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Report on Post Tsunami Survey along the Myanmar Coast for the December 2004 Sumatra-Andaman Earthquake

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Abstract: The tsunami heights from the 2004 Sumatra-Andaman earthquake were between 0.4 and 2.9 m along the Myanmar coast, according to our post tsunami survey at 22 sites in Ayeyarwaddy Delta and the Taninthayi coast. Interviews to coastal residents indicate that the tsunami arrived between 2 to 5.5 hours after the earthquake, although nobody felt ground shaking. Much smaller tsunami than the neighboring Thai coast, where the tsunami heights were 5 to 20 m, explains relatively slighter tsunami damage in Myanmar; the casualties were reported as 71, compared to about 8300 in Thailand. The smaller tsunami was probably due to the fact that the tsunami source did not extend to Andaman Islands. The tsunami travel times and maximum heights computed from a 700 km long source are basically consistent with the observation. For a nearby tsunami source, the tsunami hazard would be more significant in Myanmar, because coastal houses are unprotected for tsunamis and no infrastructure exists to disseminate tsunami warning information.

Keywords: Sumatra-Andaman earthquake, tsunami, field survey, Andaman Sea, Myanmar, Thailand.

1. Introduction

A giant earthquake occurred off Sumatra Island of Indonesia, at 00:58:53 UTC (07:28 Myanmar time) on December 26, 2004. The earthquake was the largest in size (Mw 9.1–9.3) in the last 40 years in the world, since the 1960 Chilean earthquake (Mw 9.5). The earthquake was an interplate event, caused by the subduction of Indian (or Indo-Australian) plate beneath Andaman (or Burma) microplate (Lay *et al*., 2005). While the epicenter was located west off Sumatra Island, the aftershock zone extended through Nicobar to Andaman Islands, the total length being more than 1,000 km (Figure 1). The eastern boundary of the Andaman (or Burma) microplate is bounded by the Sagain fault in Myanmar, the spreading center in Andaman Sea, and the Sumatra fault, from north to south.

This earthquake generated a tsunami which devastated the shores of Indonesia, Sri Lanka, South India, and Thailand as far as the east coast of Africa. More than 200,000 people are thought to have died as a result of the tsunami (Figure 2). The number of victims, death and missing altogether, is the largest in Indonesia (~164,000), followed by Sri Lanka (~36,000), India (~16,000), Thailand (~8,300), and as far away as Somalia (International Federation of Red Cross and Red Crescent Societies, 2005). In Myanmar, the damage and casualties (71) are relatively small compared to the above countries.

For the scientific studies of tsunamis, coastal damage and wave height are the basic data to be collected. To document the tsunami disaster and measure the tsunami heights, many scientists from all over the world visited the coasts of Indian Ocean. This report is to summarize the survey results to document the effect of tsunami along the Myanmar coast. The post tsunami survey in Myanmar is particularly important to identify (1) why the tsunami damage was much smaller than the neighboring Thai coast, and (2) vulnerability to the Myanmar coast for future tsunamis.

2. General Description of Myanmar Coastal Area

Myanmar has about 1900 km long coastal line, and can be divided into three parts; namely, Rakine coastal area to the west, Ayeyarwaddy Delta in the middle, and Taninthayi coastal area to the south (Fig. 1). The Rakine Coast, about 700 km long, is situated the western part of Myanmar around the Bay of Bangal, and its northern part is built up of shallow sea with a chain of islands and some delta growth. The well-known Ayeyarwaddy Delta is being built up at mouth of Ayeyarwaddy River and is about 200 km wide. Sedimentation and annual delta growth rate increase lead to further shallow water sandbars in the Martaban Sea up to 50 km southward. The 900 km long Taninthayi coastal line is almost straight in north-south direction. The southern part of Taninthayi coastal line, from north of Dawei to Kawthaung, the southern end of Myanmar, is composed of chain of islands called Myeik Archipelagos.

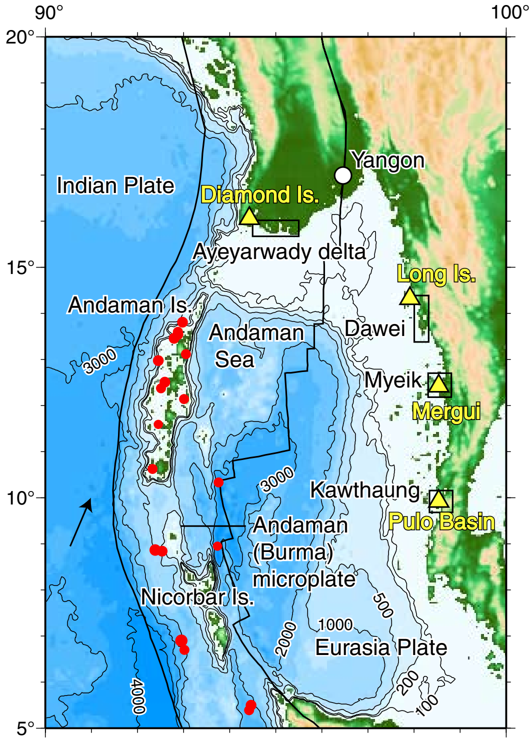


Fig. 1. Tectonic map showing the aftershock distribution of the Sumatra-Andaman earthquake (red circles) along the active plate boundary (according to USGS). Yellow triangles are the locations where the tide levels were computed.

