Learning from Earthquakes

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

Editor's Note: *In responding to the Sumatra earthquake and subsequent Indian Ocean tsunami, the National Science Foundation (NSF) funded multiple teams to work in the many affected areas. Some teams were supported by NSF through EERI's Learning from Earthquakes Program, while others were funded directly through a Small Grant for Exploratory Research. The NSF/EERI teams worked in Indonesia, India, Sri Lanka, and the Maldives, and work is planned for East Africa.*

The teams included faculty and researchers from Cornell University, the Georgia Institute of Technology, Oregon State University, Portland State University, Texas A&M University, the University of Arizona, the University of Southern California, and the University of Washington; they were joined by researchers from the USGS and New Zealand, and by local scientists from India, Indonesia, the Maldives, and Sri Lanka.

We will publish a number of their reports in the EERI Newsletter. The first two follow here, and subsequent ones will appear in the April and May issues. Their publication is funded by EERI's Learning from Earthquakes Program under NSF grant #CMS-0131895.

Report #1

Field Survey of Northern Sumatra

Jose Borrero of the Department of Civil Engineering at the University of Southern California is a member of the International Tsunami Survey Team (ITST). He was supported by NSF through EERI's LFE Program and entered the Aceh region of northern Sumatra on January 3, 2005.

Introduction

At 00:58:49 GMT (07:58 local time) on Sunday December 26, 2004, a strong earthquake of magnitude Mw=9.0 struck at 3.09˚N, 94.26˚E southwest of Banda Aceh in northern Sumatra. This official USGS magnitude is based on the Harvard Centroid Moment Tensor solution. However, studies of the normal modes excited by this event suggest that the actual magnitude is considerably higher: Mw=9.3. According to Stein and Okal (2005), the higher moment may represent slower slip on the northern end of the rupture zone. The earthquake triggered giant tsunami waves that propagated throughout the Indian Ocean, causing extreme inundation and destruction along the northern and western coast of Sumatra. Within hours, the tsunami devastated the distant shores of Thailand to the east as well as Sri Lanka, India, and the Maldives to the west. The tsunami also caused deaths and destruction in Somalia and other nations of east Africa and was recorded on tidal stations throughout the oceans of the world.

I collected the information in this report and used it in conjunction with satellite imagery from before and shortly after the earthquake to describe the effects of the tsunami and earthquake in terms of runup height, inundation distance, flow depth, levels of structural damage, shoreline erosion, and earthquake-related subsidence. Field data collected in Banda Aceh and nearby areas consisted of profiles to determine runup heights, GPS-located photographs of flow depth marks, and traces indicating flow direction. Additional information on wave arrival and behavior was collected through interviews with witnesses and survivors and from videos taken during the tsunami impact.

Post-Tsunami Field Surveys

I conducted a survey of select points along the northeast coast of Sumatra as well as a detailed sur-

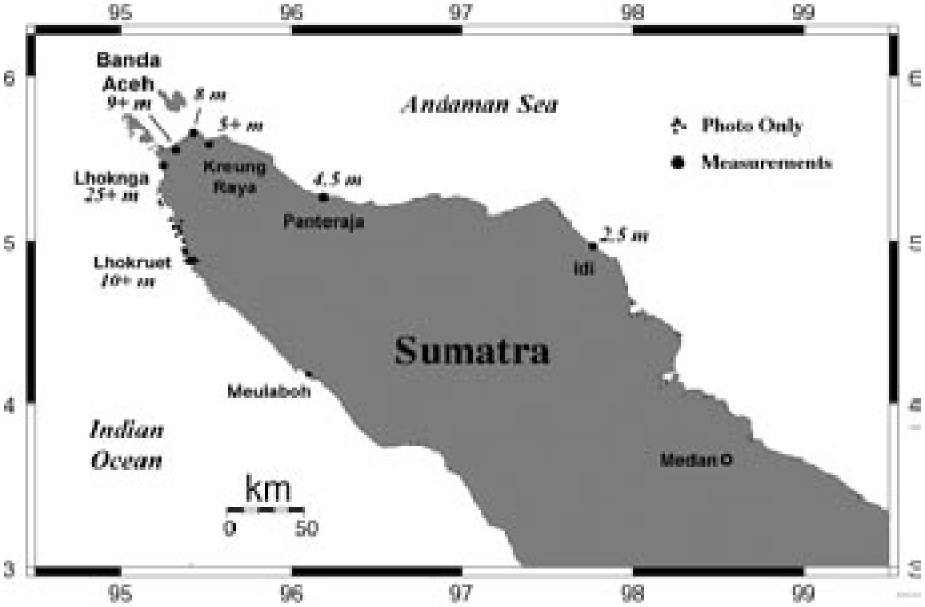

Figure 1. *Numbers adjacent to locations give a representative value of maximum runup or flow depth at each site.*

