Field Survey northern Sumatra and Banda Aceh, Indonesia and after the Tsunami and Earthquake of 26 December 2004.

Jose C. Borrero

- *Department of Civil Engineering, University of Southern California, Los Angeles, CA 90089-2531, USA*

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Introduction

On Sunday December 26th at 0058 UTC (0758 local at the epicenter), a great earthquake occurred 250 km southwest of Banda Aceh in northern Sumatra, Indonesia. With a moment magnitude of 9.3, it was the second largest instrumentally recorded earthquake in history (Stein and Okal, 2005) The earthquake generated a large tsunami, which caused extreme inundation and destruction along the northern and western coast of Sumatra as seen in the cities of Banda Aceh and Meulaboh. 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.

The rapid response of an International Tsunami Survey Team (ITST) to the Banda Aceh, Sumatra region after the December 26th, 2004 earthquake and tsunami led to the recovery of important data on the characteristics of the tsunami inundation. This data was used in conjunction with satellite imagery obtained 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 video taken during the tsunami attack.

Post Tsunami Field Surveys

A member of the International Tsunami Survey Team (ITST) entered the Aceh region of Sumatra on January 3, 2005 and conducted a survey of select points along the northeast coast of Sumatra as well as a detailed survey 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).

Field Methods

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

1) Observing and recording water height and inundation indicators such as debris, water marks buildings, elevation of damage such as broken windows and stripped roof tiles, debris and sand deposited on stairs, upper floors and roofs. Care was taken in interpreting watermarks as they relate to episodes when the water was still enough to leave a mark, almost always at levels less than peak water height.

2) Interviewing eyewitnesses. It is easy to misinterpret debris and strand lines unless corroborated as a tsunami deposit by eyewitnesses.

3) Surveying profiles, using optical equipment, across beaches from the water line to the maximum inland extent of inundation.

4) Interviewing government officials and aid workers and collecting reports, maps, photographs and other materials pertinent to the tsunami. A selection of photographs are included with this report, however a complete set of photographs and corresponding GPS locations have been provided to EERI for distribution by electronic means.

Field Observations

The field data collected and locations mentioned are listed in Table 1 and shown in Figure 1. All runup data are given relative to the tide level at the time of the earthquake (*Tsuji et al.*, 2005a), while flow depth measurements are relative to the ground at that location. Coseismic uplift or subsidence are not taken into account. The tsunami was severe in its destruction at the two sites surveyed along the east coast, while the effects in Banda Aceh and along the west coast can best be described as extreme.

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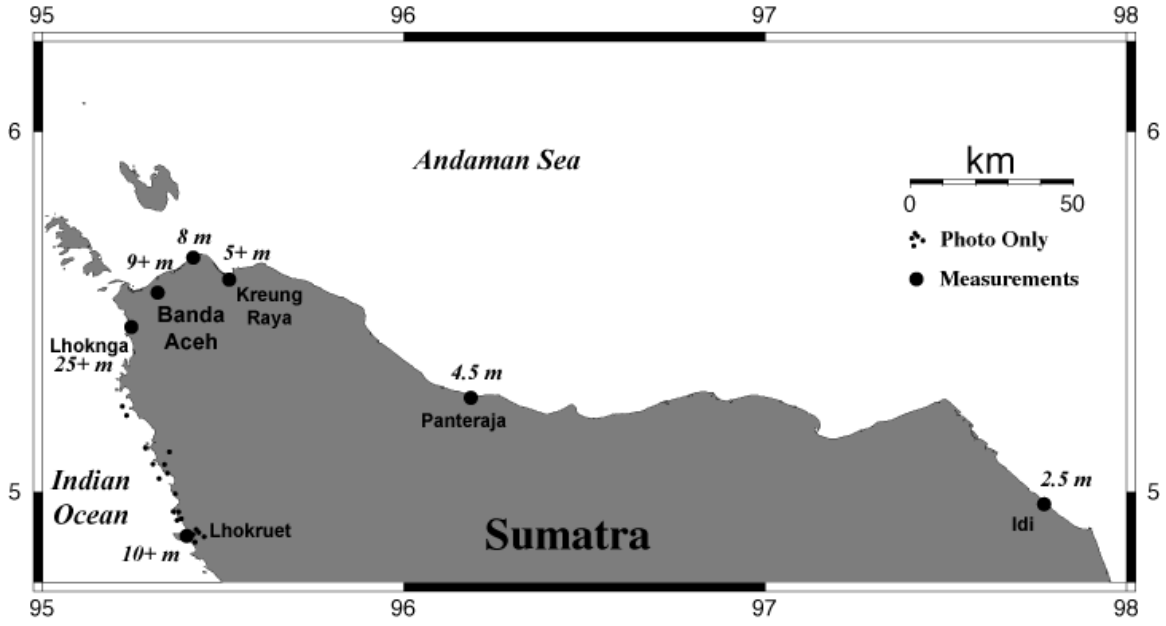

