 and had a height of about 5 m.

In addition to the eyewitness data, wave arrival times are also available from the following three sources:

(a) Data from the tidal observation station of the National Aquatic Resources Research and Development Agency (NARA) located in the Colombo Fisheries Harbor. The tidal record for December 25, 2004 – January 01, 2005 is shown in Figure 5. The tide record clearly shows the tsunami on December 26 and this unusual behavior continued until December 29. The detailed tidal record of December 26 is shown in Figure 5(b). The first wave of the tsunami is recorded at 09:48 with a water-surface elevation of 2.6 m above datum. Unfortunately, this tidal record does not contain the full time history and two time intervals are not properly recorded. It is possible that the maximum wave arrived around 12:00 consistent with eyewitness data.
(b) Time recorded on the clock tower located close to the Hambantota main bus station (Fig. 6). The clock had stopped due to the wave action at 09:22 and this time corresponds to the arrival time of the maximum wave according to an eyewitness who reported that the first wave was the biggest wave among the waves that attacked this area and the second wave was at 09:35.
(c) The arrival time reported by a seismologist (Chapman, 2005) that the first wave arrived at 09:30, followed by the maximum wave at 10:10 and the third wave at 11:10.

The locations where tsunami arrival time data were obtained from eyewitnesses are shown in Figure 7, with the arrival times given in Table 1. We analyzed the reported wave arrival times to scan for obviously unreliable data that are inconsistent with other data and these are given in italics in Table 1. Some of the discrepancy in the eyewitness information may be due to residents who did not have watches during the tsunami and depended only on their sense of time. It is also possible that some eyewitnesses did not see all the waves as they escaped after the arrival of the first wave, and that some of them did not see the first wave

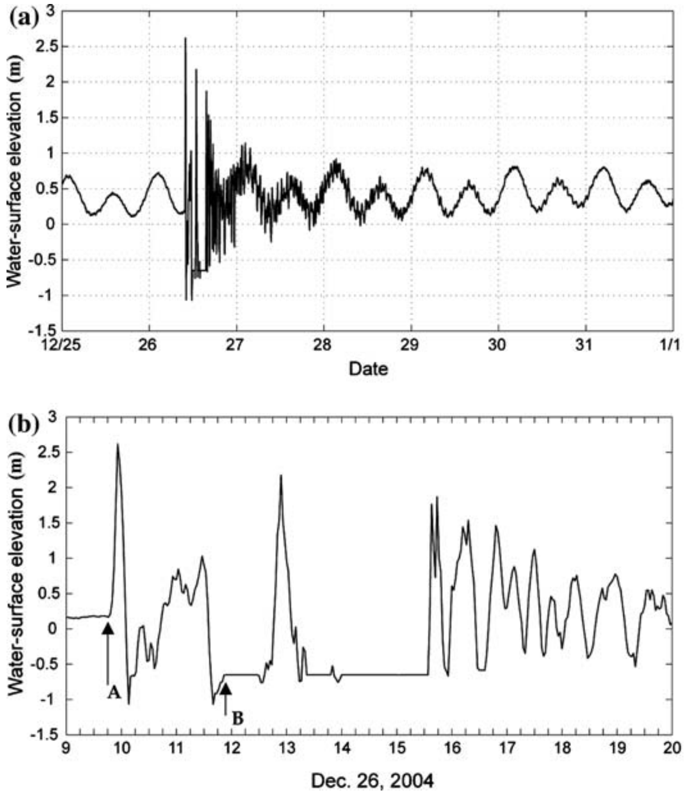

Figure 5
Tide-gauge record from Colombo Fisheries Harbor for (a) December 25, 2004–January 01, 2005, and (b) 09:00–20:00 December 26, 2004. The arrows in (b) indicate the first arrival recorded at 09:48 (A) and the probable arrival of the maximum wave at around 12:00 (B).

because they were not near the ocean at that time. For that reason, the first wave or maximum wave of an eyewitness does not necessarily correspond to the actual first wave or maximum wave.