vey of the city of Banda Aceh and the nearby locations of Lhoknga and Kreung Raya. Additional locations along the inaccessible regions of the west coast of Sumatra were photographed from the air and one location at Lhokkruet was surveyed (Figure 1).

The goals of the ITST are to document *inundation* (the horizontal extent of water penetration) and *runup* (the maximum vertical elevation of the water on the land), and to collect information on the human impact of the tsunami. The following standard tsunami field survey techniques (Tsuji et al. 1995; Okal et al. 2002) were used:

1) Observing and recording water height and inundation indicators such as debris and water marks on buildings; damage such as broken windows and stripped roof tiles; and debris or sand deposited on stairs, upper floors, and roofs. Care was taken in interpreting watermarks, as they can relate to episodes when the water was still strong enough to leave a mark, but at levels less than peak water height.
2) Surveying, using optical equipment, across beaches from the water line to the maximum inland extent of inundation.
3) Interviewing eyewitnesses. It is easy to misinterpret debris and sand lines unless they are corroborated as tsunami deposits by eyewitnesses.
4) Interviewing government officials and aid workers and collecting reports, maps, photographs, and other materials pertinent to the tsunami.

A complete set of photographs and corresponding GPS locations are available on the EERI web site. A detailed table with measured flow depths and directions is also on the EERI web site.

Table 1. *Measured runup heights*

Location Number	Location Name	Latitude (deg)	Longitude (deg)	Runup (m)
002	Idi	4.96653	97.77177	2.5
004	Panteraja	5.2611	96.18528	4.2 - 4.7
072	Lhoknga	5.45777	95.24513	25.0
103	Between Banda Aceh and Kreung Raya	5.65125	95.4231	8.0

Field Observations

The locations of field data collection are shown in Figure 1, and data are displayed in Table 1. All runup data are given relative to the tide level at the time of the earthquake (Tsuji, Namagaya, and Ito 2005), while flow depth measurements are relative to the ground level at that location. Coseismic uplift or subsidence are not taken into account.

East Coast — Medan to Banda Aceh: The earthquake was widely felt throughout northern Sumatra. In Medan, it was described as a long, gentle rocking that did not cause damage. Further north at Idi, residents reported feeling earthquake shaking for ten minutes. About 1.5 hours after the earthquake, witnesses there reported seeing the ocean recede more than 500 m. The tsunami came in as two waves, with the second wave the larger. A cross-shore profile of the inundation zone showed that the wave penetrated more than 500 m inland and attained a height of 2.5 m above sea level.

It is possible to determine the upper limit on the wave height at the shoreline because the tanks at the prawn hatchery were not overtopped. Wood construction at the shoreline was destroyed, while reinforced concrete construction generally survived. There were no fatalities. The residents said locally stationed Navy personnel warned them that a tsunami was coming; however, they reported that many ignored the warning.

