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STATE OF BANDA ACEH BEACH BEFORE AND AFTER THE TSUNAMI

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The Great Sumatra Earthquake of December 26, 2004 and resulting tsunami largely devastated the coastal zone of Banda Aceh, Sumatra, Indonesia, because it was located so close to the epicenter. Sustainable management of the coastal zone of Banda Aceh in future requires knowledge about the impact of the tsunami on the coast of Banda Aceh and knowledge on the morphological development of the coastal zone since the tsunami. Therefore, the aim of this paper is to quantify the changes in coastline due to the tsunami and to determine the sediment composition before and after the tsunami. Changes in coastline were derived from satellite images and revealed that the coastline retreat is in the order of several hundred meters. Grain sizes of tsunami deposits, determined from samples taken five months after the tsunami, varied from 90 – 210 µm. This is within the range of grain sizes observed in the nearshore zone before the tsunami, indicating that the sediment composition did not change significantly due to the tsunami and that the source of tsunami deposits was probably the nearshore zone of the Banda Aceh coast.

INTRODUCTION

On December 26th 2004, 7:58 hr local time (i.e. North Sumatra Time = GMT + 7 hours), South-East Asia was hit by an earthquake with a magnitude of at least 9.0 (Stein and Okal 2005), often referred to as the Great Sumatra Earthquake. The epicenter was located at the Indian Ocean, about 150 km west of the island of Sumatra (see Fig. 1a). The earthquake generated a tsunami, which lead to immense flooding in many coastal areas along the Indian Ocean.

Nanggroe Aceh Darussalam, one of the provinces of the Republic of Indonesia, and its capital Banda Aceh were among the most severely hit areas, being so close to the epicenter (see Fig. 1b). The earthquake caused severe land subsidence in the area around Banda Aceh, i.e. about 2 m at the west coast and about 0.3 – 0.6 m at the northwest coast (e.g. Gibbons and Gelfenbaum 2005). The tsunami caused large inundation depths, severe coastal erosion and large tsunami deposits inland (Tsuji et al 2005; Jaffe et al. 2005) and destroyed almost

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everything in the coastal zone of Banda Aceh. Sustainable management of the coastal zone of Banda Aceh in future requires knowledge about the impact of the tsunami on the coast of Banda Aceh and knowledge on the morphological development of the coastal zone since the tsunami.

Figure 1. (a) Location of epicenter of Great Sumatra Earthquake, west of Sumatra, Indonesia (left panel) (b) Location of Banda Aceh, capital of Aceh province, Sumatra, Indonesia (right panel).

Therefore, the first objective of the current study is to quantify the changes in coastline due to the tsunami and since the tsunami. This is achieved by analyzing satellite images taken before and directly after the tsunami. In addition, beach profiles and some developments of the coastline have been observed in May 2005 and August 2006.

In order to understand the morphological development since the tsunami, it is important to have information on the sediment composition in the coastal zone before and after the tsunami, which is the second objective of this study. This is realized by collecting information from literature about sediment composition before the tsunami and by some measurements of sediment composition five months after the tsunami, carried out during a field study in May 2005.

This paper starts with a general description of the coastal zone of Banda Aceh. Next, the state of Banda Aceh beach before the tsunami is presented in terms of (i) position of the coastline and global bathymetry and topography of the coastal zone and (ii) sediment composition in the coastal zone. Then the state of Banda Aceh beach within half a year after the tsunami is presented in terms of (i) changes in coastline position due to the tsunami and (ii) composition of sediment on and near the beach half a year after the tsunami. Finally, some field observations of the state of Banda Aceh beach over a period of 1,5 years since the tsunami are presented in terms of beach recovery for the west coast and developments at the northwestern coastline. The paper closes with a short discussion on the results and some first conclusions that can be drawn from this study.

GENERAL DESCRIPTION OF BANDA ACEH BEACH

Banda Aceh, the capital of Nanggroe Aceh Darussalam, is a city of about 300,000 inhabitants, located at the northern tip of Sumatra Island. Banda Aceh beach is about 25 km long and stretches between the headlands Ujong Pancu and Ujong Batee. It is surrounded by the Indian Ocean on the west, the Andaman Sea on the north, and the Straits of Malacca on the east. Clear landmarks in the coastal area are a ferry port (partly submerged after the tsunami), and two branches of Krueng Aceh River. One of the branches is an artificial floodway channel (see Fig. 2).