Arrival times of the first wave and the maximum wave listed in Table 1 are shown in Figure 8. Here it can be seen that the first wave arrived at the eastern coast between 8:20–9:00, the southern coast between 9:00–9:22 and the western coast between 09:30–09:55. The maximum wave arrived at the eastern coast between 8:35–9:23, the southern coast between 9:13–9:50 and the western coast between 09:55–12:00. The velocity of the maximum wave along the western coast is observed to be slower than that of the first wave. It is most likely that at most locations, there were one or two waves before the maximum wave. The wave period on the western coast was greater than 30 min and on the eastern coast was less than 30 min. Before the maximum wave, the sea retreated for several hundred meters in some locations.

Figure 6
A broken clock close to the main bus station in Hambantota indicates 09:22. The Hambantota bay is on the left.

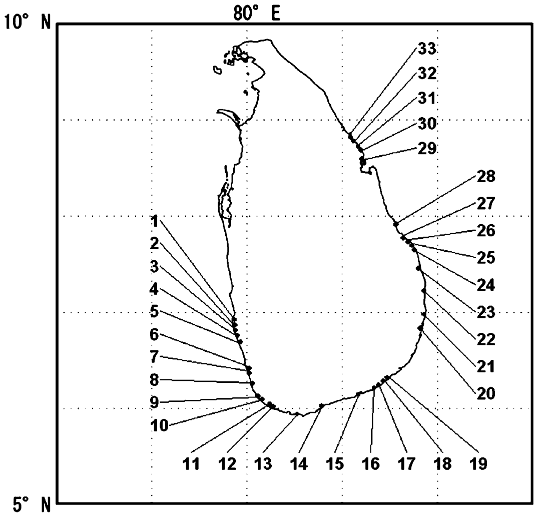

Figure 7
Locations of tsunami arrival time data obtained from eyewitnesses. The data is given in Table 1.

3. Tsunami Inundation Heights and Inundation Depths

Tsunami height measurements are very important for many purposes such as tsunami modeling, tsunami disaster mitigation planning and tsunami education. During the second field visit from March 10–18, 2005, tsunami height measurements were carried out on the east and the SE coasts in Sri Lanka, based on tsunami evidence such as water marks, broken branches on trees, debris carried by the tsunami, dead vegetation and plants, and eyewitness accounts from tsunami survivors. The tsunami height measurements carried out were, tsunami inundation

Table 1

Tsunami arrival times obtained from eyewitnesses

No.	Location	Date	Time (Local)	Tsunami arrival time		
				First wave	Second wave	Third wave
1	Colombo	01/02/05	12:20	9:15-30	**10:00-15**	-
2	Dehiwala	01/02/05	-	9:45	**11:45**	-
3-a	Mt. Lavinia	12/31/04	10:10	*8:45*	9:45	-
3-b	Mt. Lavinia	12/31/04	10:10	9:45	10:15	-
3-c	Mt. Lavinia	12/31/04	10:10	9:45	**11:35**	-
4	Moratuwa	12/31/04	10:45	*10:30*	11:00	**11:05-10**
5	Panadura	12/31/04	11:10	*7:30*	9:30	**10:30-11:00**
6	Beruwala	12/31/04	13:00	9:45	10:30-11:00	-
7	Bentota	12/31/04	14:20	9:55	10:30	**11:30**
8-a	Ahungalla	03/17/05	12:00	9:20-35	**10:15**	-
8-b[1]	Ahungalla	12/26/04	-	9:30	**10:10**	11:10
9	Pereliya	12/31/04	18:00	9:45	**10:30**	-
10	Hikkaduwa	12/31/04	17:10	9:30-35	**9:50-10:00**	-
11	Galle Fort	01/01/05	9:20	9:00-30	9:30-45	**9:50**
12	Talpe	01/01/05	10:30	-	**9:45**	-
13	Matara	01/01/05	11:55	9:15	9:25	**9:40**
14	Tangalla	01/01/05	13:40	8:45-9:15	-	**9:20**
15-a	Hambantota	01/01/05	15:40	**9:22**	9:35	-
15-b	Hambantota	01/01/05	16:20	**9:10**	-	-
16	Kirinda	03/16/05	14:30	**9:15**	-	-
17	Palatupana	03/15/05	14:45	**9:14**	-	-
18	Palatupana	03/15/05	16:00	9:15-20	**9:18-23**	-
19	Yala	03/16/05	10:24	**9:10-15**	-	-
20	Arugam Bay	03/15/05	6:45	8:20	***8:25***	-
21	Komari	03/14/05	18:10	8:45	**9:20-25**	-
22	Akkaraipattu	03/14/05	16:45	8:45	**9:00**	-
23	Kalmunai	03/14/05	15:30	8:45	-	-
24	Kirittona	03/14/05	9:10	8:30	-	-
25	Kirittona	03/14/05	7:30	9:00	**9:05**	-
26-a	Navatkuda East	03/13/05	18:50	8:30-55	**8:40-9:05**	-
26-b	Navatkuda East	03/13/05	18:50	8:15	**8:45**	-
27-a	Batticaloa	03/13/05	16:50	8:30	**8:31-32**	-
27-b	Batticaloa	03/13/05	16:50	8:30	**8:35**	-
28-a	Pasikkudah	03/13/05	12:05	8:45	**8:50**	-
28-b	Pasikkudah	03/13/05	12:05	**9:00**	-	-
28-c	Pasikkudah	03/13/05	12:30	8:58	**9:15**	-
28-d	Pasikkudah	03/13/05	12:45	9:05	**9:20**	-
29	Trincomalee	03/12/05	16:00	8:45-9:15	**8:46-9:16**	-
30	Nilaveli	03/12/05	10:00	8:55	**9:00**	-
31	Nilaveli	03/12/05	11:05	9:00	**9:05**	-
32	Punkadimalai	03/12/05	12:05	8:45	**9:10-15**	-
33	Kuchchaveli	03/12/05	15:00	8:45	**8:52-53**	8:58