At Panteraja, residents stated the

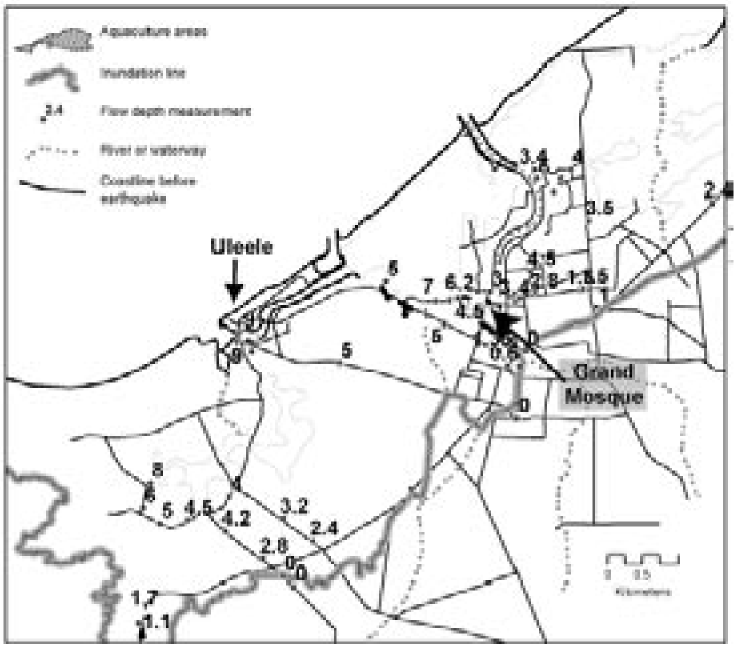

Figure 2. *Map of Banda Aceh with flow depths as measured in the field.*

***Figure 3.** Roof tiles were removed by the flooding wave in Banda Aceh.*

earthquake shaking lasted approximately ten minutes. The shaking was severe in this area, with residents reporting not being able to walk or even squat during the shaking without being knocked to the ground. The also described two shaking episodes: the first with a horizontal east-west oriented back-and-forth motion, and the second feeling more "up and down." Earthquake damage to structures in the area was reported to be minor, but the tsunami effects were severe. The tsunami began with an initial sea withdrawal about 30 minutes after the earthquake. The local residents reported three waves, with the third being the largest. That wave penetrated up to 1 km inland and attained a height of 4.2 to 4.7 m above sea level.

Banda Aceh: Banda Aceh lies on a river delta created by the Aceh River reaching the Andaman Sea. Two large forks of the river split the city, with the main one one running through the center of town and the other lying 15 km to the east. The central area of Banda Aceh was separated from the open sea by nearly 2 km of low-lying wetland, probably used for aquaculture. Only on the sand spit of Uleele were there significant structures built on the shoreline (Figure 2).

The entire city of Banda Aceh was strongly affected by the earthquake shaking, with several collapsed buildings and evidence of structural damage in large reinforced concrete structures. One resident reported being unable to stand during the shaking, said that cracks opened up in the ground, and observed significant building damage throughout the city. This witness, who was in the center of town near the Grand Mosque, said he was able to close his shop after the earthquake and travel to another shop he owned closer to the ocean. He then traveled to his house before returning to the store he was at originally. By the time he reached the store, the water was flowing into the center of Banda Aceh. He estimated it was 25 minutes from the time of the earthquake until the water arrived at the city's center.

The inundation line was observed at between 3 and 4 km inland throughout the city. Flow depths over ground were observed to be at over 9 m in the northern seaside section of Uleele, tapering landward. The level of destruction was observed to be more extreme on the northwestern flank of the city in the areas immediately inland of the aquaculture ponds. The area towards the sea was wiped clean of nearly every structure, while closer to the river, dense construction in a commercial district showed the effects of severe flooding. The spaces between the buildings served as conduits for the flow spilling over the riverbanks and through the city's streets. The flow depth was just at the level of the second floor, and there were large amounts of debris piled along the streets and into the ground floors of stores (Figure 3). A video taken in the vicinity of the Grand Mosque shows that the flood depth did not exceed the level of the second floor on these buildings. A survivor of the

***Figure 4.** Satellite view of Lhoknga. The estimated runup at the trim line above the barge was 25 m.*

Figure 5. The trim line at a small headland at Lhoknga. This hill was previously covered by dense jungle to the waterline.

tsunami from Uleele described three waves, with the first rising only to the foundation of the buildings, followed by a large withdrawal of the sea before the second and third waves hit.

Kreung Raya: The port and oil transfer facility of Kreung Raya is 45 km east of Banda Aceh. Here the earthquake was felt strongly but did not cause severe damage to structures. The oil storage tanks at the facility appeared to be in good condition, with the exception of one tank that was moved off its foundation by the force of a tsunami wave. The extent of inundation was on the order of 1 km, and flow depths were observed to be 5 m throughout the inundation zone. On a steeper section of coastline between Banda Aceh and Kreung Raya, a clear inundation line and runup mark were identified and measured at 8 m.

Workers at the oil facility reported that a tanker was offloading oil at the time of the earthquake and said the captain was killed after he leapt off the bridge of the ship into the water. The crew apparently managed to control the ship and move it offshore.

