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# Reconnaissance report of the 2004 Great Sumatra-Andaman, Indonesia, Earthquake – Damage to geotechnical works in Banda Aceh and Meulaboh –

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## ABSTRACT

One of the largest earthquakes in our history occurred at 7:58AM (local time) on December 26 2004, off the west coast of Northern Sumatra Island, Indonesia ($M_w$ 9.3). The earthquake triggered a huge tsunami along the coastlines of the Indian Ocean and caused a huge number of casualties. From March 1 to 6, 2005, reconnaissance was conducted in the region of Banda Aceh and Meulaboh, Indonesia, where strong shaking and tsunamis were observed. The primary objective of reconnaissance was to investigate and record damage mainly due to strong motions and to estimate the seismic intensity in the region. This paper reports on the damage to earth structures, waterfront structures, and roads washed away by tsunamis. Eyewitness evidence of liquefaction in Banda Aceh, about 250 km away from the epicenter, was likely caused by the strong shaking of $M_w$ 9.3. In Kuala Bubon village located about 15 km north of Meulaboh, settlements of embankments attached to bridge abutments collapsed just after the earthquake and before the arrival of the tsunami, so villagers could not use motorcycles or bicycles to evacuate. Lessons must be learned from this devastating earthquake, and disaster mitigation improved.

## 1. INTRODUCTION

### 1.1 Background on Research

One of the largest earthquakes ($M_w$ 9.3) in our history occurred at 7:58AM (Local time) on December 26 2004, off the west coast of Northern Sumatra Island, Indonesia (**Fig. 1**) (Kanamori, 2006). The rupture started off the north of the Simalur Island and spread over 1,300 km by propagating northward at roughly 2.8 km/s for approximately 8 minutes (Ishii *et al*., 2005). The great earthquake triggered a devastating tsunami that struck countries bordering the Indian Ocean; Indonesia, Sri Lanka, India, Thailand, Malaysia, Myanmar, Maldives, Bangladesh, Somalia, Kenya, Tanzania, and Seychelles. A total of 233,000 persons have been reported killed or missing (April 2005). Although the Indonesian meteorological agency had installed a seismometer in Banda Aceh about 250 km away from the epicenter, the strong motion of the main shock was too large for the seismometer to record its maximum amplitude.

Considering the size of the event, the effects of strong motion were expected to be devastating in cities or villages on the west coast Sumatra Island. To investigate and record the damage and estimate the seismic intensity in the region, a reconnaissance team (Leader: Prof. Hirokazu Iemura, Kyoto University) was organized to survey the region of Banda Aceh and Meulaboh, Indonesia, from March 1 to 6, 2005. The seismic intensity estimated based on the results of a questionnaire survey of 381 respondents in Banda Aceh was 5+ to 6- on the JMA seismic intensity (corresponds to MMI = VIII) (Honda *et al*., 2005). The level of intensity seems to be consistent with the damage in the area. However, it was difficult to estimate how many buildings collapsed as a result of the strong motion because tsunamis swept almost everything away except the foundations of houses.

Damage caused by tsunamis has been well documented by researchers and related organizations all over the world (e.g., Iwan,

