Tsunami Runup Survey along the Southeast Indian Coast

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The 26 December Indian Ocean tsunami was an extraordinary event in the history of natural hazards. It severely affected many countries surrounding the Indian Ocean: Indonesia, Thailand, Malaysia, Myanmar, Bangladesh, India, Sri Lanka, the Maldives, and African countries. Unlike the previous tsunami events in the last 40 years, the seriously affected areas are so vast that a traditional ground-level tsunami survey covering all the necessary areas by a single survey team was impractical. This destructive event will undoubtedly provide many opportunities to explore both basic and applied research in tsunami science and engineering fields and will lead to better preparedness for future disasters. A tsunami runup survey was conducted that spans Vedaranniyam (10° 23.5′ N) to Vodarevu (15° 47.6′ N)—more than 600 km of the southeast Indian coast—which suffered from the distant tsunami, whose source was more than 1,500 km away. [DOI: 10.1193/1.2202651]

TSUNAMI SURVEY

It is customary to conduct a rapid reconnaissance tsunami survey with international collaboration. All of the recent tsunami events listed in Table 1 were surveyed by the International Tsunami Survey Team (ITST)—the exceptions were the 1994 Skagway landslide tsunami and the 2003 Tokachi-oki tsunami that were surveyed by a U.S. team and by a Japanese team, respectively. The international collaboration is necessary partly because only a few scientists (mostly in Japan and the United States) are experienced in carrying out such a survey, whereas the local scientists must play a leading role in arranging the survey logistics under often-chaotic and stressful situations in the disaster areas, usually within days of the tsunami attack. By conducting cooperative surveys, the local scientists gain experience for future events. Unlike other natural disasters (e.g., earthquakes, hurricanes, tornadoes, droughts, and floods), tsunamis can affect broader areas. As the 26 December 2004 tsunami clearly demonstrated, tsunamis are not only a

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Table 1. Major tsunamis in the last 15 years

Date	Location	Earthquake magnitude	Fatalities	Maximum runup (m)
Sep. 1992	Nicaragua	M_s 7.2, M_w 7.6	93	9.9
Dec. 1992	Flores, Indonesia	M_s 7.5	1,712	26.0
Jul. 1993	Okushiri, Japan	M_s 7.2	233	32.0
Jun. 1994	East Java, Indonesia	M_s 7.2	223	11.3
Oct. 1994	S. Kuril Islands	M_s 8.1	12	7.1
Nov. 1994	Mindoro, Philippines	M_s 7.0	74	7.3
Nov. 1994	Skagway, Alaska	na	1	–
May 1995	East Timor, Indonesia	M_s 6.9	8	–
Oct. 1995	La Manzanilla, Mexico	M_w 8.0	–	~5.0
Feb. 1996	Irian Jaya, Indonesia	M_w 8.0	110	7.7
Feb. 1996	Chimbote, Peru	M_s 6.8, M_w 7.5	12	5.0
Jul. 1998	Aitape, PNG	M_s 7.1, M_w 7.0	~2,000	15.0
Nov. 1999	Vanuatu	M_s 7.3	1	–
Jun. 2001	Southern Peru	M_w 8.3	26	4.0
Dec. 2002	Stromboli, Italy	na	–	–
Sep. 2003	Tokachi-oki, Japan	M_w 8.0	–	4.2
Dec. 2004	Sumatra, Indonesia	M_w 9.3	>230,000	36.0

[a] Not applicable, because the event was a landslide

local problem but also pose potential problems for many distant countries. From this viewpoint, a tsunami survey by a multinational team is not only justified, but essential.

Our multinational team was comprised of eight members with very distinct disciplinary backgrounds: three members from India (a seismologist, an ocean scientist, and a graduate student), one member from Japan (a social engineer), and four members from the United States (a tsunami hydrodynamist, a sedimentologist, and two geotechnical engineers). Two of the members had substantial field survey experience. Prior to the survey, every team member had reviewed the IOC Post-Tsunami Survey Field Guide (IOC 1998). We also discussed and coordinated detailed needs for data and metadata with the Earthquake Engineering Research Institute (EERI) staff.

