Northern Sumatra Field Survey after the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami

Jose C. Borrero,[a] Costas E. Synolakis,[b] and Hermann Fritz[c]

A field survey of earthquake and tsunami effects was conducted in the region around Banda Aceh in northern Sumatra. The field data included visual observations of watermarks, which were located via handheld GPS units and then photographed. Where possible, watermarks were surveyed along cross-shore profiles to determine runup height. Additional information on wave arrival and behavior—including the timing and the number of waves—was collected through interviews with witnesses and survivors and from video recorded during the tsunami event. These data were 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. This data set is far from complete, and additional information is needed to fully assess the tsunami effects in northern Sumatra. [DOI: 10.1193/1.2206793]

INTRODUCTION

On Sunday, 26 December 2004 at 00:58 UTC (07:58 local time 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. 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. This report summarizes data collected on two trips to Banda Aceh in January and February 2005. The first trip was on 4–9 January 2005, with a follow-up visit on 22–25 February 2005.

[a] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089-2531; E-mail: jborrero@usc.edu and ASR Ltd. Marine Consulting and Research, Raglan, New Zealand; E-mail: j.borrero@asrltd.co.nz
[b] Department of Civil Engineering, University of Southern California, Los Angeles, CA 90089; E-mail: costas@usc.edu and Department of Environmental Engineering, Technical University of Crete, 73100, Chania, Greece
[c] School of Civil and Environmental Engineering, Georgia Institute of Technology, Savannah, GA 31407-3038

Note: Portions of this manuscript and selected figures were published previously in a special insert of the March 2005 ***EERI Newsletter*** **39** (3), as well as in Borrero, J. C., 2005. ***Seismol. Res. Lett.*** **75** (3), 312–320.

Earthquake Spectra, Volume 22, No. S3, pages S93–S104, June 2006; © 2006, Earthquake Engineering Research Institute

Table 1. Measured runup

Location	Latitude (°)	Longitude (°)	Runup (m)
Idi	4.96653	97.77177	2.5
Panteraja	5.2611	96.18528	4.2–4.7
Lhoknga	5.45777	95.24513	31.0
E. of Banda Aceh	5.65125	95.4231	8.0
Breuh Island	5.67	95.1296	20.1
Deudap Island	5.602	95.14	10.7

POST-TSUNAMI FIELD SURVEYS

The goals of a post-tsunami field survey are to document inundation, which is the horizontal extent of water penetration; to document runup, which is the maximum vertical elevation of the land flooded; and to collect information on the number and timing of waves and the sequence of events. The field data collected in Banda Aceh and nearby areas consisted of visual observations of watermarks, which were located via handheld GPS units and then photographed. Where possible, watermarks were surveyed along cross-shore profiles to determine runup height. Additional information on wave arrival and behavior—including the timing and the number of waves—was collected through interviews with witnesses and survivors and from video recorded during the tsunami event. These data were 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 OBSERVATIONS

The runup data collected and the 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. A complete list of georeferenced flow depth measurements is provided in Borrero (2005). 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.

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. Farther north at Idi, residents reported feeling earthquake shaking for 10 minutes. About 1.5 hours after the earthquake, witnesses reported seeing the ocean recede more than 500 m. The tsunami came in as two waves, with the larger wave second. A cross-shore profile of the inundation zone shows an inundation distance of over 500 m inland and a maximum water height of 2.5 m above sea level (Figure 2, upper panel). One can infer an upper limit on the wave height at the shoreline from the observation that tanks at a prawn hatchery were