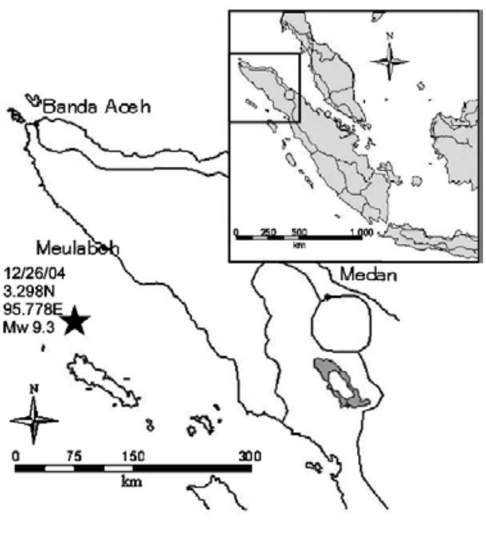



**Fig. 1** Epicenter of the 2004 Great Sumatra-Andaman Earthquake

KEY WORDS: 2004/12/26, Sumatra, Earthquake, Tsunami, Geotechnical works

2006; Kawata *et al*., 2005). However, few studies have reported on damage due to the strong shaking because the affected area was limited to the west coast of Sumatra Island (Saatcioglu *et al*., 2006). Sengara *et al*. (2006) reports geotechnical engineering aspects of building and infrastructure damage and emphasizes the need for a seismic microzonation study to identify the spatial variability of strong ground shaking for reconstruction and future planning of affected cities.

This report focuses on the damage and performance of geotechnical works, such as earth structures, waterfront structures and roads in Banda Aceh and Meulaboh areas. The major feature of damage in these areas is the combined hazards in addition to the hydrodynamic effects of the tsunami.

## 2. BANDA ACEH REGION

The City of Banda Aceh is located at the northern edge of Sumatra Island (**Fig. 1**). It is a low-lying area underlain by a Holocene fluvial formed by Aceh River (**Fig. 2**) and estuarine deposition. The city area stretches over 20 km from east to west and 10 km from north to south. The surface and subsurface geology in the area is classified mainly as silt and clay, and sand deposits were found on the right bank of Aceh River near the grand mosque and coastline (**Fig 2**) (Wafid, 2005). Back marshes used as shrimp farms are typically located behind the sand dunes that form the coastline of Banda Aceh. Buildings or houses located from 3 to 5 km inland were affected by a tsunami as shown in **Fig. 2**. The height of the tsunami in Banda Aceh ranged from 5 to 30 m (Tsuji *et al*., 2005). The inundated area is shown with a black line with small arrows in **Fig. 2**.

As the city was built on predominantly soft soil, large RC structures such as government and private buildings, shopping centers, hospitals and hotels (**Fig. 3**), whose natural period was relatively long, were damaged by strong motion. However, it should be noted that damage to those buildings varied from total collapse to minor damage depending on the type of foundation, local ground conditions and spatial variation of strong ground motions. The sharp contrast in the damage that occurred in the coastal and inland hilly area indicates that the soft ground conditions might have been a significant factor in the damage to buildings in the coastal area of Banda Aceh.

### 2.1 Loss of coastlines

The coastlines of Banda Aceh receded several hundred meters after the tsunami (**Fig. 4**). Houses located on sand dunes near a small fishery port at Ulee Lheue were completely swept away from their foundations, and only wave-dissipating blocks remained about 20 m off the seashore (**Fig. 4**). Based on measuring the difference in the water mark heights on the front and rear walls, the current speed was estimated to be 25.2 km/h (Matsutomi *et al*.,