Lhoknga: The most severe tsunami effects were observed to the west of Banda Aceh on the coastline that faces the Indian Ocean and the epicenter of the earthquake. On the beach at Lhoknga, stripped bark on trees indicated a sustained flow depth of over 13 m at the shoreline. A mining facility at the south end of the beach was severely damaged by the tsunami, and two large ships were affected. A 90-m long coal barge was moved from the shore more than 160 m to the base of a hill with its tugboat still attached. At the jetty in front of the mining facility, a 100-m freighter was capsized at its moorings (see Figure 4).

A clearly defined trim line was visible all along a steep hill that backed the beach 300 m from the shoreline. The height of this trim line was estimated to be 25 m high, but it was not measured precisely in the field during this survey. That value was later confirmed by comparing a satellite photograph of the inundated region to a 90-m digital elevation model, which gave a value of 23 m at that location. Later surveys by Tsuji et al. (2005) reported runup heights at that location to be 22 and 32 meters (see Figure 5).

Helicopter Reconnaissance

I took photographs during a helicopter flight along the west coast to the south of Lhoknga (locations shown in Figure 1). GPS locations over the inland extent of inundation were compared with digital elevation data to suggest inundation distances of 1-3 km. Photographs were correlated with GPS locations. At Lhokkruet, flow depth measurements suggest a minimum of 8-9 m.

Preliminary Data Analysis

The field data were used in conjunction with satellite imagery and digital topography to examine the extent of inundation.

Maximum Runup: At Lhoknga, the maximum water level could not be precisely measured; however, flow depth evidence suggested 12-15 m of sustained flow depth, and visual observation indicated runup of 20-25 m. The GPS location of the high water mark was compared with sat-

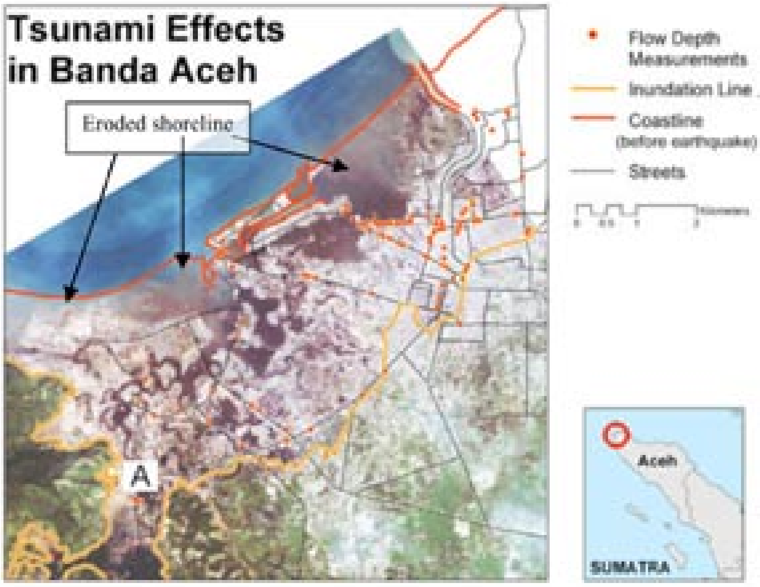

Figure 6. Satellite image of Banda Aceh after the arthquake and tsunami.

ellite imagery and a 90-m digital elevation model (CIAT 2004). The satellite imagery of the high water mark lines up with the 25 m contour in the DEM and provides a first order check to the rough field estimate. A second survey team to reach the area of the runup in the Lhoknga area found a range of values between 15 and 35 m (Tsuji et al. 2005).

Subsidence and Scour: Comparing before-and-after satellite images shows a drastic change in the shoreline of Banda Aceh. Figure 6 compares the shoreline before the tsunami to a satellite image taken shortly after the tsunami, revealing extensive erosion. The sand spit at Uleele was washed through in several places. A narrow strip of land between the sea and the aquaculture fields was completely washed away, effectively moving the shoreline inland by several hundred meters.

Inundation: A witness interviewed at location A in Figure 6 reported that a wave approached from both directions. Analysis of satellite imagery taken after the tsunami shows that the tsunami flowed across the northwestern tip of Sumatra. Digital elevation data show an area of low elevation cutting across a small ridge.

Final Observation

This data set is far from complete. Additional surveys will be needed to fully assess the tsunami effects from Banda Aceh south to Meulaboh, the area that probably experienced the largest waves during this event.