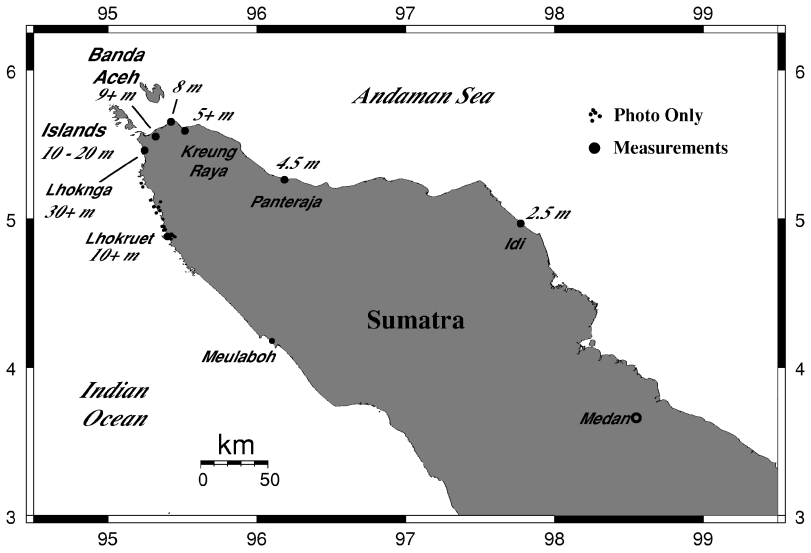

Figure 1. Survey sites, with a representative value for the maximum wave height or runup at each location.

not overtopped. Wood construction at the shoreline was destroyed, while reinforced concrete (RC) construction generally survived. There were no fatalities. The local residents said that locally stationed Navy personnel warned them that a tsunami was coming; however, they also reported that many people ignored the warning.

Continuing north along the coast, we observed the damage at Panteraja. Residents stated that the shaking lasted for approximately 10 minutes. The shaking was severe in this area: residents reported not being able to walk or even squat during the shaking, and that they were knocked to the ground. They 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. The tsunami effects were more severe here than at Idi. The tsunami attack began with an initial withdrawal about 30 minutes after the earthquake. Local residents reported three waves, with the third being the largest. The wave penetrated up to 1 km inland and attained a height of 4.2–4.7 m above sea level at the time of the tsunami (Figure 2, lower panel).

BANDA ACEH

Banda Aceh lies on a river delta created as the Aceh River flows into the Andaman Sea. The river has two large branches, one running through the center of town and the other 15 km to the east. 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 Uleelheule had significant structures been built on the shoreline (Figure 3).

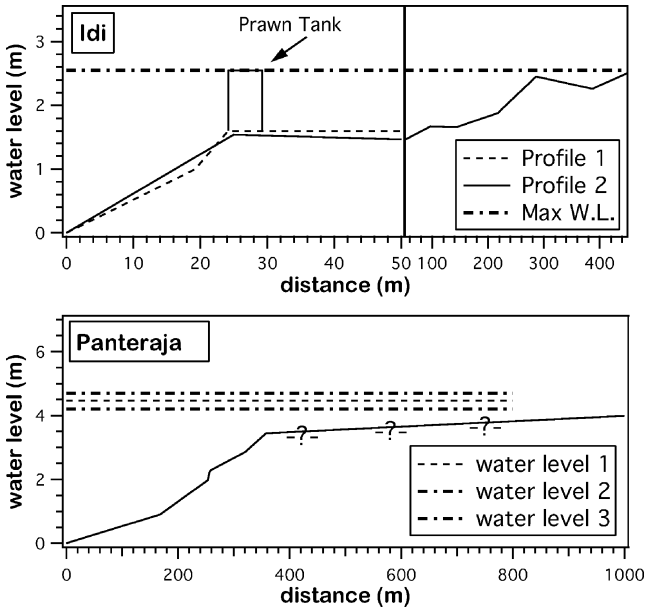

Figure 2. Cross-shore profiles at Idi and Panteraja. The question marks on the Panteraja profile indicate that this was not directly surveyed; however, the land was made up of relatively flat agricultural fields, and the inundation distance was on the order of 1 km.