Figure 1: Locations mentioned in the text. Numbers give a representative value of maximum runup or flow depth at each site.

East Coast, Medan to Banda Aceh

The earthquake was widely felt throughout northern Sumatra. It was described as a long lasting gentle rocking in Medan that did not cause damage. Further north at Idi, residents reported feeling earthquake shaking for 10 minutes. About 1 and a half hours after the earthquake, witnesses reported seeing the ocean recede more that 500 m. The tsunami came in as 2 waves with the larger wave second. A cross-shore profile of the inundation zone showed that the wave penetrated over 500 m inland and attained a height of 2.5 m above sea level (figure 2).

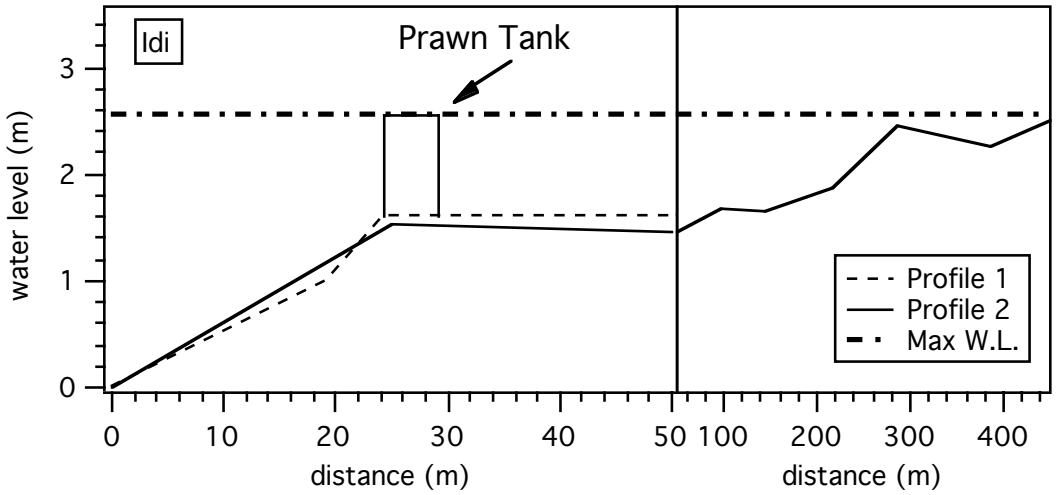

Figure2: Profile of data taken at Idi, northeastern Sumatra. Note the scale change.

We have an 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 local residents said locally stationed Navy personnel warned them that a tsunami was coming, however they also reported that many ignored the warning.

Continuing north along the coast, we observed the damage at Panteraja. Residents stated the earthquake as lasting for approximately 10 minutes. The shaking was severe in this area, residents reported not being able to walk or even squat during the shaking, that they were knocked to the ground. The also describe 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. The tsunami effects were much more severe here. The tsunami attack began with an initial withdrawal about 30 minutes after the earthquake. The local residents reported three waves with the third being the largest. The wave penetrated up to 1 km inland and attained a height of 4.2 to 4.7 m above sea level at the time of the tsunami (figure3).