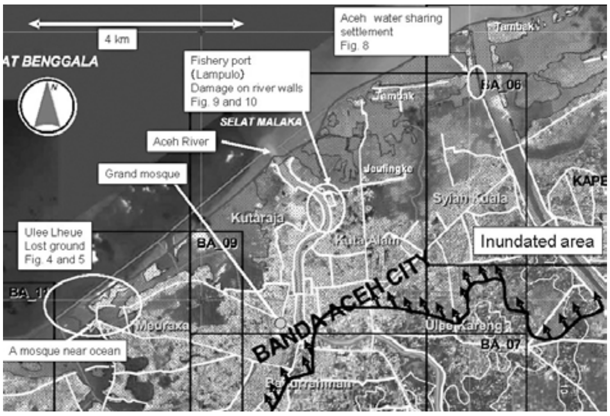



**Fig. 2** Inundated area of Banda Aceh (DLR, 2005)

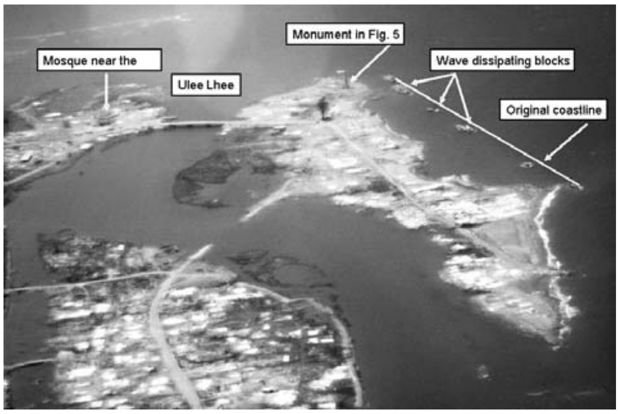



**Fig. 4** Aerial view of lost coastline near Ulee Lheue (taken on March 4, 2005)

**Fig. 3** Soft-story (1st story) collapse of a 5-story building


**Fig. 5** Erosion behind the monument located at Ulee Lheue

2005). The inundation height of wave at Ulee Lheue Port was 12.2 m above the sea level. There was a local scour behind a monument standing near the fishery port and that might indicate the speed of waves (**Fig. 5**).

Results of the reconnaissance indicate that the loss of land along coastlines submerged into the sea was mainly due to erosion by the hydrodynamic force of tsunamis; however, liquefaction also likely contributed. According to the witness accounts of residents, liquefaction occurred before the tsunami struck. The sites consist of clean sand with an average particle size of 0.2 - 0.3 mm (**Fig. 6**). The epicentral distance of the liquefied site in Banda Aceh, although it might not be the farthest site for this event, can be plotted in the figure developed by Ambraseys (1988) from the worldwide databse of shallow earthquakes (**Fig. 7**). As seen in **Fig. 7**, the distance between Banda Aceh and an epicenter of 250 km for an earthquake of $M_w$ 9.3 is consistent with existing findings.

### 2.2 Damage to levees

Aceh Water Sharing (**Fig. 2**) was constructed and completed in 1992 in the eastern part of the city for flooding countermeasures of the Aceh River, which meanders through the middle of the city. The Overseas Economic Cooperation Fund (OECF) issued by the government of Japan was used for the construction (CTII, 2005). Although some covering soil of the jetty at the river mouth was eroded and unwoven fabrics to protect the levee were exposed, its shape barely remained. The left bank of the levee was sandwitched by the water channels, i.e., the Aceh River and the straight channel that connected the marshlands of shrimp farms to the sea. Significant damage was found on the left bank of the channel about 1 km from the river mouth (**Fig. 8**), where marshland and the straight channel merged. The levee's body was laterally expanded in the transverse direction with remaining slope-protection stones, and its crown settled near the water surface (**Fig. 8b**). Taking account of its failure mode and the ground water depth at the site, the damage could be due to loss of bearing capacity with liquefaction.

Considering that the right bank near the river mouth was more eroded than the left bank, the tsunami waves might have initially struck the right bank and then been reflected to the left bank. This may indicate a north-west incidence of tsunami waves at this location. The wave velocity was estimated from the collapsed bridge at the river mouth of the Aceh Water Sharing. Its bridge girder was supported by U-shaped concrete slabs attached on to the top of piers. When the tsunami struck the bridge girders, they pushed the upstream side of the U-shaped slabs and as a result girders fell. Based on the dimensions and strength of the concrete, the wave velocity was estimated to be 12 km/h (Scawthorn *et al*., 2005).