The team operated in two groups. The first group began its field survey along the southeast Indian coast (in Tamil Nadu and Pondicherry, 10° 23.5′ N to 13° 23.9′ N), gathering data during 7–11 January 2005. During 22–23 February 2005, the second group surveyed the area north of the first survey—that is, along the coast of Andhra Pradesh (13° 25.0′ N to 15° 47.6′ N)—and briefly revisited the village of Devanaanpattinam (11° 44.6′ N). Figure 1 shows the areas we surveyed. The second group also made a brief survey in the Andaman-Nicobar Islands, located within the near-source area of the fault rupture.

The survey teams measured maximum tsunami runup heights and inundation distances; measured flow patterns of tsunami runup and rundown; recorded eyewitness ac-

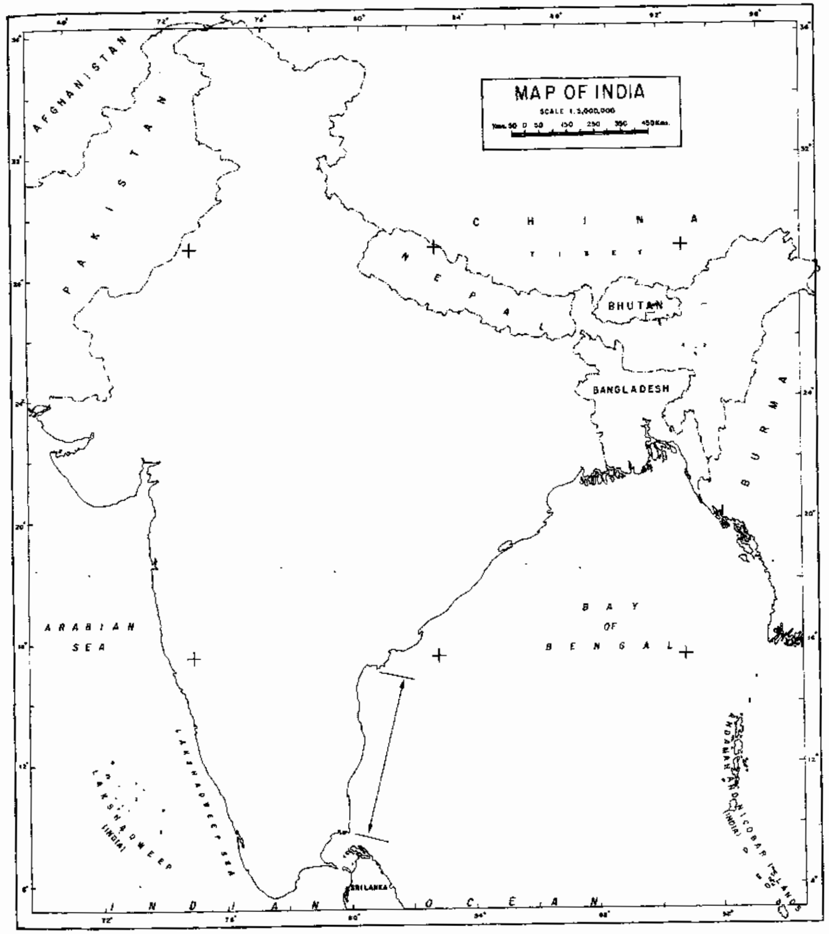

Figure 1. The survey area along the southeast Indian coast and the Andaman-Nicobar Islands. A line with an arrowhead at each end indicates the regions we surveyed.

counts; examined sediment deposits; and observed structural and infrastructure damage (including scour), human responses, and social impacts (Chadha et al. 2005). Because the tsunami's origin was distant, no evidence of subsidence, uplift, or landslides was observed, although we did examine geomorphological changes made by the tsunami. In this paper, we focus on one of the primary objectives for the rapid reconnaissance survey, namely, the tsunami runup measurements.