Banda Aceh was strongly affected by the earthquake, with several collapsed buildings and evidence of structural damage in large RC structures. One resident reported that he was unable to stand during the shaking, 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 (Figure 3), described being able to close his shop after the earthquake and travel to another shop that he owned closer to the ocean. He then traveled back to his house before returning to the first shop. By the time he reached that first shop, the water was in the center of Banda Aceh. From this route, he estimated that 25 minutes had elapsed from the time of the earthquake until the water reached the area near the Grand Mosque.

The inundation line was observed to lie 3–4 km inland throughout the city. Flow depths over the ground were observed to be over 9 m in the seaside section of Uleelheule 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 toward 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 flow depth was just at the level of the second floor, and there were large amounts of debris piled along the streets and in the ground-floor storefronts. A survivor

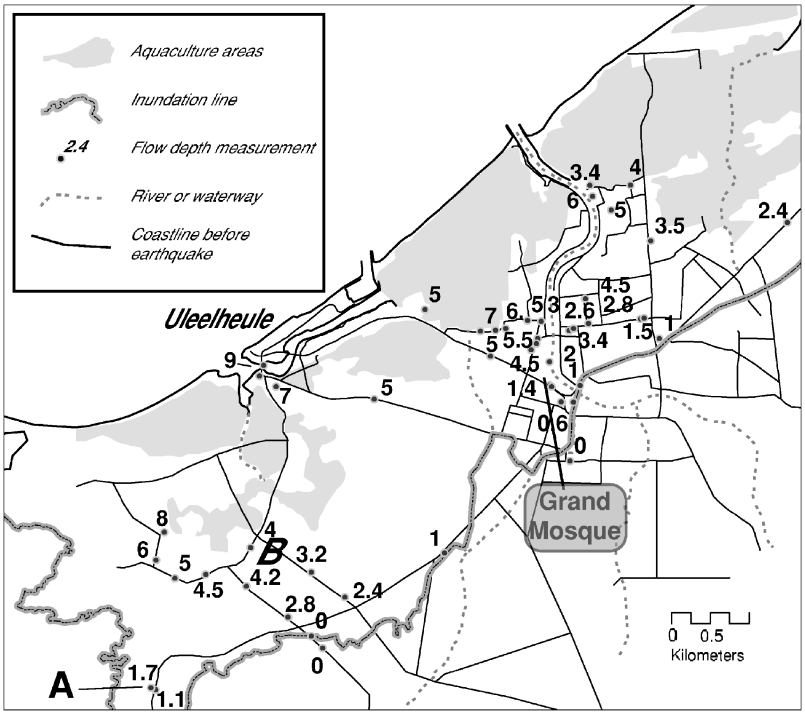

Figure 3. Banda Aceh, with numerals indicating the flow depth measured above the ground level at each location.

of the tsunami from Uleelheule 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 arrived.

KREUNG RAYA

The oil transfer facility of Kreung Raya is located 45 km east of Banda Aceh. The earthquake was felt very strongly at this location, but it did not cause severe damage to structures. The extent of inundation was on the order of 1 km, and flow depths were observed to be 5 m throughout the inundation zone. Of the nine oil storage tanks located at the site, three were moved over a distance of several hundred meters (Goto 2005). The tanks were probably floated off their foundations during the return flow of the tsunami, as their final resting place was seaward of the initial location. The unmoved tanks were either undamaged or only slightly damaged from the impact of the moved tanks. Detailed investigation by Goto (2005) determined that the moved tanks were the least full at the time of the tsunami.