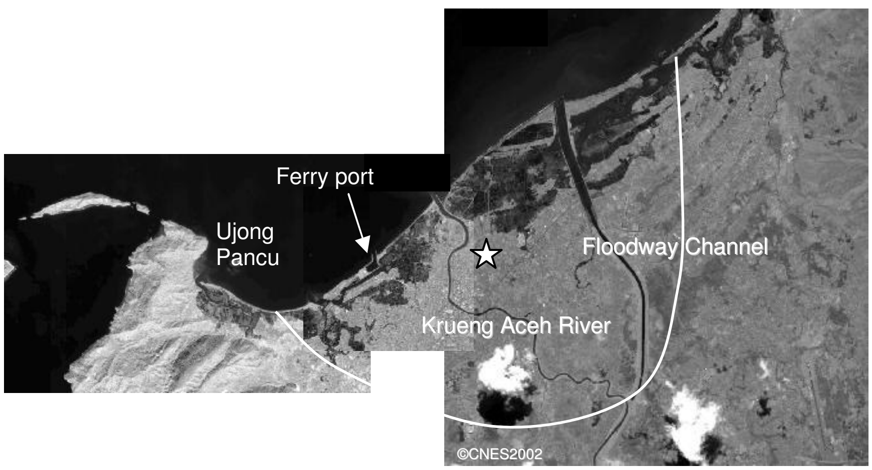

Figure 2. SPOT satellite image of Banda Aceh beach, showing Ujong Pancu headland, Krueng Aceh River and the artificial Floodway Channel. The white line indicates the location of the urban area of Banda Aceh and the white star the location of the city center.

Before the tsunami, the coastal area of Banda Aceh was intensively used for human activities, such as housing, fish ponds, shrimp ponds, tourism and small industries. The fish and shrimp ponds are visible in Fig.2 as the dark-colored areas to the sides of the floodway channel.

STATE OF BANDA ACEH BEACH BEFORE THE TSUNAMI

Coastline, Global Bathymetry and Topography

The coastline of Banda Aceh between the headlands is formed by rather narrow sandy beaches. In front of the coastline, a continental shelf exists with depths of up to 200 m. On the east side, at the Strait of Malacca, the continental shelf is very narrow, whereas on the northwestern and eastern side of Banda Aceh beach a somewhat wider continental shelf exists. Beyond the continental shelf, the abyssal plain of the Andaman Sea has depths of 1000-2000 m (see e.g. Rodolfo 1969, Thomascik 1997).

Beach profiles have slopes varying between 1:50 and 1:300. Along the northwestern coast, the steepest beaches are located near Ujong Pancu Headland. Syiah Kuala beach (between Krueng Aceh River mouth and the Floodway Channel) has slopes of about 1:200. At the eastern part of the northwest coast (between Krueng Aceh River mouth and Ujong Batee Headland), the beach has a slope of about 1:300 (Anonymous, 2003). At Syiah Kuala beach, the tidal range varies between about 0.5 and 1.3 m (Anonymous, 2003), indicating that the intertidal area here has a width of about 100 – 260 m.