Figure 2. Sighting the runup elevation with the hand-level on a tripod.

Tsunami runup heights and distances were measured by using simple surveying hand-levels, staffs, and tapes (Figure 2). Vertical elevations of the runup marks were measured from mean sea level at the time of the measurements by noting the measurement time and location (Figure 3). After the survey, the measured runup heights were converted to values of runup at the time of the tsunami attack. This conversion was made on the basis of tide level corrections between the time of measurement and the time of the tsunami attack. Every tsunami mark used for the runup measurement was photographed for archiving, and its location was identified by a global positioning system (GPS). Because of the uncertainties involved in even carefully measured data, we anticipate an approximate 25-cm range of potential error in runup heights.

Figure 3. The mean sea level is used as the datum for the runup measurement (Arcattuthurai, 10° 23.612′ N, 79° 52.014′ E).

Figure 4. The mud line on the building wall is used as a reliable tsunami inundation level (Periakalapet, 12° 01.708′ N, 79° 51.950′ E).

Tsunami runup marks were identified by the following observations. Flooding mud watermarks on structural walls are considered reliable evidence of runup height (Figure 4). Such a watermark in a protected area (e.g., inside a house) may be considered the "true" runup height or inundation level (Figure 5). That is because such marks represent flowing water depths that are generally devoid of turbulent surge or splashup. Accumulated marine-origin objects are also considered another type of reliable runup mark (Figure 6).

Other types of runup marks are (1) scratch marks on buildings or tree trunks caused by the collision of waterborne objects (Figure 7) and (2) unusual materials found at abnormal locations, such as seaweed on tree branches or a fishing net clinging to a roof, as shown in Figure 8. Those tsunami marks are probably affected by local splashup action

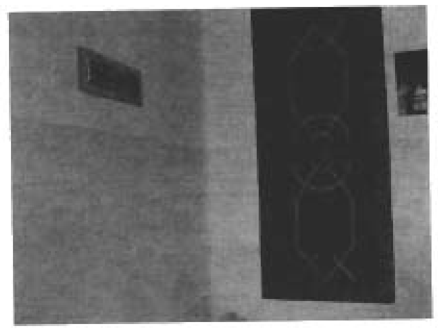

Figure 5. The mud line inside the building is considered to represent the true inundation level (Perangipettinam, 11° 30.965′ N, 79° 45.947′ E).

Figure 6. The line of accumulated floatable debris is another reliable tsunami mark for the runup height and penetration (Periakalapet, 12° 01.544′ N, 79° 51.888′ E.

and should not be considered reliable evidence of true inundation elevations. In fact, the elevation of the fishing net shown in Figure 8 was approximately 2 m higher than the watermark level found inside a building that was only 20 m away. It is noted that, upon arriving at several tsunami sites, we found recently hand-drawn signs indicating the tsunami levels (Figure 9); evidently, a local survey team must have made those marks prior to our arrival. Those elevations were measured and included in our data.

Runup distances from the shoreline were measured via 100-m-long surveying tapes. Where the tape measurements were impractical, we supplemented distance measurements by recording the differences in the GPS readings between the shoreline and the maximum inundation location. This may have produced less accurate measurements of inundation distance, although they are still acceptable for the rough measurements of

Figure 7. The scratch mark and roof tile damage are used as the estimate of tsunami inundation (Devanaanpattinam, 11° 44.567′ N, 79° 47.317′ E).

Figure 8. A piece of fishing net clinging to the roof is another type of tsunami mark (Nagapattinam, 10° 45.785′ N, 79° 50.928′ E).