Site Nos. correspond to locations given in Figure 7.
Arrival time of maximum wave shown in bold. Doubtful data in italics.
[1] CHAPMAN (2005).

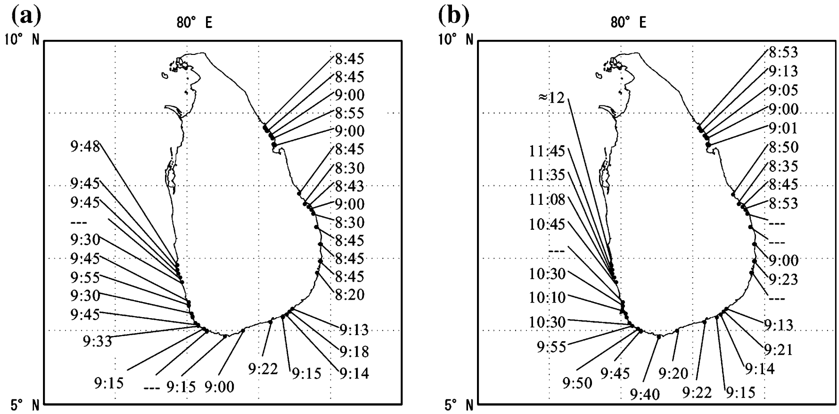

Figure 8
Arrival times of (a) first wave and (b) maximum wave, given in Table 1. When arrival times in Table 1 are given as a time range, the average is taken. For locations where data from multiple sources are available, the most consistent data was selected. Dashes indicate data is unavailable or inconsistent.

heights (heights measured from sea level), and tsunami inundation depths (heights measured from ground level) as defined by IUGG Tsunami Commission (2005).

Tsunami inundation and inundation depths were measured using laser rangefinders and optical survey equipment. Position information was obtained by using a differential Global Positioning System (GPS). All tsunami height measurements were obtained by adopting the detailed guidelines given by Intergovernmental Oceanographic Commission (1998). Because the sea-surface level at the time of tsunami arrival generally differs from that at the time of measurement, we corrected our observations using an astronomical tide table around the Indian Ocean given by Tsuji *et al.* (2005). Tsunami inundation heights and inundation depths are given in Table 2.

Corrected tsunami inundation heights measured at 17 locations (Table 2, 2nd column from right) are shown in Figure 9. On the east coast, the tsunami inundation height north of Trincomalee varies from 3.4–8.4 m, while south of Trincomalee it varies from 4.7–10.7 m. On the eastern and southeastern coast where the measured inundation height was greater than 5 m, most of the houses were swept away or severely damaged by the tsunami. Of the regions surveyed on the east coast, Kuchchaveli and Komari were the most severely affected areas. On the other hand, in the southeastern coast, in particular around Yala National Park, the inundation height is variable, which might be due to the local shallow coastal topographies. In Palatupana close to Yala National Park, the inundation height at the back of the lagoon is around 60% less than the inundation height at the front of the lagoon, indicating that the tsunami would be reduced by the lagoon.