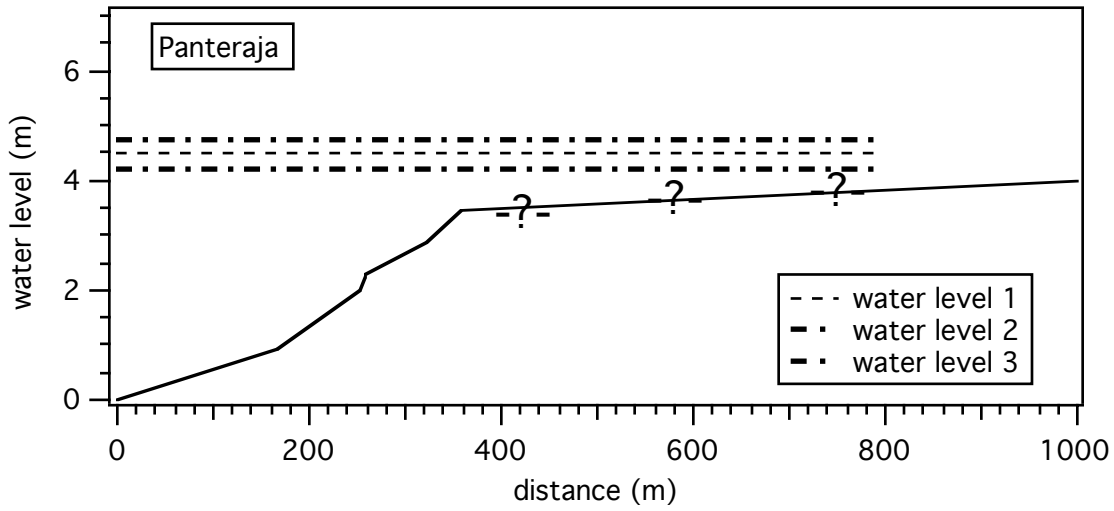

Figure 3: Profile at Panteraja. Question marks indicate that this region was not surveyed, however it was observed to be relatively flat rice fields that were completely inundated. Three water levels were measured on two different structures along this profile.