### 2.3 Damage to the river protection wall of the fishery port at Lampulo

Lampulo, a small fishery port on the right bank of Aceh River, is located about 3 km north of the grand mosque (**Fig. 2**). At the time of reconnaissance, small fishing boats were moored directly

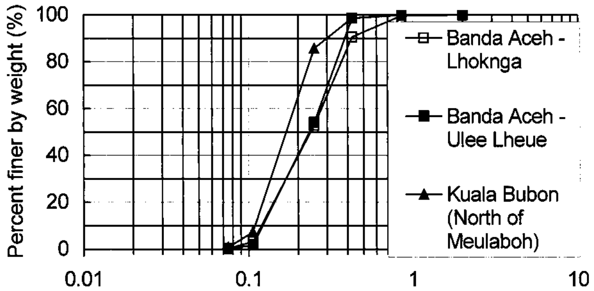



**Fig. 6** Grain size distribution curve of sand samples collected at Banda Ache and Meulaboh

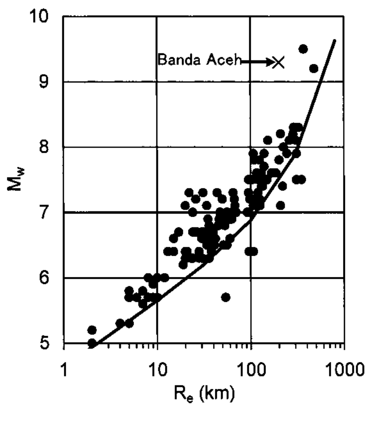
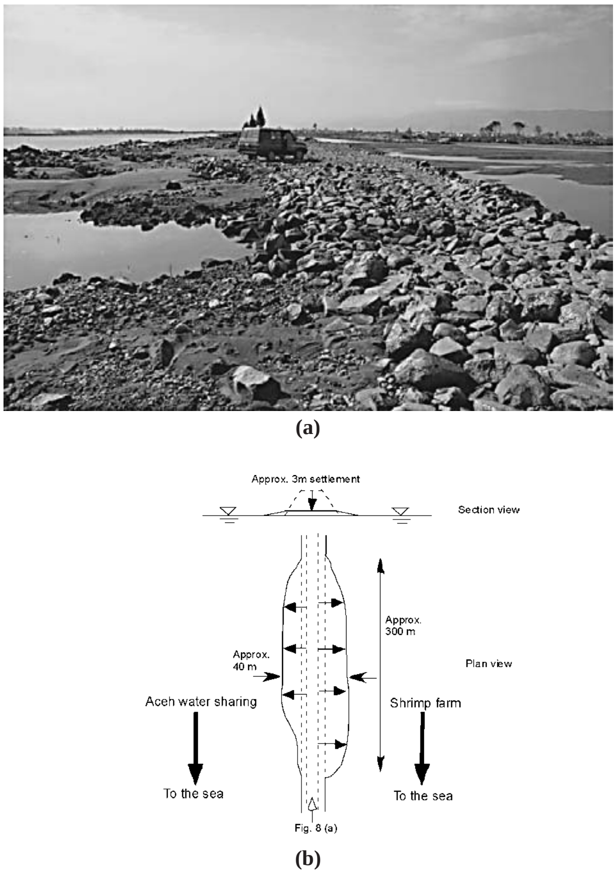



**Fig. 7** Maximum epicentral distance to liquefied sites $R_e$ and moment magnitude $M_w$ (after Ambraseys 1988)




(a)

(b)

**Fig. 8** **(a)** Collapsed levee (left bank of the Aceh Water Sharing), **(b)** Schematic view to less damaged river protection walls and fishermen were trading fish.

At this location, river protection walls were constructed by L-shaped concrete slabs, whose height was 2 m and the width at the bottom was 1.5 m (**Fig. 9** and **10**). The walls were displaced toward the river and in some parts totally collapsed. The material behind these river walls was mainly sandy clay and interbedded sands and gravels. Strong shaking and hydrodynamic force might have caused the damage to the river walls.

### 2.4 Damage to the embankments for oil pipelines

At Malahayati, east of Banda Aceh, an embankment to support oil pipelines suffered minor damage (**Fig. 11**). Its main body was not cut or submerged in the sea, only its shoulders were eroded; however, pipelines were cut and dislocated to the other side of the slope from their original position by tsunami induced force. The embankment was jutting into the sea about 1 km, and near the end the pipeline was supported by piled piers. The pier and machine cabin were undamaged.