Because of highly reliable information provided by Chapman (2005), we recorded tsunami inundation data at Ahungalla on the west coast of Sri Lanka. Chapman (2005) experienced the tsunami while a guest at a local hotel and reported details such

Table 2

Tsunami inundation heights and inundation depths along the east and SE coasts of Sri Lanka

No.	Location	Date	Time (Local)	Latitude (N)	Longitude (E)	Descriptions	Rating	Rmax (m)	Corr. (m)	Corr. Rmax (m)	Inu. depth (m)
1	Nilaveli	3/12/05	10:25	8° 41.542′	81° 11.674′	coconut tree - EE	A	8.6	−0.2	8.4	
2	Nilaveli	3/12/05	11:10	8° 42.420′	81° 11.269′	water mark on wall of house	B				2.0
3	Nilaveli	3/12/05	11:15	8° 42.437′	81° 11.361′	coconut tree - EE	A	5.6	−0.2	5.4	
4	Punkadimalai	3/12/05	12:20	8° 47.421′	81° 07.265′	top of the bridge	A	3.5	−0.1	3.4	
5	Kuchchaveli	3/12/05	15:00	8° 49.326′	81° 05.833′	coconut tree - EE	A				6.7
6	Kuchchaveli	3/12/05	15:00	8° 49.315′	81° 05.827′	water mark inside house	B				1.1
7	Trincomalee	3/12/05	16:55	8° 34.134′	81° 11.928′	water mark on wall of NARA guest house	B	3.3	0.5	3.8	
8	Pasikkudah	3/13/05	12:10	7° 55.442′	81° 34.064′	broken branch on tree	B	6.2	−0.1	6.1	
9	Pasikkudah	3/13/05	12:45	7° 55.280′	81° 34.127′	top of roof of hotel - EE	A				8.0
10	Batticaloa	3/13/05	17:30	7° 43.045′	81° 42.631′	water mark on wall of house	B				0.8
11	Batticaloa	3/13/05	17:30	7° 43.060′	81° 42.636′	water mark on wall of building	B				1.3
12	Navatkuda East	3/13/05	18:45	7° 41.129′	81° 44.452′	death of the coconut tree - EE	A	8.6	0.4	9.0	
13	Kirittona	3/14/05	8:20	7° 38.250′	81° 45.531′	water mark on wall of house - EE	A				0.8
14	Putukudiyiruppu	3/14/05	10:05	7° 34.884′	81° 47.022′	water mark on wall of house - EE	A				1.1
15	Kalmunai	3/14/05	15:35	7° 25.400′	81° 49.866′	death of the coconut tree - EE	A	7.2	0.4	7.6	
16	Akkaraipattu	3/14/05	17:00	7° 11.943′	81° 51.710′	coconut tree - EE	A	4.2	0.5	4.7	
17	Komari	3/14/05	18:15	6° 59.013′	81° 51.824′	broken branch on the tree - EE	A				5.3
18	Komari	3/14/05	18:30	6° 59.001′	81° 51.888′	coconut tree - EE	A	10.3	0.4	10.7	
19	Arugam Bay	3/15/05	6:50	6° 50.489′	81° 49.966′	cloth on tree - EE	A	5.7	0.3	6.0	
20	Palatupana	3/15/05	15:20	6° 14.845′	81° 23.286′	debris - EE	A	4.9	0.2	5.1	
21	Palatupana	3/15/05	16:05	6° 14.796′	81° 22.774′	coconut tree - EE	A	3.2	0.3	3.5	
22	Yala	3/16/05	10:35	6° 20.459′	81° 29.829′	broken branch on tree	B	5.8	−0.1	5.7	