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Report #2

Tsunami Survey along the Southeast Indian Coast

A team gathered data from January 7 through January 11, 2005, along a 350-km stretch of the southeast Indian coast. It was composed of eight members: five from India (a seismologist, an ocean scientist, a graduate student, and two assistants); two from the United States (a sedimentologist and a tsunami hydrodynamist); and one from Japan (a social engineer).

Five contributed to this report: Harry Yeh, Oregon State University; Curt Peterson, Portland State University; R. K. Chadha, National Geophysical Research Institute, Hyderabad, India; G. Latha, National Institute of Ocean Technology, Chennai, India; and Toshitaka Katada, Gunma University, Japan. The team was supported by the National Science Foundation as part of EERI's LFE Program, the National Geophysical Research Institute in Hyderabad, the National Institute of Ocean Technology in Chennai, and Gunma University in Japan.

Introduction

The strong earthquake of December 26, 2004, triggered giant tsunami waves that killed more than 300,000 people in Indonesia, Thailand, Malaysia, Myanmar, Bangladesh, India, Sri Lanka, the Maldives, and some African countries. The aftershock pattern indicates that the fault rupture spanned more than 1,200 km of the India plate subduction beneath the overriding Burma plate.

The affected areas are so extensive, literally the entire Indian Ocean basin, that the traditional ground-level tsunami survey was difficult. Here we report a portion of the International Tsunami Survey Team effort, covering from Vedaranniyam (10˚23.5'N) to Pulicat (13˚23.0'N) in India. The area is more than 1,500 km from the tsunami source.

Tsunami Survey

Both initial media reports and our preliminary numerical predictions indicated that the most affected area was south of Chennai, so that was the area we targeted. The survey consisted of measurements of maximum tsunami runup heights and distances, average runup heights and areas of inundation, flow patterns of runup and rundown, and recording of eyewitness accounts.

Because of the distant source, no observations of subsidence, uplift, and landslides were made, although we examined geomorphological changes and sediment deposits from the tsunami.

Runup: The maximum tsunami runup height is defined as the vertical water surface elevation reached by the tsunami above sea level. It was measured using standard surveying instrumentation. The maximum runup locations were determined visually based on watermarks on structures or the ground, breakage of tree limbs, scratch marks on trees or structures caused by waterborne objects, or the locations of waterborne debris. Every mark used for the runup was photographed for archiving and its location was identified using a global positioning system (GPS).

Because we found clear watermarks on and in the buildings at almost every site we visited (Figure 1), we did not need to rely on less reliable tsunami marks such as scratch marks on structures and debris in trees. Such quality tsunami marks remained because there had been no rain or strong winds between the event and our survey, and many of the coastal structures are made of reinforced concrete or masonry, which withstood the tsunamis and were intact.

Table 1 shows the measured tsunami runup heights from the estimated tide level at the time of the tsunami, as well as maximum inundation distances from the shoreline. Also shown are the maximum distances of the tsunami sediment deposits.

***Table 1.** Tsunami runup surveys along the coast of Tamil Nadu and Pondicherry.*

Sl. No	Location	Latitude °N/ Longitude °E	Runup elevation (m)	Lateral Inundation(m)	Max Sand Distance (m)
1.	Pulicat	13°23.040’ 80°19.984’_ _	3.2	160	90
2.	Pattinapakam	13°01.263’_ 80°16.722’_	2.7	145	120
3.	Kovalam	12°47.455’_ 80°15.003’_	4.3	180	120
4.	Kalpakkam	12°30.378’ _ 80°09.688’ _	4.1	360	190
5.	Periakalapet	12°01.544’ _ 79°51.888’ _	3.9	170	130
6.	Puttupatnam	11°51.618’ _ 79°48.926’ _	2.6	--	--
7.	Devanaam-patnam	11°44.576’ _ 79°47.230’ _	2.5	340	180
8.	Parangipettai	11°30.965’ _ 79°45.947’ _	2.8	700	400
9.	Tarangambadi	11°01.620’ 79°51.350’_ _	4.4	400	150
10.	Nagapattinam	10°45.785’ _ 79°50.928’ _	5.2	800	430
11.	Vedaranniyam	10°23.597’ _ 79°52.014’ _	3.6	--	--

Note: Almost all of the values reported above for runup elevation are based on the sandy-mud-line marks that remained inside of houses. Such highly reliable quality data were possible because of our rapid reconnaissance.