Figure 9. The signs of tsunami inundation levels found on the building walls (Kalapakkom, 12° 30.327′ N: 80° 09.600′ E and Nagapattinam, 10° 46.477′ N, 79° 50.790′ E).

horizontal distances. In addition, flow directions for both runup and rundown processes were inferred from the direction in which trees had fallen and from the patterns of debris formation. We note that accounts from eyewitnesses who were often under stressful conditions are considered less reliable, and thus we used such accounts for reference only.

Unlike most previous events, this event fortunately left clear watermarks on and in the buildings at almost every site we visited in the southeast Indian coast. The reasons why high-quality tsunami marks remained are (1) our rapid deployment to the sites, within 12 days of the tsunami attack; (2) favorable weather conditions (no rain or no strong winds between the event and our survey); and (3) some of the coastal structures made of reinforced concrete or masonry had withstood the tsunami forces and were intact.

Again, in this paper, the tsunami runup height identified by the mud line in a protected area (e.g., inside a house) or an open-field debris line is called the "true inundation level," as distinguished from the "local tsunami runup" measured by a mark that was probably affected by tsunami splashup.

RUNUP DISTRIBUTION

Table 2 shows the measured tsunami runup heights. A determination of the tsunami arrival time was needed for calculating tide corrections to our surveyed runup data. A numerical simulation by George (2005) shows that the tsunami arrived almost simultaneously all along the southeast Indian coast, approximately 2 hours and 40 minutes after the earthquake. This computed arrival time is consistent with the tide-gauge record at Chennai (NIO 2005), where the first wave arrived at 3:35 A.M. GMT (9:05 A.M. IST). The tide-gauge record also shows the formation of a leading elevation wave. The maximum runup probably occurred during the next successive tsunami, according to general indications by eyewitness accounts. The arrival time of the second tsunami crest is estimated to have been 40 minutes after the first tsunami attack. This is a rough estimate based on the satellite altimetry data from which Gower (2005) estimated the wave length to be 430 km, with a wave period of approximately 40 minutes. The estimated wave period is consistent with eyewitness statements reported by Chapman (2005) in Sri Lanka. Because of the uncertainty, we assume a tsunami arrival time along the southeast Indian coast at 3:40 A.M. GMT (9:10 A.M. IST) for the purpose of tide-level corrections for our runup data. The resulting estimated error caused by variability of the estimated arrival time of the second wave is at most ±0.1 m in tide level.

For reference purposes, we also present the runup heights based on the Indian datum (the datum used for the tide-gauge data) in Table 2. The tide levels at the survey locales were computed by interpolation from tide tables for Kakinada (16° 56′ N, 82° 15′ E), Madras (Chennai) (13° 06′ N, 80° 18′ E), and Nagapattinam (10° 46′ N, 79° 51′ E). Note that the runup data collected in the Andaman Islands were based on the tide table for Port Blair (11° 41′ N, 92° 46′ E), which assumes the arrival time to be at 1:30 A.M. GMT (7:00 A.M. IST). Although the tidal amplitude in this region is small (less than ±50 cm), the tsunami struck the coast almost at high tide, resulting in maximum tsunami effects in the region.