23	Yala	3/16/05	11:20	6°	20.657′	81°	29.840′	broken branch on tree - EE	A	10.6	−0.1	10.5	
24	Palatupana	3/16/05	13:40	6°	16.523′	81°	25.310′	broken branch on tree	B	5.9	0.1	6.0	
25	Palatupana	3/16/05	13:45	6°	16.588′	81°	25.233′	roof of hotel broken by the water current	B				9.7
26	Palatupana	3/16/05	13:50	6°	16.593′	81°	25.240′	debris on tree	B				11.0
27	Kirinda	3/16/05	14:55	6°	13.071′	81°	20.183′	water mark on wall inside shelter	B	8.5	0.2	8.7	
28	Kirinda	3/16/05	15:20	6°	13.078′	81°	20.157′	water mark on wall of house	B				2.8
29	Ahungalla	3/17/05	12:05	6°	18.687′	80°	01.879′	water mark on wall of Triton Hotel - EE	A	4.3	−0.1	4.2	

EE - eyewitness evidence.
Rating - A, very reliable physical evidence; B, moderately reliable, based on physical evidence and/or eyewitness.
Rmax - uncorrected tsunami inundation height.
Corr. - correction to account for tide difference between tsunami arrival time and measurement time.
Corr. Rmax - tsunami inudation height after tidal correction.
Inu. depth - inundation depth.
Location names taken from 1:50,000 topographical maps from Survey Dept., Sri Lanka.

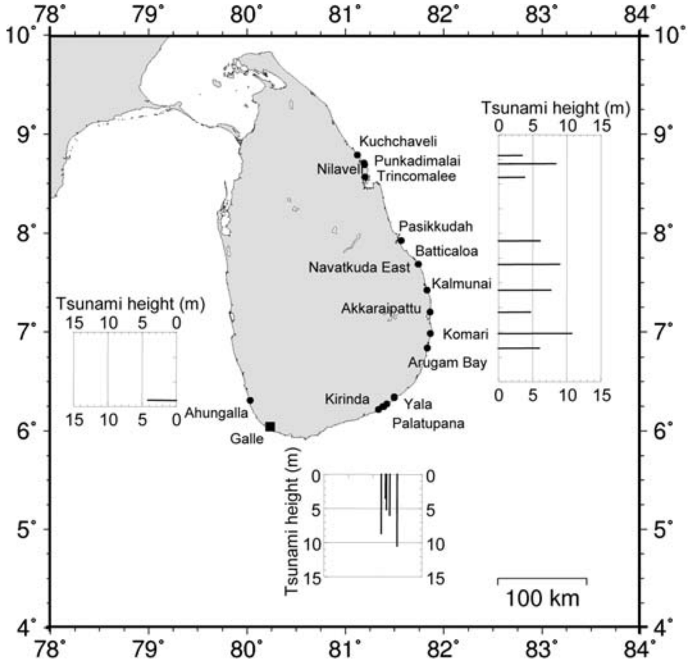

Figure 9
Corrected tsunami inundation heights along the east and SE coasts of Sri Lanka. The astronomical tide level at Galle was used as the reference site for the tide correction.

as the arrival time, the sequence of waves, and the response of the hotel guests and staff. A hotel staff member who had observed the tsunami was also interviewed. According to CHAPMAN (2005) and the hotel staff member, the biggest wave came at 10:10. The tsunami inundation height was estimated to be 4.2 m above sea level at the time of the event. The largest tsunami inundation height measured on the east coast was 10.7 m at Komari and on the southern coast was 10.5 m at Yala. LIU *et al.* (2005) have recorded the largest inundation heights of approximately 7.0 m at Kalmunai and Palatupana.

4. *Investigation of Inundation Area in Batticaloa*

Batticaloa located on the east coast of Sri Lanka, was one of the districts that was severely affected by the tsunami. The number of deaths, missing people, completely damaged and partially damaged houses in the affected districts are given in Appendix B. In Batticaloa district 3,873 people were reported dead or missing while the number of completely damaged and partially damaged houses were 15,939 and 5,665, respectively. During the second field trip in March a GPS survey was carried out in the coastal region of Batticaloa.