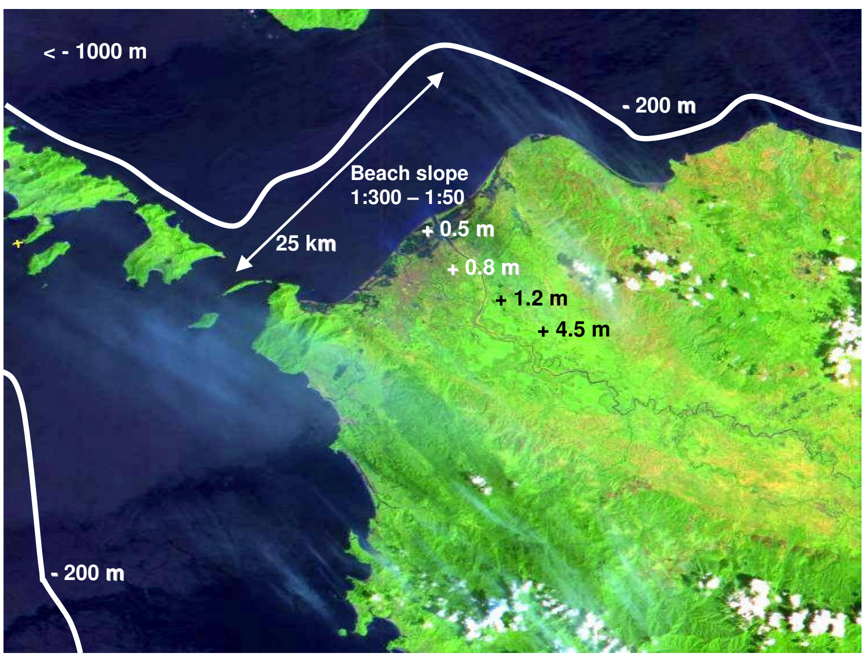

Figure 3. Summary of findings on coastline, bathymetry and topography of Banda Aceh beach before the tsunami, overlaid on a satellite image of the area.

The city of Banda is located in between the headlands, in the valley of Krueng Aceh river. This area is relatively flat with elevations going up from about 0.5 m above mean see level, close to the coastline, to about 4.5 m above mean see level at a distance of about 10 km inland.

The presented findings about the coastline, and global bathymetry and topography of Banda Aceh beach before the tsunami are summarized in Fig. 3

Sediment Composition in the Coastal Zone

Some information is available about the sediment composition of the coastal area of Banda Aceh before the tsunami. The seabed of the deep abyssal plain of the Andaman Sea consists of very fine material, i.e. silty clay with grain sizes of 4 – 16 µm (Rodolfo 1969). The sediments in the sea bed of the Strait of Malacca cover a much wider range with grain sizes varying between 12 and 500 µm.

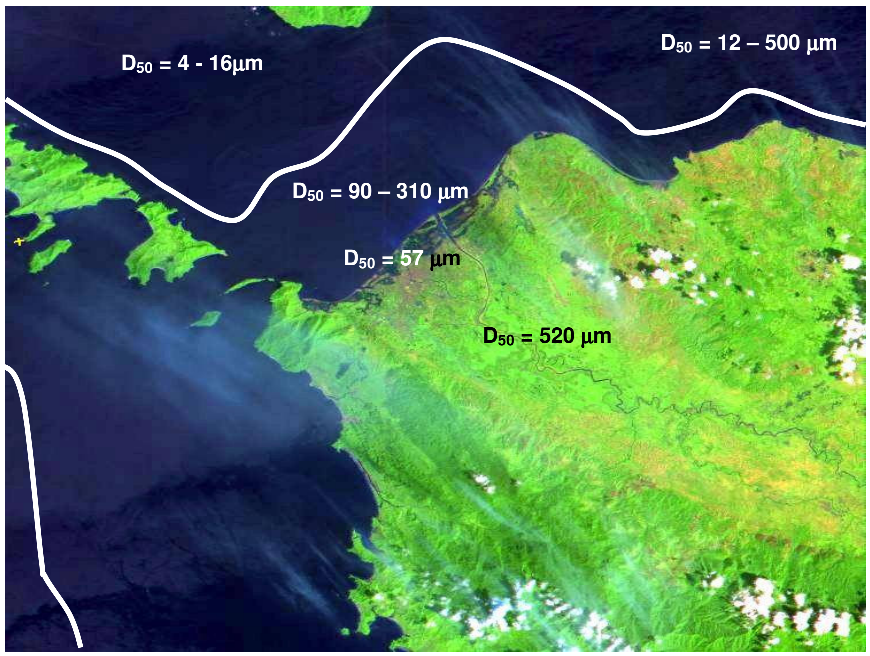

Figure 4. Summary of findings on sediment composition in the coastal zone of Banda Aceh beach before the tsunami, overlaid on a satellite image of the area (for reference the 200 m depth contour, indicating the edge of the continental shelf is included in the figure, i.e. the thick white line).