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

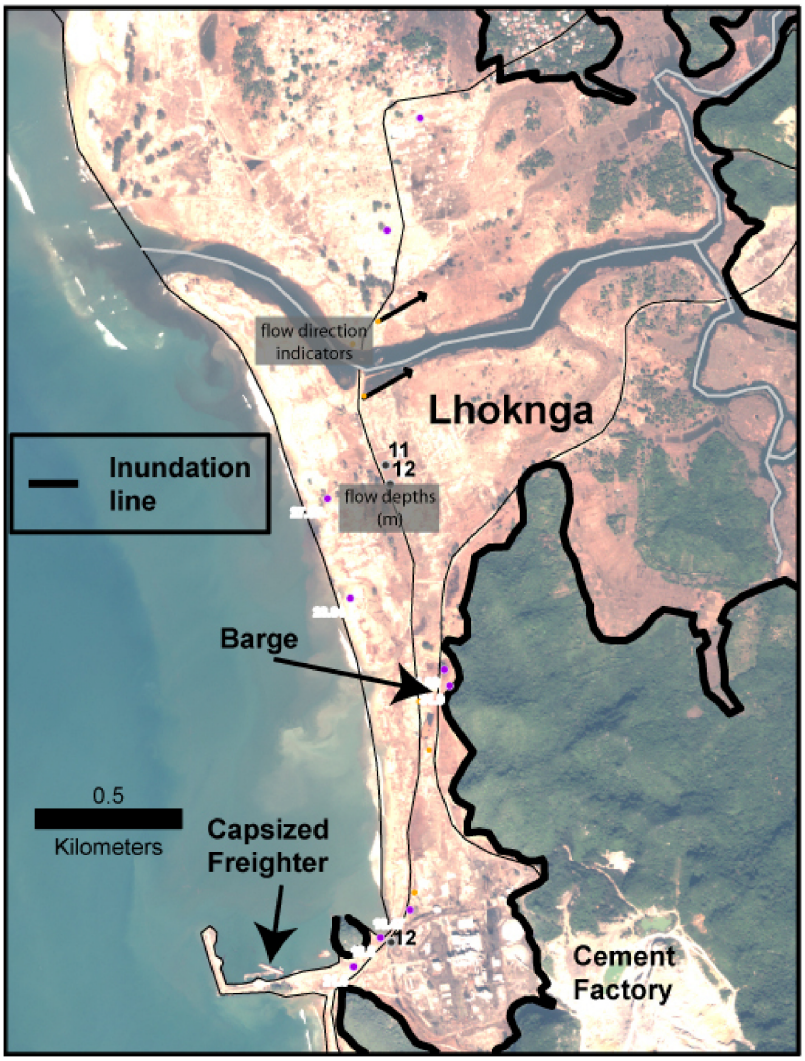

Figure 4. Satellite photo of the shoreline after the tsunami in the area around Lhoknga. The heavy black line marks the limit of tsunami inundation.

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 the open Indian Ocean and the epicenter of the earthquake. On the beach at Lhoknga (Figure 1), stripped bark on trees indicated a sustained flow depth of over 13 m at the shoreline. A cement factory at the south end of the beach (Figure 4)

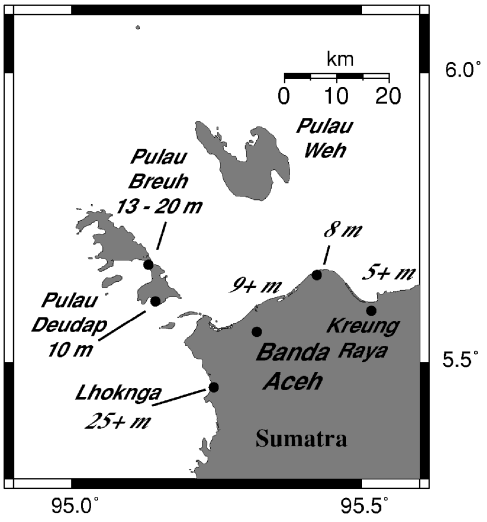

Figure 5. The northern tip of Sumatra, and nearby islands.

was severely damaged by the tsunami. The waves penetrated well over 1 km inland here and reached a height of 20 m above the ground level while stripping the steel siding off of the exterior walls of the factory. There were two large ships that were affected by the tsunami. A 90-m 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 (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 visually estimated to be 20–25 m. The trim line is also clearly visible in satellite imagery (Figure 4). During a follow-up survey, a maximum runup point was measured at 31 m on a steep hill at the shoreline fronting the cement factory.