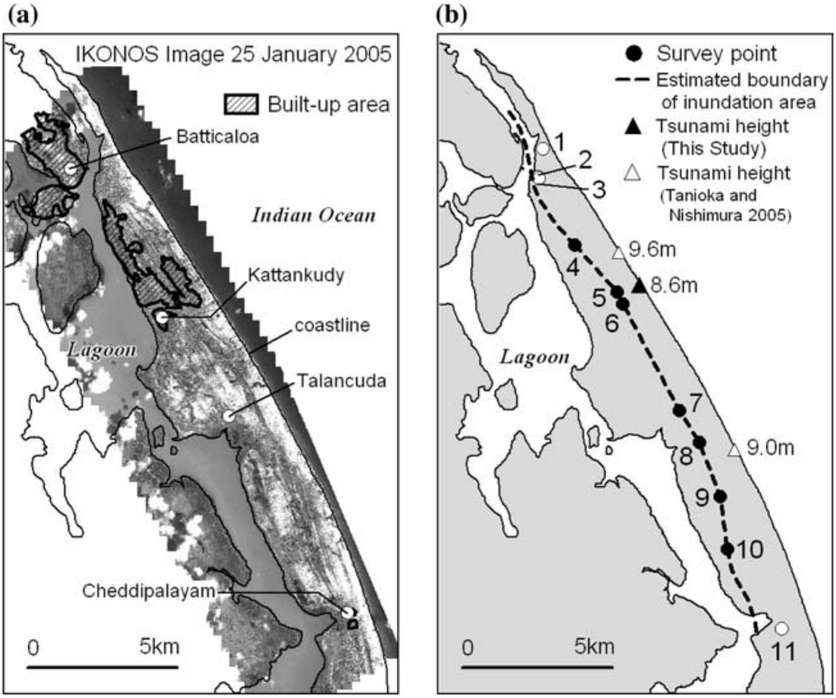

Figure 10
(a) IKONOS image with built-up areas in Batticaloa, (b) Locations of GPS survey points and estimated boundary of inundation area. Measured inundation depths and inundation distances are given in Table 3.

Figure 10(a) shows the map of the study area in Batticaloa with the IKONOS satellite image of 25 January, 2005. The hatched areas indicate the built-up areas taken from a land use map prepared in 1985. The survey was conducted in the spit area approximately 18 km by 10 km which is bordered by the Indian Ocean on the east and a lagoon on the west. Triangles in Figure 10(b) show the location of tsunami height measurements of TANIOKA and NISHIMURA (2005) and of this study, showing that tsunami waves with nearly 10 m heights attacked the region.

The boundary of the inundation area was determined based on the evidence of the tsunami eyewitness since it was difficult to detect the inundation boundary by using traces of the tsunami. The locations of the inundation boundary were measured by using a differential GPS (Ashtech ProMark2) which provides more accurate positions and elevations than stand-alone observations. One of the instruments was installed in Batticaloa Town as the reference site and the other was used for the observations. Horizontal locations and ground elevations are computed from the difference of the observation site and the reference site. Solid circles in Figure 10(b) show the locations of the inundation distance observations. Table 3 shows the measured inundation depth and the distance from the coastline at each site.

Table 3

Tsunami inundation depths and inundation distances in Batticaloa District

No.	Latitude N (deg.)	Longitude E (deg.)	Ground elevation (m)	Inundation depth (m)	Distance from coastline (m)
1*	7.7263	81.7119	-	-	270
2	7.7177	81.7106	-	1.3	870
3	7.7173	81.7107	-	0.8	880
4	7.6971	81.7215	2.3	0	1,140
5	7.6828	81.7343	1.8	0	820
6	7.6793	81.7360	1.6	0	870
7	7.6471	81.7529	1.4	0	1,090
8	7.6375	81.7589	1.9	0	980
9	7.6213	81.7652	1.8	0	1,190
10	7.6053	81.7674	2.6	0	1,710
11*	7.5814	81.7837	0.9	0.2–0.3	920

* The tsunami crossed over into the western lagoon.
Site numbers correspond to locations given in Figure 10.
Sites 4–10 yield inundation distance measured from the coastline.

According to the accounts of eyewitnesses, the tsunami crossed over into the western lagoon at sites 1 and 11 located in the northern and southern part of the survey area, respectively. Inundation depths were measured at sites 2 and 3 from tsunami traces left on the building walls. The depths at the sites were 1.3 m and 0.8 m, respectively. The dotted line in Figure 10(b) shows the extent of inundation estimated by taking into account the results of the GPS observations, the inundation depths and the accounts of the eyewitnesses. The result shows that the inundation distance from the coastline was between 800 and 1,800 m.