In 2003, the Hydraulic Laboratory of Syiah Kuala University in Banda Aceh carried out a survey for the design of Syiah Kuala beach (located between Krueng Aceh River mouth and the Floodway Channel). During this survey sediment samples were taken in the nearshore zone which revealed that the coastal profile consists of very fine to medium sand with median grain sizes of 90 – 300 µm (Anonymous 2003). Part of this sediment is brought into the coastal zone by Krueng Aceh River. At a distance of about 10 km from the river mouth, the sediment in the river has a median grain size of about 520 µm, whereas very close to the river mouth it is much finer with a median grain size of about 57 µm. The presented findings about the sediment composition in the coastal zone near Banda Aceh before the tsunami are summarized in Fig. 4.

STATE OF BANDA ACEH BEACH WITHIN HALF A YEAR AFTER THE TSUNAMI

Changes in Coastline Position due to the Tsunami

To quantify the changes in coastline position due to the tsunami, three satellite images from three different dates have been analyzed, i.e. one image from before the tsunami, and two images during/directly after the tsunami:

1. Landsat7 ETM image
   15 August 2001
   resolution: 30 m
2. SPOT image
   26 December 2004, 11.23 hrs. local time (= 3.5 hours after earthquake)
   resolution: 20 m
3. Landsat7 ETM image
   29 December 2004 (= 3 days after the earthquake)
   resolution: 30 m

These images were analyzed for the presence of water in the following way: first, the two Landsat7 images were set in the same coordinate system as the SPOT image, which was used as base map. Next, a subset of each image was taken such that the corners of these sub-images were located at exactly the same x,y-coordinates. Finally, the position of the waterline in each of these sub-images was delineated (digitized) and connected to the coordinates of the lower left, upper left and upper right hand corner to form polygons that are covered by water in each of the images. The results are presented in Fig. 5, which shows:

1. The areas where no water was observed in any of the three images (the white areas in the figure).
2. The areas where water was observed in all of the three images (these areas are labeled '150801' in the figure).
3. The areas where water was observed in the image of 26 December 2004, but not in the image of 29 December 2004 (labeled '261204' in the figure).
4. The areas where water was observed in the image of 29 December 2004 and in the image of 26 December 2004 (labeled '291204' in the figure).

The areas described under point 1 and 2 are both areas of 'no change' in terms of inundation, i.e. in these areas there was either always land or always water. The combination of the areas described under point 3 and point 4 are the areas that were inundated on 26 December 2004 at 11.23 hrs, i.e. 3.5 hours after the earthquake. At this time, tsunami waves may still have been active in the area, e.g. due to reflections, etc. The areas described under point 4 are the areas that were still inundated on 29 December 2004, i.e. 3 days after the earthquake.

This might indicate that these areas are more or less permanently inundated since the tsunami.