During the survey, the elevation of each tsunami watermark was measured using the mean swash (i.e., the sea level at the shore) as the datum. The tide level adjustment was made subsequently by comparing the sea levels at the measurement and those at the time of the tsunami. The first tsunami wave hit Chennai (13˚N) at about 03:10 (GMT) on December 26, which was 8:40 am local time. However, the maximum runup may have occurred in the successive tsunami as eyewitness accounts generally indicate the second wave was the largest.

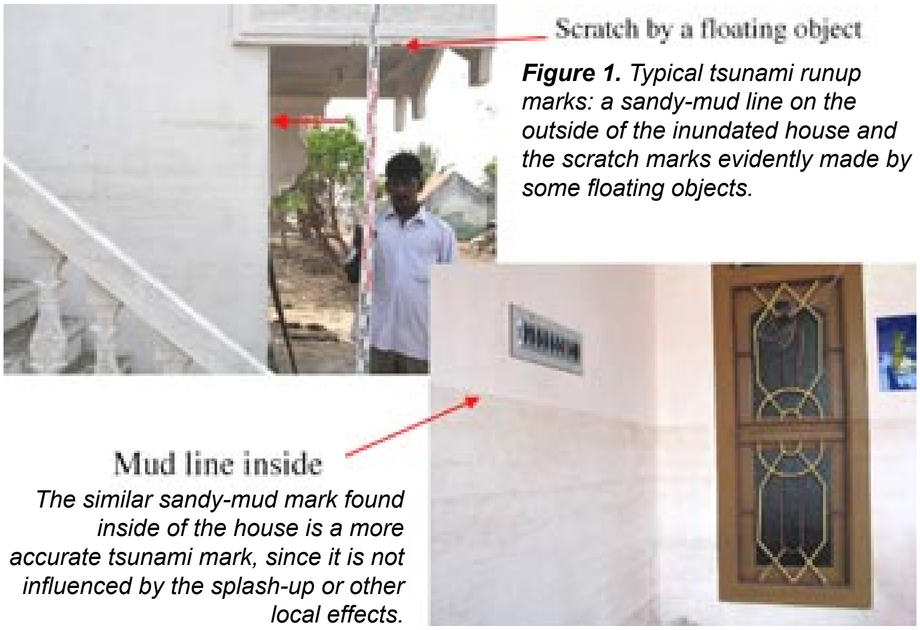

***Figure 1.** Typical tsunami runup marks: a sandy-mud line on the outside of the inundated house and the scratch marks evidently made by some floating objects.*

The similar sandy-mud mark found inside of the house is a more accurate tsunami mark, since it is not influenced by the splash-up or other local effects.

By using satellite altimetry data, the arrival time of the second tsunami crest can be estimated at 40 minutes after the first tsunami wave (**http://www.aviso.oceanobs.com/html/ applications/geophysique/tsunami_uk.html**). With the same satellite data, Gower (2005) estimated the wavelength at 430 km, with the wave period being 37 minutes.

This wave period is consistent with the statement made by eyewitness Chris Chapman about Sri Lanka (Cyranoski 2005). Because of the uncertainly, we arbitrarily assumed that the tsunami arrival time on December 26 was at 03:40 (GMT); the estimated error is at most ± 0.1 m.

The measured runup heights are plotted with the numerical predictions (discussed earlier) in Figure 2, and they are fairly consistent. The numerical prediction model is based on a 3.7 km x 3.7 km grid system,