ISLANDS NORTH OF BANDA ACEH

To the north of Banda Aceh lie three small islands: Weh, Breuh, and Deudap (Figure 5). The tsunami effects on two of the islands (Breuh and Deudap) were extreme, with a runup of 10–20 m on the west-facing shores. Coastal villages were completely destroyed by the tsunami waves. On Pulau Weh, however, the situation was different. This island experienced strong surges in the port of Sabang, yet there was little damage. Tsuji et al. (2005a) reported runup values of 3–5 m on Pulau Weh, which was most likely shadowed from the direct tsunami attack by the islands to the southwest.

MAXIMUM RUNUP

At Lhoknga, flow depth evidence including bark stripped from trees on the shoreline suggests 12–15 m of sustained flow depth. Initially, the runup was conservatively esti-

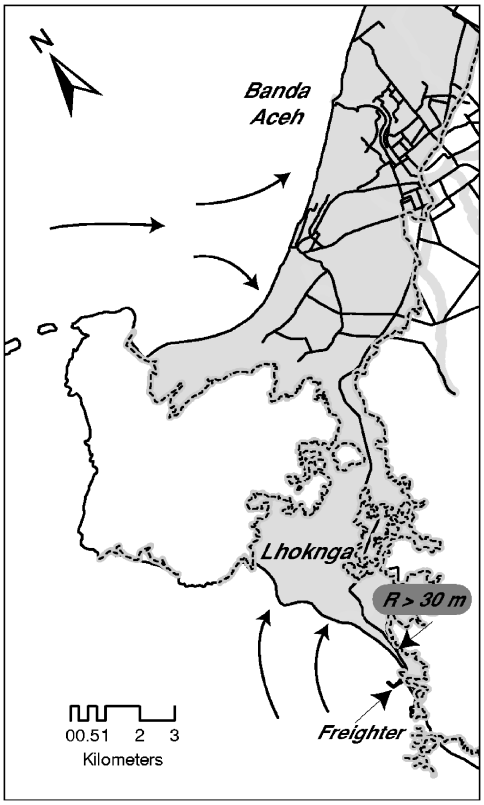

Figure 6. An overview of the tsunami-inundated area between Banda Aceh and Lhoknga. Also shown is the location of the freighter that had capsized.

mated to be 20–25 m. In the second field survey, the maximum runup was measured at 31.5 m via a laser rangefinder. The height of the trim line along the hills behind the beach was 22–27 m. The GPS locations of the high water marks were compared with satellite imagery and a 90-m digital elevation model (CIAT 2004). The satellite imagery of the high water mark lines up with a 24-m pixel in the digital data and provides a first-order check to the initial field estimate.

INUNDATED AREA

A witness interviewed at location A in Figure 3 reported that a wave approached from "both directions." Analysis of post-tsunami satellite imagery clearly shows that this would be possible if the tsunami wave attacking Lhoknga inundated across the northwestern tip of Sumatra to meet the incoming wave at Banda Aceh. Indeed, the digital elevation data show an area of low elevation cutting across a small ridge. Figure 6 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. To the extent that the

Figure 7. Still frames from a video that was recorded at location B in Figure 3, looking west. The upper frame shows the tsunami attack; the lower frame shows the post-tsunami damage. The flow is 2–3 m deep, as indicated by the water level at the house.

available satellite imagery enabled measurements to be made, it appeared that the total inundated area between Lhoknga and Banda Aceh was on the order of 65 km^2.