Banda Aceh

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

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

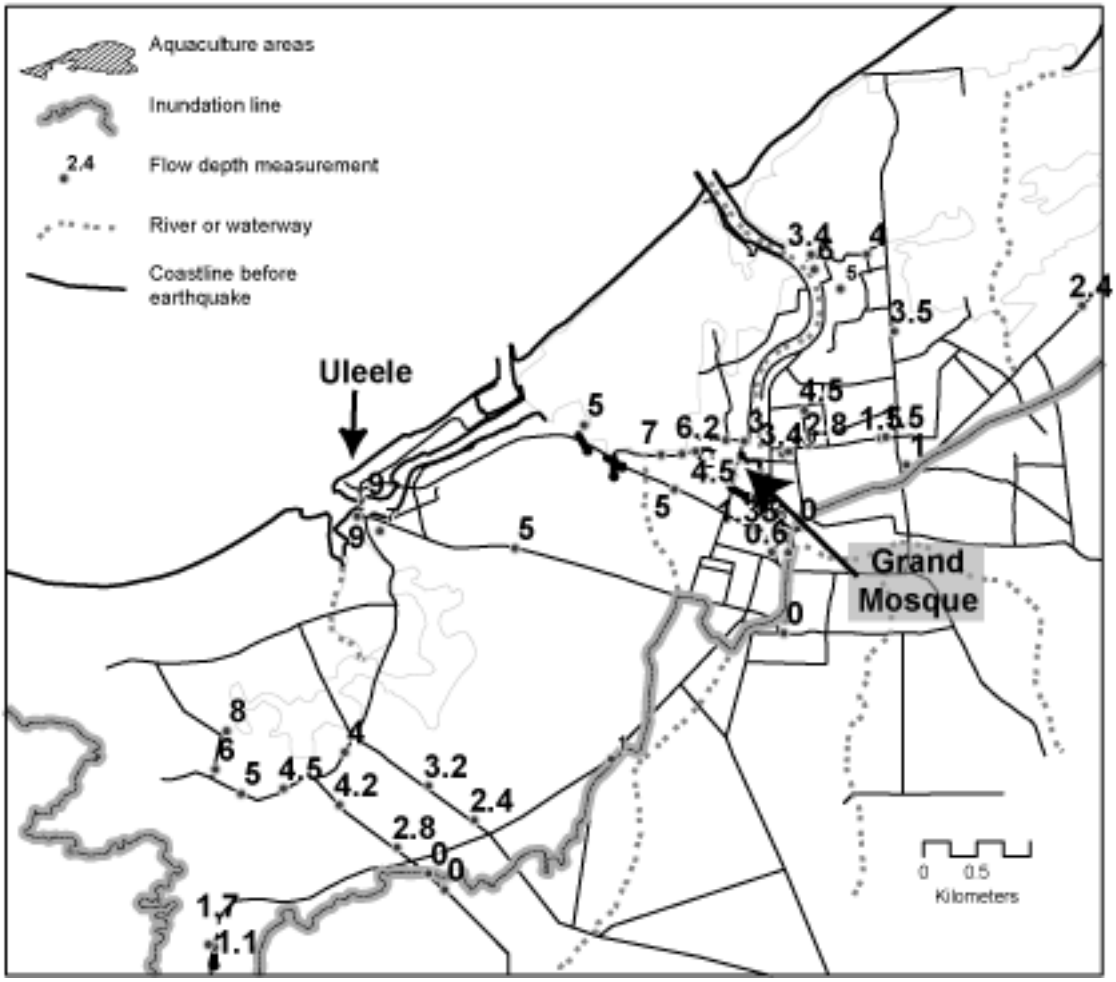

Figure 4: Map of Banda Aceh with flow depths as measured in the field.

The inundation line was observed to lie between 3 and 4 km inland throughout the city (figure 4). Flow depths over ground were observed to be over 9 m in the northern seaside section of Uleelee and tapered 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 from the flow spilling over the riverbanks and through the cities 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 in to the ground floor storefronts. A survivor of the tsunami from Uleele

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

Video taken during the tsunami attack show the effects of the flow being channeled through narrow city streets. The video was taken in the vicinity of the Grand Mosque and clearly shows that the flood depth did not exceed the level of the 2nd floor on these buildings.

Kreung Raya

45 km East of Banda Aceh is the port and oil transfer facility of Kreung Raya. The earthquake was felt very strongly, but it 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 the 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.

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

Lhoknga

The most severe tsunami effects were observed to the west of Banda Aceh on the coastline that faces towards open Indian Ocean and the epicenter of the earthquake. On the beach at Lhoknga (figure 5), 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. There were two large ships that were affected by the tsunami. A 90-m long coal barge was deposited over 160 m from shore on the beach at 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.

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.* (2005b) reported runup heights at that location to be 22 and 32 meters.