Table 2. Measured tsunami runup, inundation, and sediment-deposit data.*

	A	B	C	D	E	F	G	H	I	J	K	L
1 2	Location code	Location	Latitude	Longitude	Date	Time	Tsunami marks	Distance from survey to shoreline (m)	Measured runup elevation (m)	Runup elevation after tide-level adjustment (m)	Runup elevation from the datum (m)	Maximum inundation distance (m)
3	Vo-1	Vodarevu	15°47.61	80°24.803	2/23/05	14:35	Thatch fence	124	3.66	2.69	3.83	
4	Vo-2	Vodarevu	15°47.52	80°24.652	2/23/05	15:10	Debris on slope	112	2.74	1.80	2.94	
5	Vo-3	Vodarevu	15°47.513	80°24.763	2/23/05	14:43	Debris/nets/boat	109	2.74	1.78	2.92	
6	Pa-1	Palipan-Kottapatnam	15°26.277	80°10.855	2/23/05	10:05	Compost box	61	3.35	3.14	4.25	
7	Pa-2	Palipan-Kottapatnam	15°26.123	80°10.573	2/23/05	9:20	Crop burn limit	254	3.05	2.93	4.05	
8	Pa-3	Palipan-Kottapatnam	15°25.983	80°10.42	2/23/05	9:30	Crop burn limit	–	3.35	3.22	4.33	
9	My-1	Mypadu-Nellore	14°30.315	80°10.712	2/22/05	18:30	Bridge approach marks	210	4.57	4.53	5.56	
10	Pu-1	Pulicat	13°24.997	80°19.658	2/22/05	9.30	Lighthouse fence marks	-	4.27	4.07	5.01	
11	**Pu-2***	**Pulicat**	**13°23.016**	**80°19.967**	**1/11/05**	**13:30**	**Sand sheet in the Green Shrine**	**90**	**3.37**	**2.67**	**3.59**	**160**
12	Pu-3	Pulicat	13°22.982	80°19.935	1/11/05	13:30	Debris line		1.92/2.12	1.22/1.42	2.14/2.34	
13	**Pu-4***	**Pulicat**	**13°22.957**	**80°19.975**	**1/11/05**	**13:15**	**Mud line on house**	**89**	**4.1**	**3.44**	**4.36**	
14	Ch-1	Chennai	13°06.262	80°18.593	2/21/05	16:30	Floated/tipped containers		5.79	5.56	6.46	
15	**Ch-2***	**Chennai**	**13°01.263**	**80°16.722**	**1/7/05**	**16:17**	**Water line on a pink house**	**145**	**2.92**	**2.69**	**3.56**	
16	**Ch-3***	**Pattinapakkam**	**13°01.047**	**80°16.626**	**1/7/05**	**15:35**	**Water line on a yellow house**	**139**	**3.08**	**3.01**	**3.88**	**140**
17	Kov-1	Kovalam	12°47.455	80°15.003	1/7/05	10:16	Max. inundation in a narrow alley	197	4.96	4.34	5.19	180
18	**Kov-2***	**Kovalam**	**12°47.455**	**80°15.003**	**1/7/05**	**10:16**	**Mud line inside of the house**	**125**	**3.77**	**3.15**	**4**	
19	**Kov-3***	**Kovalam**	**12°47.324**	**80 15.234**	**1/8/05**	**9:20**	**Clear watermark on the ground; flooded swimming pool**	**74**	**3.07**	**2.71**	**3.56**	
20	Kov-4	Kovalam	12°47.231	80°15.206	1/8/05	10:00	Clear watermarks on the ground in the plantation; broken wall	133	3.82	3.35	42	

Table 2. (cont.)