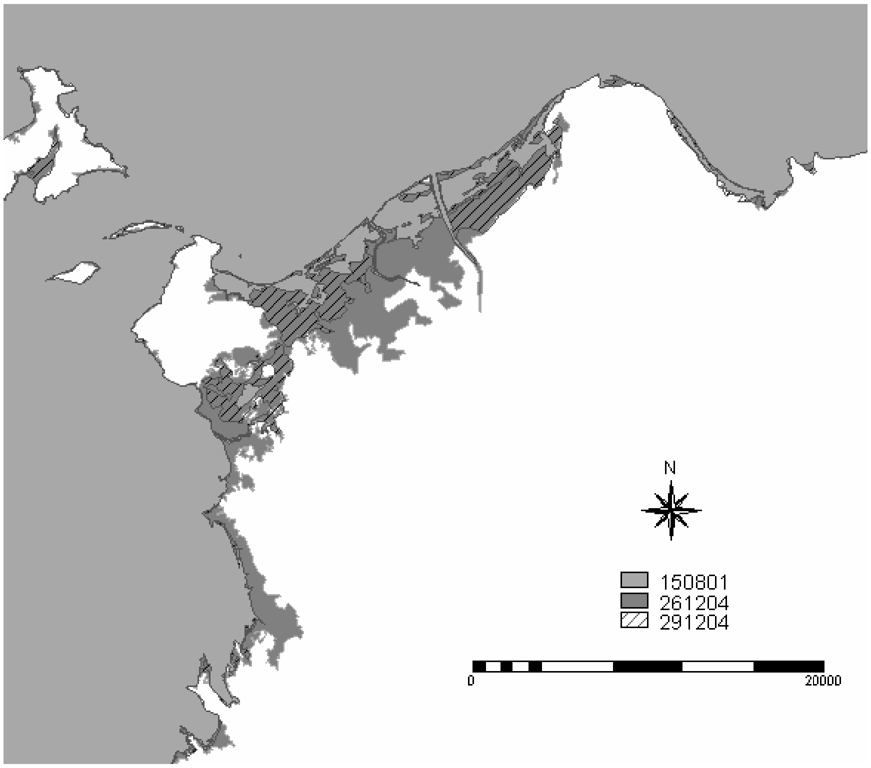

Figure 5. Analysis of satellite images which shows where water was observed on the different dates before and directly after the tsunami (scale bar in meters).

The map presented in Fig. 5 is available within a GIS environment. Therefore, the surface areas of the parts covered by water can be calculated automatically. By subtracting the surface area covered by water at 15 August 2001 from the surface area covered by water at 29 December 2004, the surface area of 'permanently' inundated land due to the tsunami can be determined. This yields the following results:

- Inundated land at the west coast: 10.6 km^2
- Inundated land at the northwest coast: 12.1 km^2

These surface areas are based on satellite images with a minimum resolution of 30 m. Digitizing the waterline may have been accurate to about 1 - 3 grid points (i.e. 30-90 m). Therefore, the estimated accuracy of this calculated surface area is about +/- 0.6 km^2 (or about 6%).

To get an idea of the order of magnitude of coastline retreat, these surface areas are divided by a rough estimate of the length of the coastal stretch (i.e. about 25 km each). This yields the following results:

- Order of magnitude of coastline retreat at the west coast: 422 m
- Order of magnitude of coastline retreat at the northwest coast: 485 m

To understand the morphological development of this coast after the tsunami it is important to determine which part of this coastline retreat is due to subsidence as a result of the earthquake and which part is due to erosion of the beach as a result of the tsunami. Some considerations in this respect are presented in the discussion section of this paper.

Sediment Composition Five Months after the Tsunami

In order to get an idea about the sediment composition in the coastal zone after the tsunami, some sediment samples of tsunami deposits were taken during a field study in May 2005. The question was to investigate whether the sediment composition had changed due to the tsunami. Sediment samples were taken at five locations along Banda Aceh beach, see Fig. 6. The samples were taken to the Soil Mechanics Laboratory of Syiah Kuala University, Banda Aceh for analysis of the physical characteristics of the sediment, i.e. grain size distribution, fall velocity, specific gravity and color (by vision). For grain sizes coarser than 62.5 μm, the grain size distribution was obtained from a sieve analysis, while for the finer grains, grain size distribution was derived from settling velocities, measured using a settling tube.

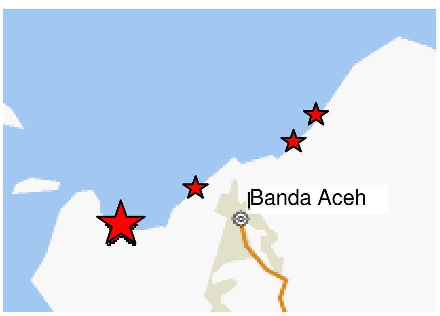

Figure 6. Location along Banda Aceh beach where sediment samples were taken; the big star indicates Peukan Bada

In this paper we present the results for two sediment samples from one location, i.e. Peukan Bada, marked by the big star in Fig. 6. The samples were taken at two positions along the coastal profile. The first position (PB1) was located inland at a distance of about 250 m from the current shoreline and the second position (PB2) was located closer to the coast at a distance of about 110 m from the current shoreline.

The deposit at PB1 (inland) was 7.6 cm thick. Within this deposit, two layers of different sediment textures and colors could be distinguished. The top layer (PB1-top) which had a thickness of 3.0 cm consisted of finer (D_{50} = 110 μm) and darker (dark grey) sediment than the sub layer (PB1-sub; D_{50} = 200 μm, color = light grey), which had a thickness of 4.6 cm. Figure 7 presents the grain size distributions of both samples, which shows that a substantial part of the top layer consisted of very fine material, like silt and clay, i.e. 24% of the sediment in the layer was finer than 74 μm and the sediment had a D_{10} of only 30 μm (D_{50}/D_{10} = 3.7). On the coarse end of the distribution, the variation is smaller with a D_{90} of 240 μm (D_{90}/D_{50} = 2.2). The sub layer contained much less of this very fine material, i.e. only 8% was finer than 74 μm; the D_{10} of the sample being about 93 μm (D_{50}/D_{10} = 2.2). Also for this sample the distribution was narrower for the coarser grains with a D_{90} of about 300 μm (D_{90}/D_{50} = 1.5).