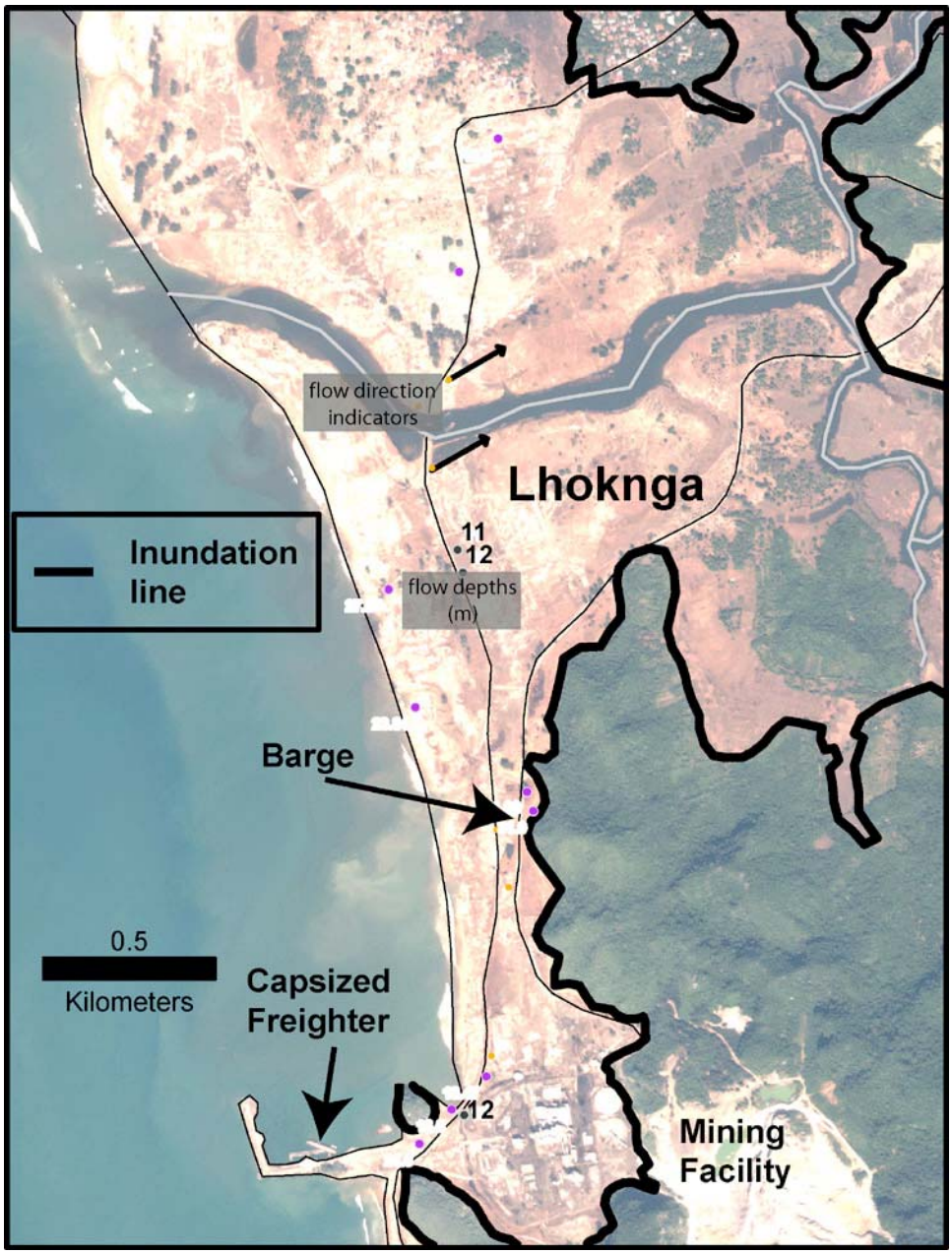

Figure 5: Satellite view of Lhoknga. The 25 m was the estimated runup at the trim line above the barge.

West Coast Helicopter

Photographs taken during a helicopter flight along the west coast of Sumatra to the south of Lhoknga clearly show the extent of tsunami inundation. GPS location over the inland extent of inundation and a comparison with digital elevation data suggest inundation distances of between 1 and 3 km. Photographs were correlated with GPS locations. At Lhokkruet, flow depth measurements suggest a minimum flow depth between 8 and 9 m. The locations where GPS correlated photographs were take are shown in figure 1.

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, based on the flow depth evidence suggesting 12-15 m of sustained flow depth and visual observation of the field conditions, the runup was conservatively estimated to be 20 to 25 m. The GPS location of the high water mark was compared with satellite imagery and a 90-m digital elevation model (SRTM, 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 precisely measured the runup in the Lhoknga area and measured a range of values between 15 and 35 m (*Tsuji et al.*, 2005b).

Land lost to subsidence or scour

Comparing before and after satellite images shows a drastic change in the shoreline of Banda Aceh. Figure 6 shows a comparison of the shoreline from before the tsunami to a satellite image taken shortly after the tsunami. Extensive erosion can be seen all along the shoreline. 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.