	A	B	C	D	E	F	G	H	I	J	K	L
21	Kov-5	Kovalam	12°47.003	80°15.045	1/7/05	10:16	Foam block on roof near papaya tree	161	6.05	5.43	6.28	
22	Kal-1	Kalapakkom	12°30.398	80°09.495	1/8/05	12:40	Fresh debris plus solid eyewitness	381	3	2.34	3.16	
23	Kal-2*	Kalapakkom	12°30.378	80°09.688	1/8/05	12:05	Clear watermarks on the interior walls in a yellow church schoolhouse	122	4.78	4.11	4.93	
24	Kal-3*	Kalapakkom	12°30.327	80°09.600	1/8/05	12:40	Mud line on SE corner of green apartment building	196	3.85	3.19	4.01	360
26	Peria-1	Periakalapet	12°01.708	79°51.950	1/8/05	16:00	Mud line on the house plus eyewitness	183	5.51	5.57	6.34	170
27	Peria-2*	Periakalapet	12°01.544	79°51.888	1/8/05	17:05	Transported boat and clear debris line	171	3.8/2.4/1.5	3.86/2.46/1.56	4.63/3.23/2.33	
28	Put-1*	Puttupatt-nam	11°51.618	79°48.926	1/9/05	9:35	Watermark on a green house		2.86	2.64	3.39	
29	Dev-1*	Devanaanpatti-nam	11°44.972	79°47.333	1/9/05	11:53	Mud line	80	2.78	2.19	2.93	160
30	Dev-2*	Devanaanpatti-nam	11°44.788	79°47.385	2/21/09	17:05	Wall marks	50	3.05	2.95	3.63	
31	Dev-3	Devanaanpatti-nam	11°44.757	79°47.290	1/9/05	11:10	Line of broken bricks on courtyard wall	88	5.08	4.59	5.33	
32	Dev-4*	Devanaanpatti-nam	11°44.576	79°47.230	1/9/05	11:10	Watermark, semi inside of yellow house	97	3	2.51	3.25	
33	Dev-5	Devanaanpatti-nam	11°44.567	79°47.317	2/21/09	15:30	Cottage roof marks, tree marks	30	9.14	8.89	9.56	
34	Dev-6	Devanaanpatti-nam	11°044.529	79046.925	1/9/05	12:40	Maximum inundation	340				340
35	Peran-1	Perangipetti-nam	11°30.984	79°45.999	1/9/05	14:30	Broken stair rail	161	3.95	3.4	4.11	
36	Peran-2*	Perangipetti-nam	11°30.983	79°45.979	1/9/05	14:30	Watermark on the outside of the green house		3.45	2.9	3.61	
37	Peran-3*	Perangipetti-nam	11°30.965	79°45.947	1/9/05	14:30	Watermarks inside and outside of the white Hindu house		3.35	2.8	3.51	

Table 2. (cont.)

	A	B	C	D	E	F	G	H	I	J	K	L
38	Peran-4	Perangipetti-nam	11°30.774		1/9/05	15:00	Maximum inundation	600				600
39	Peran-5	Perangipetti-nam	11°30.468	79°45.992	1/9/05	14:42	Position of reference point	544	3.34	2.82	3.53	
40	Tar-1*	Tarangamba-di	11°01.620	79°51.350	1/10/05	9:00?	Mud line and eyewitness	41	4.4	4.4	5.06	490
41	Nag-1*	Nagapatti-nam village	10°46.477	79°50.790	1/10/05	11:00	Mud line on government building with black arrow	505	4.64	4.34	4.97	800
42	Nag-2*	Nagapatti-nam port	10°45.785	79°50.928	1/10/05	8:00	Watermark in the guard house	40	5.1	5.16	5.79	
43	Nag-3	Nagapatti-nam port	10°45.785	79°50.928	1/10/05	8:00	A piece of fishing net on the roof	30	7.1	7.16	7.79	
44	Ved-1*	Arcattuthurai/ Vedarayam	10°23.597	79°52.014	1/10/05	11:00	Watermarks in a green house (inside)	201	3.91/3.39	3.62/3.10	4.21/3.69	
45	And-1*	South Andaman	11°40.342	92°44.322	2/24/09	16:00	Window stain	200	3.57	2.73	4.12	
46	And-2	South Andaman	11°40.31	92°44.295	2/24/09	16:20	Wall stain	200	3.60	2.84	4.23	
47	And-3*	South Andaman	11°39.315	92°45.397	2/25/05	12:50	House mark	107	3.05	2.82	4.21	
48	And-4*	South Andaman	11°38.525	92°44.917	2/25/05	13:00	Grass burn	113	2.59	2.30	3.69	
49	And-5	South Andaman	11°33.315	92°40.945	2/25/05	11:50	Wall marks	5	2.74	3.03	4.41	
50	And-6	South Andaman	11°31.675	92°43.537	2/25/05	11:40	Wall marks	30	3.61	3.98	5.37	
51	And-7	South Andaman	11°29.847	92°42.372	2/25/05	11:30	Tree debris at shoreline	50	5.94	6.11	7.50	
52	And-8	South Andaman	11°29.427	92°42.667	2/25/05	11:20	Vegetation marks	100	2.13	2.46	3.85	

* True tsunami inundation elevations are in boldface, and an asterisk appears next to their corresponding location codes.