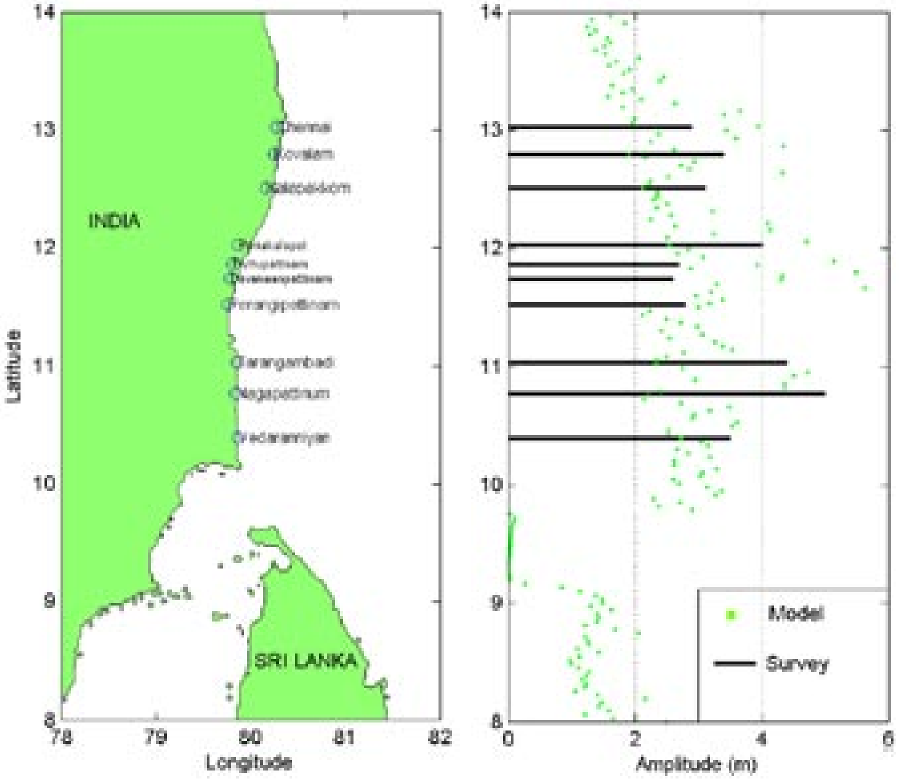

Figure 2. Comparison of the numerical predictions (provided by Philip Liu) with the measured tsunami runup heights.

which does not take into account the detailed local bathymetry and inland topography. The prediction does not include final shoaling effects of tsunami because the model assumes fictitious vertical walls (no flux condition) near the shore where the depth is less than 5 m. In spite of the simplifications in computation, the agreements are excellent. The good agreements are mainly attributed to advances in the numerical technique, as well as the bathymetry dataset made available during the last decade through the work of the General Bathymetric Chart of the Oceans (GEBCO): **http://www.ngdc.noaa.gov/mgg/gebco/gebco.html**.

The continental shelf along the southeast coast of India is narrow (ranging from 20-50 km) and the continental slope is steep. A typical bathymetry profile taken from the marine chart along N13˚ (DMA-63270) shows the continental shelf at about 40 km wide and the continental slope at approximately 1/10. The edge of the continental shelf in this region can be represented by the 100 ~ 200 m depth contour line shown in Figure 3. Also plotted on the figure are the tsunami runup heights. There appears to be some correlation between the tsunami runup height and the width of the continental shelf: the wider the shelf, the higher the runup.

Deposits: The maximum transport distances of gravel, sand, and flotsam were examined. Gravel transport ranged from 30 to 60 m from the swash zone. The gravels consisted mainly of tsunami-damaged brick walls, foundations, and roofing tiles. Maximum sand transport ranged from 90-430 m from the swash zone, as listed in Table 1. The beach widths in most profiles reached 30-50 m from the swash, except at Parangipettai and Nagapattinam with their broad sand spits, each about 300 m in width. The average sand transport distance was 130 m from the swash. Tsunami sand deposits ranged from coarse upper (700-1000 microns) to very fine upper (88-125 microns) in grain size. Tsunami sand deposit thickness ranged from several tenths of centimeters near beach backshores to 1 cm at the distal end of sand transport. Sand sheets appeared to fine in mean grain size with distance landward. Fining-upward sequences in each of 2-3 sand layers were observed at the 80 m position in profile at Devanaampatnam. Fining-upward sequences were not apparent in most of the proximal sand sheet deposits, i.e., deposits within 100 m of the shoreline.

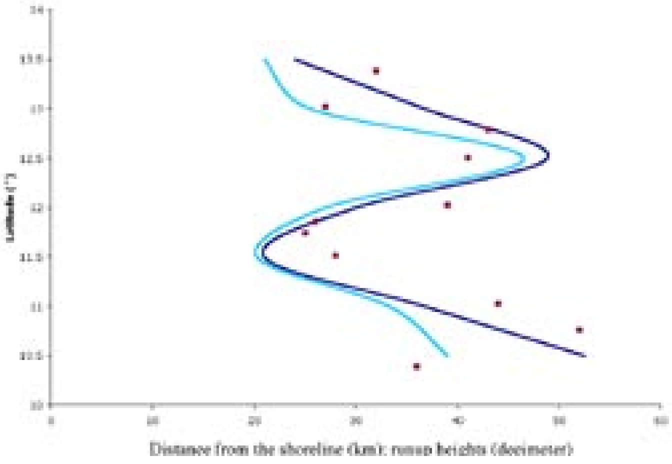

Figure 3. The breadth of the continental shelf in the survey region, presented by the 100m and tsunami runup heights in decimeters.