Inundation distances around sites 5 and 6 are approximately 800 m while at sites 9 and 10 the inundation distance was nearly double, some 1500 m. As shown in Figure 10(a), sites 5 and 6 are located in the center of a built-up area. Satellite images of sites 5 and 9 (Fig. 11) show how site 5 is surrounded by many buildings while site 9 is unpopulated and covered with sand and native bush. This suggests that inundation distances are lower in built-up areas because the momentum of tsunami would be weakened due to the collision with many buildings. It also indicates that inundation area would be wide in bare land, grassland or bushes because there are few obstacles to the propagation of the tsunami such as buildings or tall trees. More details of the inundation area in the Batticaloa region can be found in MIURA and MIDORIKAWA (2006).

5. Concluding Remarks

Measurements and observations of tsunami arrival times and inundation heights and depths were carried out on the western, southern and eastern coasts of Sri

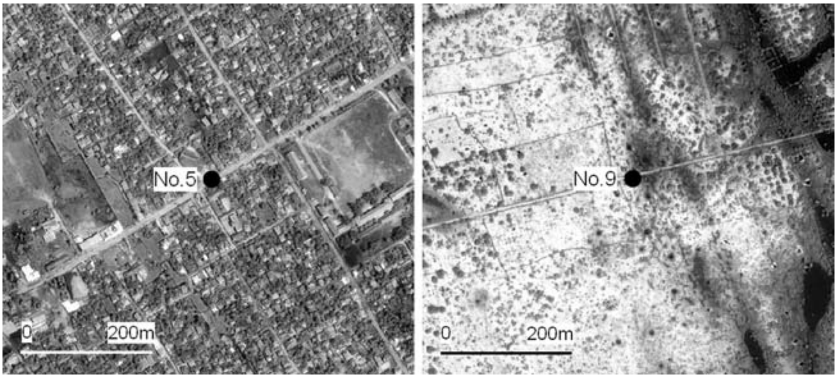

Figure 11
IKONOS images at sites 5 and 9.

Lanka. In addition a detailed survey of the inundation area was carried out in Batticaloa. In Sri Lanka the tsunami phenomenon was not limited to a single wave but a sequence of two or more main waves. The largest inundation heights were measured on the southeast coast and were greater than 10 m. The maximum inundation distance measured in Batticaloa was nearly 2 km.

This was the first time that a tsunami caused by an earthquake had affected Sri Lanka. The island nation had never anticipated a tsunami and consequent no contingency plans had been prepared. It is reported that although certain international tsunami monitoring agencies were aware of the tsunami before it reached Sri Lanka, no warning was conveyed to the Sri Lankan government, as no procedures to inform appropriate government officials were in place. Even if such a warning was received, it is doubtful that it would have been possible to inform the people living in the coastal areas, in a timely manner.

A question that was repeatedly asked by the people that were interviewed by the survey team was whether another tsunami would arrive again in the near future. It was explained that the probability of a similar magnitude earthquake triggering a tsunami from the same region was very low.

Acknowledgements

The advice and support of Prof. Tatsuo Ohmachi, COE Program Leader of CUEE and Prof. Kohji Tokimatsu, COE Program Sub-Leader of CUEE, is gratefully acknowledged. Financial support for the tsunami field surveys in Sri Lanka from the Center for Urban Earthquake Engineering (CUEE), Tokyo Institute of Technology, is gratefully acknowledged. Shusaku Inoue and Hiroyuki Matsumoto acknowledge financial support for the second field visit from the Special Coordination Funds for Promoting Science and Technology from the

Ministry of Education, Sports, Culture, Science and Technology (MEXT). Tide gauge data recorded at Colombo were provided by the National Aquatic Resources Research and Development Agency.

Appendix A

Table A

Fatalities and missing persons due to the Sumatra-Andaman earthquake

Country	Fatalities	Missing[1]	Total
Indonesia	130,736	37,000	167,736
Sri Lanka	35,322	-	35,322
India	12,405	5,640	18,045
Thailand[2]	8,212	-	8,212
Somalia	78	211	289
Maldives	82	26	108
Malaysia	69	6	75
Myanmar	61	-	61
Tanzania	13	-	13
Seychelles	2	-	2
Bangladesh	2	-	2
Kenya	1	-	1
Total	186,983	42,883	229,866

(UN Office of the Special Envoy for Tsunami Recovery, 2006).
[1] Some countries do not give separate figures for the deceased and the missing.
[2] In Thailand, fatalities include 2,448 foreign tourists from 37 other countries.