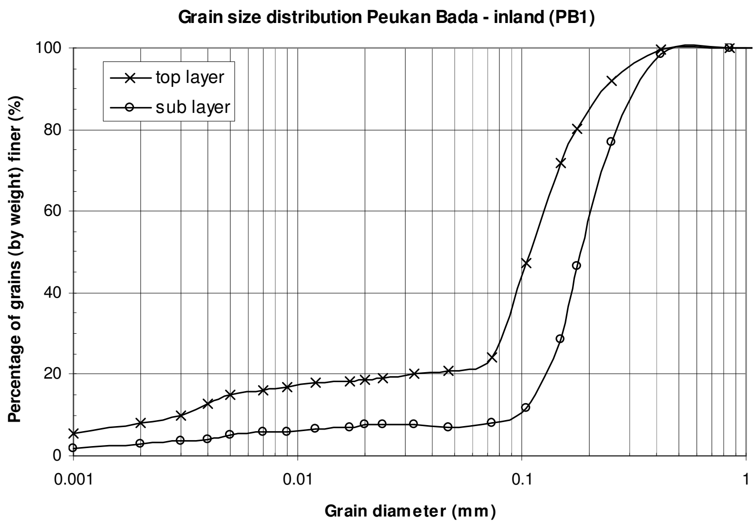

Figure 7. Grain size distribution of samples at PB1 (Peukan Bada, inland)

The deposit at PB2 (coast) consisted of a single sandy layer (with a thickness of 5.1 cm) above the existing ground material. The sediment in this layer had a median grain size of D_{50} = 90 μm. The grain size distribution (see Figure 8) shows that this layer contained even more silt and clay than the top layer of PB1, i.e. 31 % finer than 74 μm and a D_{10} of only 20 μm (D_{50}/D_{10} = 4.5). Again, on the coarse end of the distribution, the variation is much smaller with a D_{90} of about 200 μm (D_{90}/D_{50} = 2.2)

Analysis of the samples collected at the other three locations (see Meilianda et al 2005) revealed that the median grain size of the tsunami deposit varied between 90 and 210 μm. This is well within the range of grain sizes that was observed in this coastal area before the tsunami (i.e. 90 – 310 μm), indicating that the source of the tsunami deposits was probably the sediment from the nearshore zone and that therefore the sediment composition in the coastal region has not changed significantly due to the tsunami.

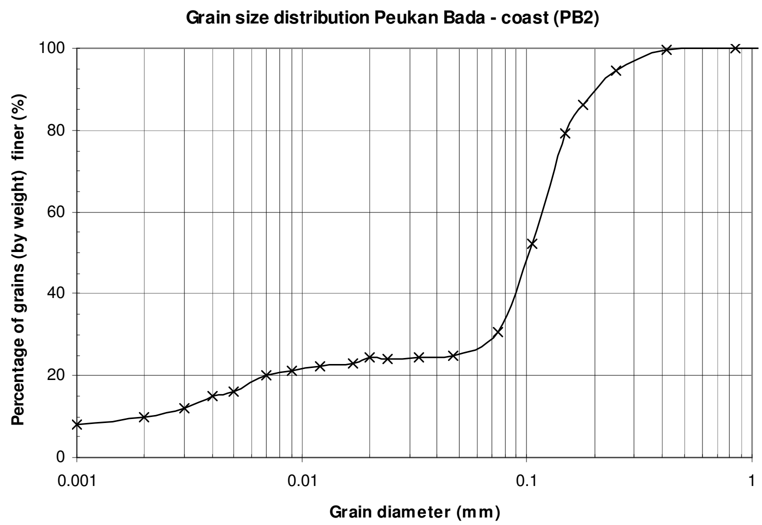

Figure 8. Grain size distribution of samples at PB2 (Peukan Bada, coast)

STATE OF BANDA ACEH BEACH OVER A PERIOD OF 1,5 YEAR SINCE THE TSUNAMI

Field visits to the coast of Banda Aceh in May 2005 and August 2006 showed some remarkable developments. At the west coast, we observed continuous built-up of beaches and development of dunes that were higher than in the pre-tsunami situation. Moreover, we observed a steeper beach face in front of these dunes. So, it seems that a significant recovery of the beach is going on in this area, which seems to be in agreement with other observations (USGS 2004, Dalrymple and Kriebel 2005).