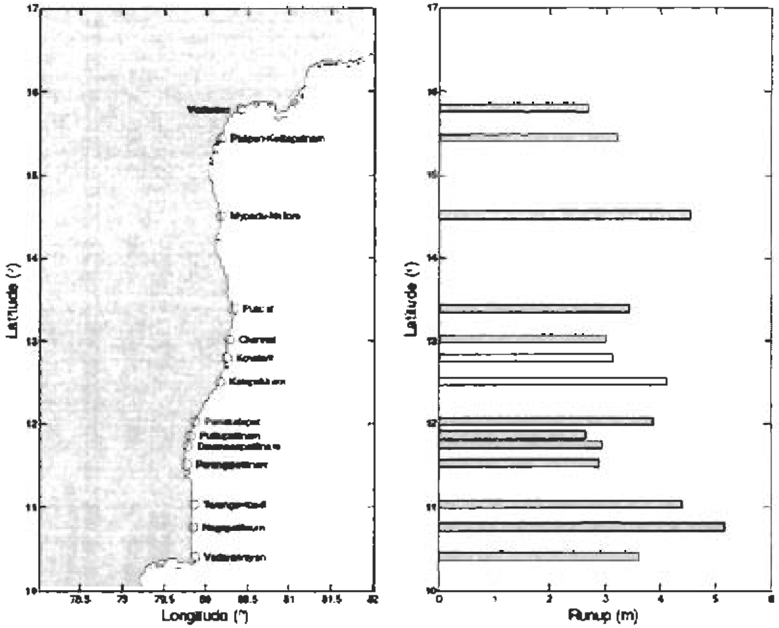

Figure 10. A plot of true inundation elevations along the southeast Indian coast.

Measured true inundation levels were plotted in Figure 10, showing fairly uniform runup heights (2.2–5.5 m) along the 600-km-long coast. The runup pattern exhibits no clear attenuation even at the most northern locale of the measurements (15° 47.61′ N). In fact, runup elevations diminished little over the 250-km span of the northern survey, ranging from 2.7 to 4.6 m, which is generally similar to the findings from the southern survey.

The uniform tsunami runup distribution along the very long coastal stretch must be attributed to the very long tsunami source (approximately 1,000 km). Unlike the west coast of Thailand, the topography along the Indian coast is quite linear and open, as shown in Figure 11, without significant features of headlands, sounds, and coves. Furthermore, the very long incident tsunami length—approximately 430 km—tended to obscure significant local amplification within relatively small-scale detailed bathymetry variations.

CLOSING COMMENTS

Because of the size of the tsunami, collecting all the necessary data remains a formidable task. This paper focuses on summarizing our effort to collect the tsunami runup

Figure 11. Typical coastal features in Southeast India (Pulicat, 13° 22.796′ N, 80° 20.009′ E).

data over approximately 600 km spanning the southeast Indian coast. In previous tsunami surveys of earthquake magnitudes less than M_w 8.0, this distance would have been more than sufficient to cover the entire tsunami-affected areas, but that is not the case for this event. Even at the northernmost survey location (15° 47.6′ N), the tsunami height is still significant (2.7 m). Additional surveying in the region of the central and northeast Indian coasts is critical to an understanding of the tsunami strength distribution.

Individual tsunami effects on the coastal areas were very similar to previous smaller tsunami events, including tsunami scours, patterns of structural damage, and inundation and deposit characteristics. What makes the 26 December 2004 Indian Ocean tsunami distinct from the previous tsunami events is the vast extent of the severely affected area and the staggering number of casualties.

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