ANALYSIS OF VIDEO IMAGERY

Video images recorded before, during, and after the tsunami attack reveal many notable features of the event. By comparing features and landmarks in the background of the videos, we were able to precisely locate where each video was recorded. Figure 7 shows a house during and after the tsunami; the house is near location B in Figure 3. A sustained flow depth of approximately 2.5 m is clear from this image. Figure 8 shows

Figure 8. Still frames from a video recorded at the grounds of the Grand Mosque. The upper panel shows the leading edge of the tsunami wave as residents run to escape. The lower panel shows the same location moments later, as the debris-laden tsunami inundation moves through the street. From the video, flow velocities were estimated to be on the order of 15 m/sec.

Figure 9. A panoramic photo of the street corner shown in Figure 8. This photo was taken from the precise location used by the videographer in Figure 8.

two frames from a video recorded near the Grand Mosque in the center of Banda Aceh. At this location, the effects of the flow being channeled through narrow city streets can be seen. Flow speeds of 10–15 m/sec. were estimated from tracking single particles over a set distance in the video frame. The video from the city center location clearly shows that the flood depth did not reach the level of the second floor in these buildings. Figure 9 shows what this street corner normally looks like. A detailed analysis of the flow characteristics at different locations on the basis of video imagery is currently under way.

SUMMARY AND CONCLUSIONS

A field survey of the earthquake and tsunami effects in the region around Banda Aceh in northern Sumatra was conducted. The highest runup and wave height traces were observed to the southwest of Banda Aceh, on the open west coast near the town of Lhoknga. Runup heights here exceeded 30 m (Tsuji et al. 2005b). In the city of Banda Aceh, the tsunami had 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, which is 45 km east of Banda Aceh and is 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.

An analysis of video and still images recorded before, during, and after the tsunami were used to estimate flow depths and flow speeds. The leading edge of the tsunami is shown to approach slowly and then increase in speed. The leading edge of the tsunami propagated at approximately 2 m/sec. and then increased to 10 or 15 m/sec., with faster flow speeds in the constricted narrow streets of Banda Aceh's downtown area.

ACKNOWLEDGMENTS

Travel support was provided by the Earthquake Engineering Research Institute (EERI) through its National Science Foundation grant CMS-0131895. On the ground, logistics and travel support were arranged for and provided by the National Geographic

Society. Aubrey Dugger and GreenInfo Networks provided vital GIS support, and satellite imagery was provided by Digital Globe. Additional photos, video, and text from the Banda Aceh survey can be seen at the University of Southern California's Tsunami Research Group web site, http://www.usc.edu/dept/tsunamis

REFERENCES

Borrero, J. C., 2005. Field survey of northern Sumatra and Banda Aceh, Indonesia after the tsunami and earthquake of 26 December 2004, *Seismol. Res. Lett.* **75** (3), 312–320.

Goto, Y., 2005. Tsunami damage to oil storage facilities in Aceh Province, Sumatra, Indonesia, *Memorial Conference on the 2004 Giant Earthquake and Tsunami in the Indian Ocean, Tokyo, Japan December 14–15, 2005.* http://www.eri.u-tokyo.ac.jp/sumatra/Abstract051202b.pdf.

International Centre for Tropical Agriculture (CIAT), 2004. Hole-filled seamless SRTM data V1. http://srtm.csi.cgiar.org/index.asp

Stein, S., and Okal, E. A., 2005. Size and speed of the Sumatra earthquake, *Nature* **434**, 581–582.

Tsuji, Y., Namegaya, Y., and Ito, J., 2005a. Astronomical tide levels along the coast of the Indian Ocean Unpublished Internet report. http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/tide/index.htm

Tsuji, Y., Matsutomi, H., Tniaoka, Y., Nishimura, Y., Sakakiyama, T., Kamataki, T., Murakami, Y., Moore, A., and Gelfembaum, G., 2005b. Distribution of the tsunami heights of the 2004 Sumatra tsunami in Banda Aceh measured by the tsunami survey team Unpublished Internet report. http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/surveylog/eindex.htm

(Received 6 October 2005; accepted 1 May 2006)