Casualties

The official web sites of the governments of Tamil Nadu and Pondicherry report that more than 8,600 people perished in the area we surveyed (**http://www.tn.gov.in/tsunami/damages.htm**; **http://pondicherry. nic.in/tsunami/tsunaminew.htm**). The hardest hit location was Nagappattinam, where 6,065 people were found dead as

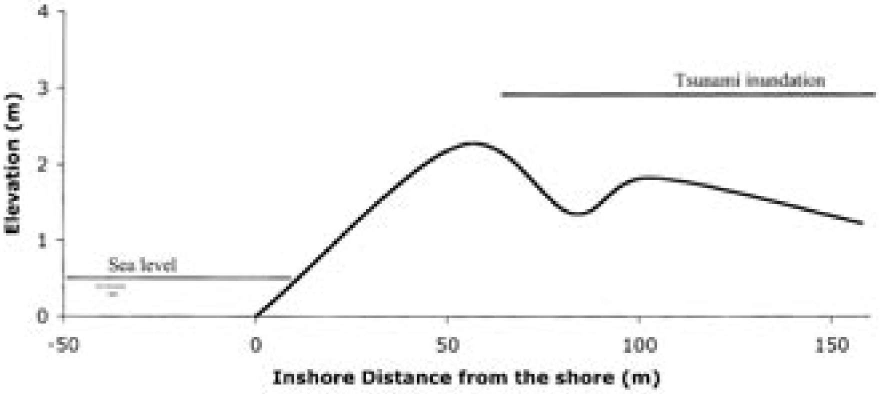

Figure 4. *A typical beach profile taken at Devanaanpattinam.*

of February 3, 2005. The measured runup height along the Tamil Nadu coast ranges from 3 m to 5 m. We found that many people (especially fishermen) dwell very close to the shore where the ground elevation is less than 1.5 m. This was not normally hazardous, because the storm surge induced by cyclones is small, owing to the narrow continental shelf (ranging from 20-50 km), and the tidal range is also small (~ 1m).

We observed that most of the victims drowned in tsunami flows with a depth of ~1.5-2.0 m. Figure 4, showing a typical beach profile at Devanaanpattinam, indicates that the tsunami flow speed could have been enhanced behind the beach berm. Thus, even a 1.5 m-deep flow had more than enough force to kill adult human beings. Because a tsunami wave period is much longer than cyclone-generated waves of the equivalent height, the tsunami's wave has very long and sustained penetration.

Structures and Infrastructure

We found that almost all of the wood frame and straw houses were totally destroyed, about half of the masonry houses survived, and almost all the reinforced concrete houses withstood the tsunami forces.

One of the prominent tsunami effects on buildings were the extensive scours around their foundations. The scour patterns were not consistent: on some buildings, the damage was found on the sea side, while on others it was on the land side. Figure 5 shows scour damage at the seaward corner of the schoolhouse at Kalapakkom, where the runup height was 4.1 m; the building was inundated to 0.95 m above the floor level. The scour depth is approximately 1.5 m with a horizontal span of 5 m.

Remote Sensing

A remarkable difference in the present survey practice from the previous ones is the use of remote sensing data, particularly satellite images. The satellite images can help in interpreting ground level observations, and vice versa. Figure 6 shows a comparison of satellite image with the ground-level survey. The washed up ship on the quay can be identified in the satellite image. The small anomaly next to the ship in the satellite image was found to be a damaged concrete block of the quay wall. In the same area, we observed many damaged boats stacked on the quay, while no such boats were observed in the satellite image that was taken after the tsunami. This discrepancy indicates that the boats were not moved by the tsunami but rather were transported after the event to that location as part of the clean-up process.

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Figure 5. *Tsunami scour and failure of a wastewater pipe at a schoolhouse at Kalapakkom.*

Figure 6. *A ship pushed up by the tsunami at Nagappattinam Port, seen in the satellite image by the arrow mark (IKONOS Image by Space Imaging).*