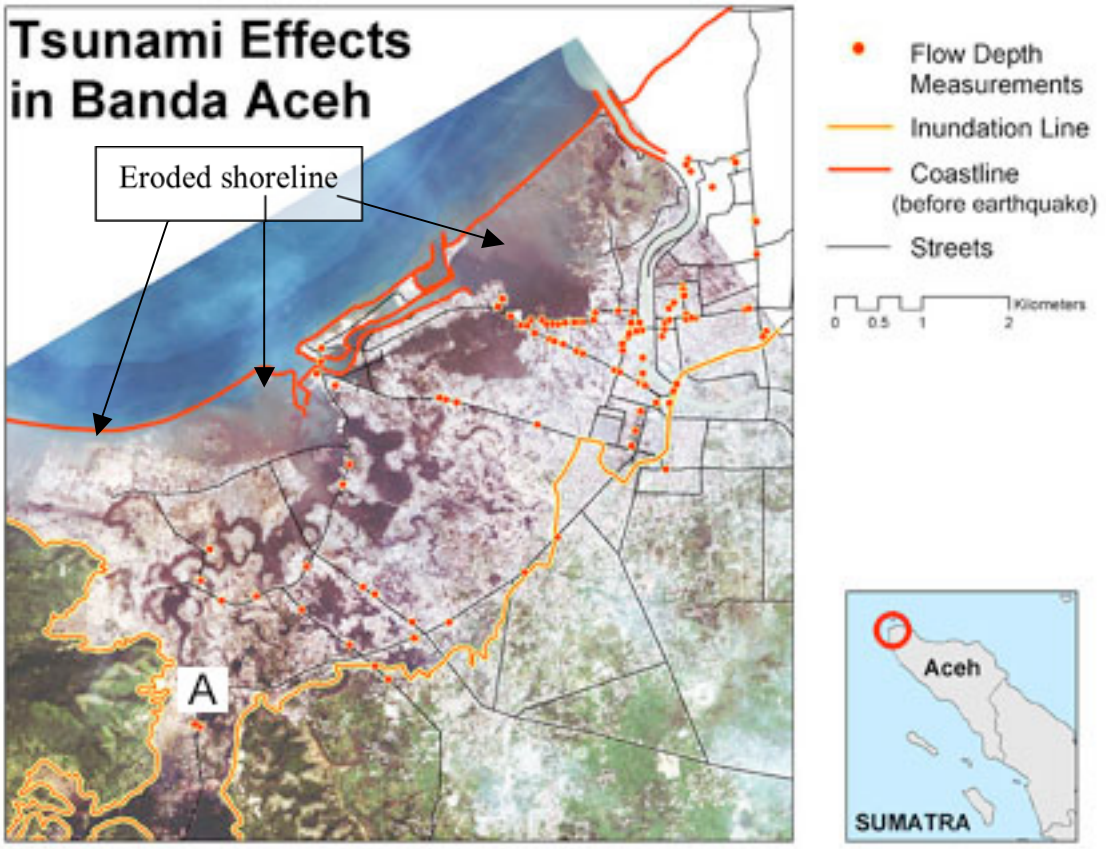

Figure 6: Satellite image of Banda Aceh after the earthquake and tsunami.

Inundated area.

A witness interviewed at location A in figure 6 reported a wave approach from 'both directions'. Analysis of satellite imagery taken after the tsunami clearly shows that the tsunami inundated across the northwestern tip of Sumatra. Digital elevation data show an area of low elevation cutting across a small ridge. Figure 7 shows the extent of inundation in the vicinity of Banda Aceh and Lhoknga. The tsunami wave fronts were able to cut across the northwestern tip of Sumatra.