Other remarkable damage at the site was that three oil storage tanks out of nine were washed away by tsunamis due to the lack of anchor bolts (Goto, 2005; Saatcioglu *et al*., 2006). One was relocated about 300 m west from its original position due to high tide of waves (**Fig. 12**). There were other relocated large objects, such as a power generating vessel and large tankers, which might have destroyed buildings and killed people in their path.

## 3. MEULABOH REGION

The suburbs of Meulaboh, the city closest to the epicenter, were investigated. Due to the limited time and road conditions, reconnaissance was restricted within 45 km along the west coast of Sumatra Island. The northernmost village was Kuala Bubon located about 15 km north of Meulaboh (**Fig. 13** and **14**) and the southernmost village was Kuala Tadu about 30 km south of Meulaboh.

### 3.1 Damage in Meulaboh

In the city of Meulaboh, although soft-story collapses of 4- to 5-story buildings due to strong shaking occurred, most buildings made by RC or RC columns and beams were undamaged except the first floors, which were scarred by floating debris.

Houses on the Ujoung Kalang peninsula (Coral Peninsula) in Meulaboh, except the three-story RC structure of the police department, were totally destroyed and only debris remained. Floor slabs of a pile supporting a passenger jetty were submerged into the sea and only piles were left (**Fig. 15**).

Inland villages about 3 to 5 km north of the peninsula were apparently undamaged by the strong shaking and the tsunamis. The contrast between damaged and undamaged areas was striking in both the appearance of buildings and the number of people killed.