Where former spits/barriers were commonly present along the west coast, the tsunami had virtually removed such features and eroded further on what was previously the landward side of lagoons along the coast. In May 2005, new beaches were being formed, dunes had increased in height rapidly and inlets along the coast had been closed again (by natural processes). Almost all beaches observed in May 2005 had accreted further in August 2006. In some cases, the beaches may be wider than the former beaches, albeit on a much more retreated coastline.

However, developments at the northwestern coast of Banda Aceh seem dominated by human intervention. We observed that a rubble mound shore-parallel breakwater was being constructed. Information from the supervisor of the project tells that this breakwater is constructed along the entire 25 km of the northwestern coastline at the location of the pre-tsunami shoreline, which for part of the coastal stretch was located offshore at the moment of the construction. Observations indicate that at some places e.g. at Syiah Kuala beach (between Krueng Aceh river mouth and the Floodway Channel, see Fig. 2) the beach was rebuilding in May 2005, but then rapidly disappeared after the construction of this breakwater.

DISCUSSION

Analysis of the surface area of inundated land directly after the tsunami indicated an average coastline retreat in the order of several hundred meters due to the tsunami. However, by taking a closer look at Fig.5, it can be seen that part of this inundated area is found rather inland, i.e. to the southeast of Ujong Pancu headland (considered as part of the inundated area of the west coast). The light grey area here indicates that there has been water in this region even before the tsunami (i.e. a lake). The image indicates that this lake has become much bigger, probably due to the subsidence as a result of the earthquake. So this part cannot really be considered as coastline retreat.

At the northwest coast, where the inundated areas are indeed located along the coastline, the retreat can be due to subsidence and/or due to coastal erosion. Gibbons and Gelfenbaum et al. (2006) concluded that the subsidence along the northwest coast was in the order of 0.3 – 0.6 m. Knowing that the beach profiles in this area may have had slopes of about 1:200 – 1:300 (see earlier in this paper), subsidence may have caused a coastline retreat of about 60 – 180 m. The other part might have been due to coastal erosion, caused by the force of the tsunami waves. However, comparing Fig. 5 with Fig. 2 shows that part of this inundated area is in the very flat inland region that used to be the location of the fish and shrimp ponds. This might mean that subsidence is responsible for most of the coastline retreat.

On the west coast, beach recovery is progressing rapidly on coasts where spits/barriers had been completed removed by the tsunami. It is expected that this material has been moved seaward by the tsunami, which would mean that a large supply of sand is available beach formation within the nearshore zone. This could explain the rapid beach recovery in these areas.

CONCLUSIONS

This paper presents the state of Banda Aceh beach before and after the earthquake and tsunami of 26 December 2004, in terms of position of the coastline and composition of the sediment. The following conclusions can be drawn from the study (where we focus on the northwestern coast):

- The position of the coastline changed dramatically due to the earthquake and the tsunami, with a coastline retreat (in terms of inundation) in the order of several hundred meters.

- Because of the flat topography of the coastal region, subsidence due to the earthquake (which is in the order of 0.3-0.6 m in this area) is probably the major source of this coastline retreat.
- Grain sizes of the sediment before the tsunami varied between 90 and 310 μm. Sediment samples of tsunami deposits taken five months after the tsunami showed a variation in median grain size from 90 – 210 μm, indicating that the sediment composition has not changed significantly due to the tsunami and that the nearshore zone is most likely the source for the sediment of the tsunami deposits.
- One and a half year after the tsunami the beaches at the west coast show a clear recovery. However, at the northwest coast the possible natural recovery is interfered by the construction of an offshore breakwater at the pre-tsunami coastline.

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