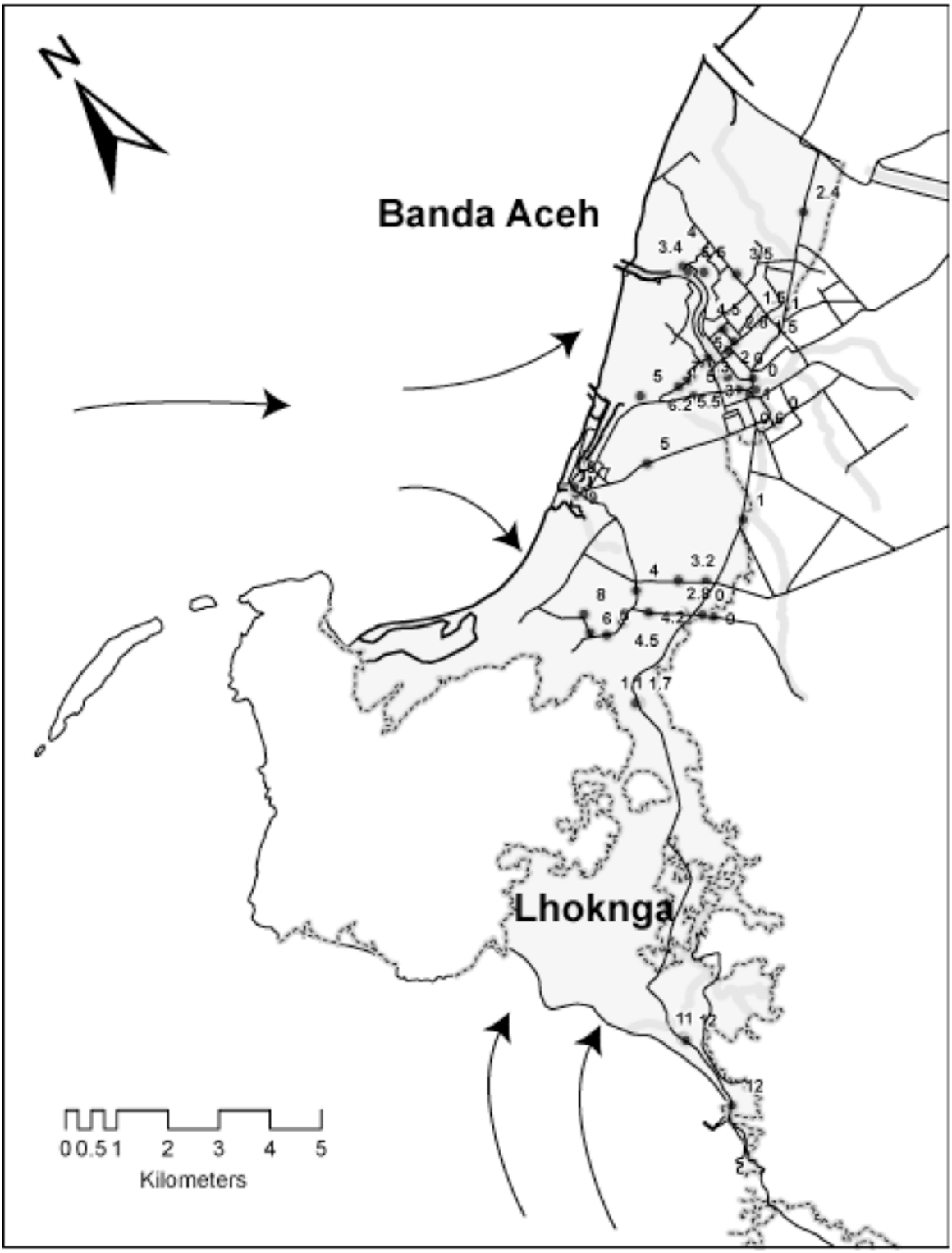

Figure 7: The over wash area between Lhoknga and Banda Aceh.

Conclusions

A field survey of the earthquake and tsunami effects in the region around Banda Aceh in northern Sumatra was conducted. Maximum runup and wave height traces were observed on the open west coast near the town of Lhoknga. Runup heights here exceeded 30 m. In the city of Banda Aceh the tsunami resulted in sustained flow depths of over 9 m at the shoreline. Flow depth values tapered landward to the limit of inundation, which was more than 3 km inland.

Other locations surveyed included Idi and Panteraja on the east coast where runup heights were 2.5 and 5 m respectively. At Kreung Raya 45 km east of Banda Aceh, the site of a marine oil transfer facility, sustained flow depths were measured at 5 m and runup was estimated to be 6 m. At another site between Kreung Raya and Banda Aceh runup was measured to be 8 m.

This data set is far from complete and additional surveys will be needed to fully assess the tsunami effects between Meulaboh and Banda Aceh, the coastal region that probably experienced the largest tsunami waves during this event.

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Table 1: Measured flow depths and directions.

Flow Depth Measurements				
Location Number	Latitude (deg)	Longitde (deg)	flow depth (m)	flow direction (towards, deg)
001	4.95193	97.76513	1.00	
002	4.96653	97.77177	0.95	
005	5.25843	96.18423	1.50	
011	5.55287	95.31903	0.60	
014	5.56123	95.31987	3.40	
015	5.56145	95.32035	2.60	
023	5.55758	95.31757	2.00	
027	5.5603	95.31622	3.00	
029	5.55973	95.31607	4.50	
030	5.56118	95.31637		120
031	5.56232	95.31663	3.00	
032	5.56242	95.31507	5.00	
033	5.56227	95.31268		130
034	5.5615	95.31248	6.20	130
035	5.56128	95.31133	6.20	
038	5.5612	95.30957	7.00	
044	5.56093	95.30557		180
045	5.56097	95.30493		120
047	5.56292	95.30258		150
048	5.56373	95.30307	5.00	
053	5.55827	95.3107	5.00	
058	5.55488	95.31763	1.80	
059	5.5547	95.31782	1.35	
060	5.56008	95.31617		
061	5.55838	95.31547		120
062	5.55902	95.31543	5.50	
063	5.51958	95.27158	1.10	180
064	5.51952	95.27158		
065	5.5198	95.27107	1.70	
066	5.47102	95.24362		60
067	5.47033	95.24283		
068	5.46872	95.24318		60
069	5.46657	95.24383	11.00	
070	5.46598	95.24397	12.00	
074	5.45182	95.24395	12.00	
077	5.5737	95.34528	2.40	
085	5.61395	95.39835	5.00	
086	5.61697	95.39807	6.25	
097	5.5886	95.51422	2.45	
099	5.58983	95.51657	5.00	
100	5.58843	95.5164	4.80	
106	5.55332	95.29717	5.00	
110	5.55608	95.2838	9.00	
111	5.5573	95.28427	9.00	
113	5.55483	95.28573	7.00	