**Fig. 9** Failure of river protection walls at Lampulo

**Fig. 11** Minor damage to the embankment for pipelines at Malahayati. Pipelines were dislocated.

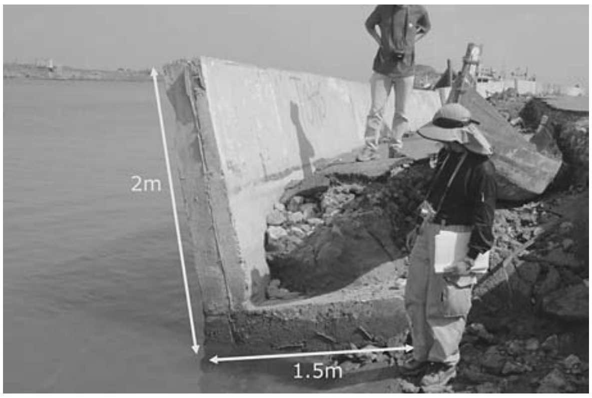



**Fig. 10** Tilted and dislocated L-shaped river protection at Lampulo

**Fig. 12** Relocated oil storage tank at Malahayati

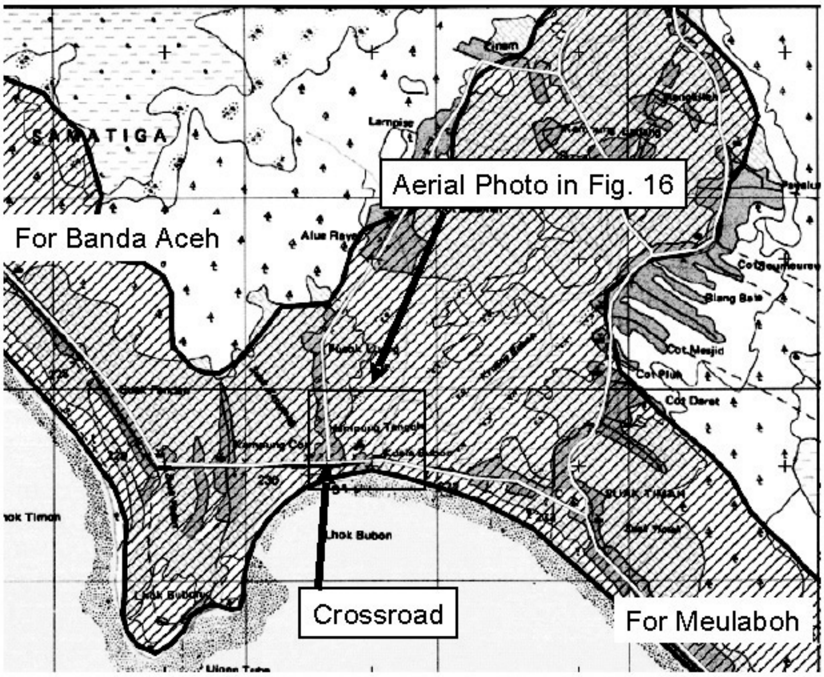



**Fig. 13** Inundated area in Kuala Bubon and the direction of the aerial photograph shown in **Fig. 16** (DLR, 2005).


**Fig. 14** Satellite image of Kuala Bubon before the earthquake and tsunami (Google Earth)

**Fig. 15** Collapsed floor slab of a passenger jetty at a ferry port in Ujoung Kalang, Meulaboh)

### 3.2 Damage in Kuala Bubon village

Small villages are commonly seen near deltas in the western part of Sumatra Island. Seen from the air, river mouths were heavily eroded and red to brownish water was pooled in back marshes. Houses along streets near the coastline were totally destroyed and debris was scattered inland from the coastline.

Kuala Bubon is located on Holocene alluvial fan at the river estuary of the Bubon River about 15 km north of Meulaboh. It was a small village with a population of 1,500 before the tsunami. A quarter of the population is thought to have been killed by the tsunami. Not only houses located near the beach, but also large amounts of deltaic deposits were lost up to several hundred meters from the coastline (**Fig. 16**).

Survivors said that they saw an unusual white band of waves gradually approaching from across the horizon, and they instinctively started to escape. Then, the tsunami struck and many villagers were swept away and some were caught by trees. One of the two palm oil storage tanks by the beach was swept away and dumped in the woods about 3 km from its original position. Splashed oil from the tank was found in the environment and may have contaminated water in the area.

Eyewitness reports of water coming out from the cracked floors of houses accounts for the occurrence of liquefaction in Kuala Bubon. The soil was sandy and the grain size distribution analysis of the sand collected in Kuala Bubon reveals the possibility of liquefaction (**Fig. 6**). The combined effects of liquefaction and tsunami might be responsible for the submersion of land near the deltas. Other eyewitness reports of liquefaction and sand boils