Appendix B

Table B

Casualties and Housing Damage in Sri Lanka

Province	District	Deaths	Missing people	Completely damaged houses	Partially damaged houses
Northern	Jaffna	2,640	540	6,084	1,114
	Killinochchi	560	1	1,250	4,250
	Mullativu	3,000	552	3,400	600
Eastern	Trincomalee	1,078	337	5,974	10,394
	Batticaloa	2,840	1,033	15,939	5,665
	Ampara	10,436	876	29,077	-
Southern	Hambantota	4,500	963	2,303	1,744
	Matara	1,342	613	2,362	5,659
	Galle	4,216	554	5,525	5,966
Western	Kalutara	256	148	2,572	2,930
	Colombo	79	12	3,398	2,210
	Gampaha	6	5	292	307
North Western	Puttalam	4	3	23	72
Total		30,957	5,637	78,199	40,911

Data as at 23/01/05 (National Disaster Management Center, 2005).

References

CHAPMAN, C. (2005), *The Asian tsunami in Sri Lanka: A personal experience*, EOS *86*(2), 13–14.

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION (1998), *Post-tsunami Survey Field Guide*, UNESCO Manuals and Guides *37*, 62 pp.

IUGG TSUNAMI COMMISSION (2005), *Compiling the trace height of Indian Ocean tsunami*, Internat. Un. Geod. Geophy. 8 pp.

LIU, P.L.-F., LYNETT, P., FERNANDO, H., JAFFE, B.E., FRITZ, H., HIGMAN, B., MORTON, R., GOFF, J., and SYNOLAKIS, C. (2005), *Observations by the International Tsunami Survey Team in Sri Lanka*, Science *308*(5728), 1595.

MIURA, M. and MIDORIKAWA, S. (2006), *Extraction of Tsunami inundation area in the eastern part of Sri Lanka due to the 2004 Sumatra earthquake using high-resolution satellite images*, Proc. *third internat. Conf. Urban Earthq. Engin.*, March 6–7, Tokyo, Japan, pp. 237–244.

NATIONAL DISASTER MANAGEMENT CENTER (2005), *Summary Report on Tsunami Disaster, Sri Lanka*, http://www.lankalibrary.com/news/summary.htm.

TANIOKA, Y. and NISHIMURA, Y. (2005), *Field Survey Result in Sri Lanka, The December 26, 2004 Earthquake Tsunami Disaster of Indian Ocean*, http://www.drs.dpri.kyoto-u.ac.jp/ sumatra/srilanka2/ (in Japanese).

TSUJI, Y., NAMEGAYA, Y., and ITO, J. (2005), *Astronomical tide levels along the coasts of the Indian Ocean*, http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/tide.

UN OFFICE OF THE SPECIAL ENVOY FOR TSUNAMI RECOVERY (2006), http://www.tsunamispecialenvoy.org/country/humantoll.asp.

USGS (2006), *Largest Earthquakes in the World since 1900*, http://earthquake.usgs.gov/regional/world/10_largest_world.php.

WIJEYEWICKREMA, A.C., INOUE, S., and SEKIGUCHI, T. (2005), *Tsunami damage in Sri Lanka due to the Sumatra earthquake of December 26, 2004 – Preliminary reconnaissance*, Proc. *Second Internat. Conf. Urban Earthq. Engin.*, March 7–8, Tokyo, Japan, pp. 181–191.

WIJEYEWICKREMA, A.C., INOUE, S., MATSUMOTO, H., MIURA, H., GUNARATNA, P., MADURAPPERUMA, M., and SEKIGUCHI, T. (2006), *Report of two field visits to assess tsunami damage in Sri Lanka due to the Sumatra-Andaman earthquake of December 26, 2004*, Proc. *Third Internat. Conf. Urban Earthq. Engin.*, March 6–7, Tokyo, Japan, pp. 219–229.

(Received June 12, 2006, accepted October 18, 2006)
Published Online First: January 30, 2007