Table 1 (cont.): Measured flow depths and directions.

Number	Latitude (deg)	Longitde (deg)	flow depth (m)	flow direction (towards, deg)
115	5.55292	95.31893	1.00	
117	5.55482	95.32108	0.00	
118	5.55288	95.32032	0.00	
119	5.51413	95.42617	0.00	
137	4.87768	95.39813	8.00	
138	4.87818	95.39897	9.00	
139	4.87802	95.39947	7.50	
146	5.56492	95.32173	4.50	
151	5.56203	95.32207	2.80	
155	5.56253	95.32817	1.50	
156	5.56263	95.3286	1.50	
158	5.57162	95.32937	3.50	
159	5.57813	95.32705	4.00	
161	5.57812	95.32235	3.40	
163	5.57687	95.32262	6.00	
164	5.57522	95.32483	5.00	
166	5.56027	95.33035	1.00	
168	5.54603	95.31992	0.00	
169	5.5354	95.30527	1.00	
170	5.53027	95.29362	2.40	
173	5.53608	95.28268	4.00	
174	5.53302	95.27748	4.50	
175	5.53468	95.2717	6.00	
176	5.53792	95.27268	8.00	
177	5.53258	95.27388	5.00	
178	5.5316	95.2822	4.20	
179	5.52797	95.28707	2.80	
180	5.52438	95.29108	0.00	
181	5.52577	95.28972	0.00	

Table 2: Measured runup heights.

Runup Measurements				
Location Number	Location Name	Latitude (deg)	Longitde (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		5.65125	95.4231	8.0

Selected Photos

Photo1: The prawn hatchery at Idi. Note how only the lower portion of the wall paneling was damaged.

Photo 2: The prawn hatchery at Idi. The tsunami wave did not over top the hatching tank.

Photo 3: The beach front at Idi. Light wood or brick structures on the shoreline were destroyed by the tsunami.

Photo 4: A flow depth indicator along the profile in Panteraja.

Photo 5: The extent of inundation in Panteraja. The tsunami wave covered the rice fields to the tree line in the distance.

Photo 6: The tower at the Grand Mosque in central Banda Aceh. The water reached this section of town and the earthquake damaged the tower. This photo was taken 3 km from the open sea.

Photo 7: Debris left in the river at Banda Aceh.

Photo 8: An example of a clear flow depth indicator. Roof tiles were removed by the flooding wave.

Photo 9: A well-built reinforced concrete structure survived the tsunami while other poorly built structures around it did not.

Photo 10: The freighter capsized at Lhoknga.

Photo 11: Bark stripped from the tree. Note the 5 m staff. Flow depths were over 10 m.

Photo 12: The view from the high water mark at Lhoknga. Note the coal barge in the foreground, the trim line along the base of the hill and the capsized freighter at the jetty in the distance.

Photo 13: The trim line at a small headland at Lhoknga. This hill was previously covered by dense jungle to the waterline.

Photo 14: Evidence of 5 m flow depths at Kreung Raya oil transfer station.

Photo 15: An example of the scale of inundation along the west coast of Sumatra.

Photo 1

Photo 2

Photo 3

Photo 4

Photo 5

Photo 6

Photo 7

Photo 8

Photo 9

Photo 10

Photo 11

Photo 12

Photo 13

Photo 14

Photo 15