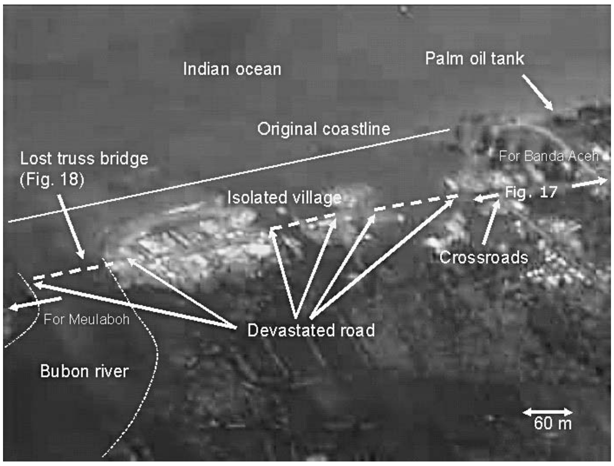



**Fig. 16** Aerial view of Kuala Bubon and devastated road (taken on March 2, 2005)

**Fig. 18** One of the bridge abutments of a collapsed steel truss bridge in Kuala Bubon

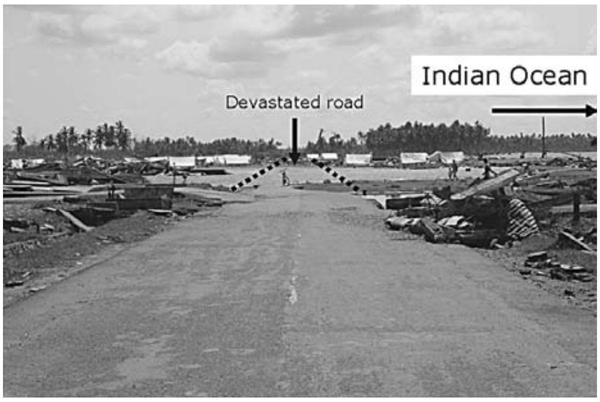



**Fig. 17** Devastated road in Kuala Bubon. Photo was taken near the crossroads shown in **Fig. 13**, **14** and **16**

**Fig. 19** Lost access road in Kuala Tadu

were found in Meulaboh and near a bridge in Kuala Tuha located south of Meulaboh. A mayor of a village near Ujoung Kalang in Meulabo reported that black smelly water suddenly oozed from the floor of his house up to the height of his knees.

### 3.3 Loss of main roads and damage to the bridges

A main road along the coastline of western Sumatra Island, which connected Banda Aceh and Meulaboh, were devastated. In the northern part of Meulaboh, because the road was constructed either on sand dunes near beaches or lowland just behind the sand dunes, parts of the roads, especially near river deltas, were completely lost (**Fig. 16** and **17**). While in the southern part of Meulaboh, the road was not damaged at all because it was constructed hundreds of meters inland from the coastline. After the earthquake, the main road was shifted to a narrow and unpaved road running inland in between Meulaboh and Kuala Bubon. The amount of traffic on the inland road, therefore, has been increased and protection works of road shoulders have been implemented using stones and mesh wires.

There was a 60 m steel truss bridge at the river estuary of Bubon River (**Fig. 14**). Its girders fell and only two bridge abutments are left (**Fig. 18**). Wave force is responsible for the bridge collapse. However, survivors said embankments to an access road to the bridge abutment settled before the arrival of the tsunami as a result of the strong shaking. People, therefore, could not escape by using bicycles or motorcycles. The settlement may be attributed to poorly compacted soil or liquefaction. This has often occurred after large earthquakes, e.g. vertical gaps at the edge of box culverts or near bridge abutments after the 2004 Mid Niigata Earthquake, Japan (Tobita *et al*., 2005). In Kuala Tadu, where similar type of damage was observed (**Fig. 19**), the people tied up palm trees as a temporary bridge to fill the gap between the main bridge girder and the access road. It takes tens of minutes to temporarily repair. Considering the time until being struck by tsunamis, escape routes should be seismically stable.

## 4. CONCLUSIONS

The damage to and performance of geotechnical works under strong motion of the Sumatra-Andaman Earthquake, Indonesia ($M_w$ 9.3) have been mainly reported based on the field investigation conducted from March 1 to 6, 2005, about 2 months after the earthquake. The team covered areas of Banda Aceh and Meulaboh in northern Sumatra Island, Indonesia. Damage, particularly, on low land, to earth structures, roads, and port facilities was found. The findings are as follows:

(1) The loss or submerging of land along the coastline in Banda

Aceh was mainly a result of the hydrodynamic force of tsunamis, and a combined effect with liquefaction is suspected.

(2) Considering the failure mode and surrounding environment, liquefaction might be the primary cause of damage to the embankments of the Aceh Water Sharing. The occurrence of liquefaction at the distance of 250 km away from the epicenter is consistent with the existing data.

(3) Damage to the river protection walls at Lampulo where clayey soil was dominant might be due to the retraction force of the tsunami.

(4) A major road between Banda Aceh and Meulaboh was destroyed. While a major road in the south of Meulaboh was undamaged except for the bridges. This is because the road in the north of Meulaboh was constructed closer to the ocean than that in the south of Meulaboh.

(5) Poor compaction and liquefaction might be responsible for the collapse of embankments adjacent to bridge abutments. If this occurs before the arrival of tsunamis, people are unable to use motorcycles and bicycles for quick evacuation. This indicates that it is important for escape routes to be seismically stable.

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