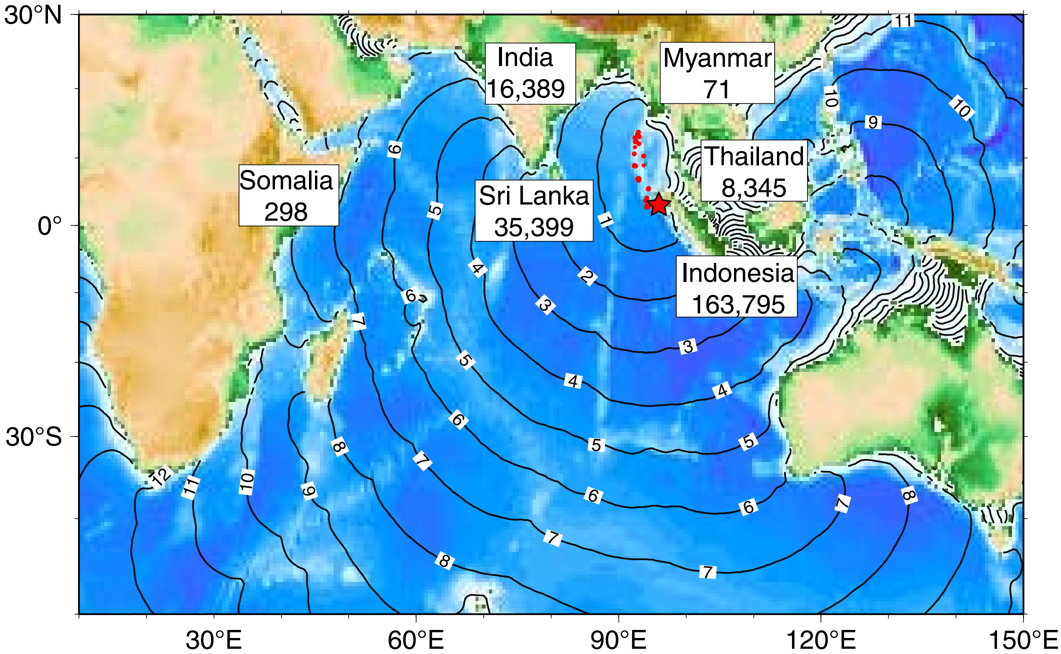


Fig. 2. Computed tsunami arrival times in the Indian Ocean (numbers indicate time in hour) from the 2004 Sumatra earthquake (red star). The red circles are aftershocks within one day. Reported casualties are also shown.

3. Survey Team and Scope of Work

The tsunami survey along the Myanmar Coastal Area was carried out from March 7 through 15, 2005. The survey includes two parts. In the first half from March 7 through 12, Dawei, Myeik and Kawthaung areas along the Taninthayi Coast and Myeik Archipelago were visited. In the second half from March 12 through 15, Pyinsalu and Kaing Thaung Islands on the Ayeyarwaddy Deltaic area were visited. The study group was constituted by scientists from Geological Survey of Japan (GSJ) and host scientists from different institutions of Myanmar. List of participants is shown in Table 1.

Table 1. List of Participants.

March 7 to 12: Taninthayi Coast		March 12 to 15: Ayeyarwaddy Delta	
Participants from Japan			
1	Kenji Satake (GSJ)	1	Kenji Satake (GSJ)
2	Yuki Sawai (GSJ)	2	Yukinobu Okamura (GSJ)
3	Than Tin Aung (GSJ)	3	Yuki Sawai (GSJ)
4	Kyaw Soe Win (NU)	4	Than Tin Aung (GSJ)
		5	Kyaw Soe Win (NU)
Participants from Myanmar			
5	Win Swe (MGS)	6	Maung Maung Soe (DMH)
6	Chit Swe (YTU)	7	Thant Zin Oo (DMH)
7	Soe Thura Tun (YU)	8	Chit Swe (YTU)
8	Tint Lwin Swe (YTU, MEC)	9	Tint Lwin Swe (YTU, MEC)
		10	Saw Htwe Zaw (MES)
GSJ, Geological Survey of Japan; NU, Nagoya University; MGS, Myanmar Geoscience Society; DMH, Department of Meteorology and Hydrology; YU, Yangon University; YTU, Yangon Technological University; MES, Myanmar Engineering Society; MEC, Myanmar Earthquake Committee.			

The general outline of survey in Myanmar is as follows.

March 6: The participants from Japan arrived at Yangon, and an introductory meeting was held at Department of Meteorology and Hydrology.

March 7: The party flew from Yangon to Dawei, and visited four sites: Maungmagan Beach, Thabawseik-Kyauksent Village, Myaw Yit Gyi Pagoda, and Sann Lan Village. The former Township Administration Officer, Tin Hlaing and Sabei Lwin, Head of Dawei DMH joined in.

March 8: The party visited three sites (Kyet Lut Beach, Kyaukmattat and Nyawbyin). Zaw Tun Thaung, a staff of Dawei DMH joined. After the survey, the results were reviewed in an evening meeting at DMH seismological station in Dawei.

March 9: The party moved to Kawthaung by a regular passenger express boat.

March 10: In the morning, the party chartered a small boat to visit three sites (Plautonton Island, Salonlay Island (Ywarthaya Village), and Salon Island (Dolphin club)). In the afternoon, the party rented a truck to visit four sites (Konnamaing Chaungwa and Tannyopada Villages, Thirimyaing Quarter and Myoma Jetty of Kawthaung).

March 11: The party took the express passenger boat again for Myeik, and then rented a motorboat to visit two sites (Thander Kyun Village and Pahtaw Village).

March 12: The party flew back to Yangon where the first part ended. The party of the second part moved to Labutta by a chartered bus.

March 13: The party moved by a chartered boat along the Pyarmalaw River to Pyinsalu island, where measurements were taken in Layyin Kwin (Air Field) Village and Kapyet Thaung Village.

March 14: The party proceeded to Kaing Thaung Island and collected data and information in Thit Poke Village, Kaing Thaung Island Pagoda, Kaing Thaung Village and Aung Hlaing Village.

March 15: The party moved back to Yangon where the second part of survey concluded.

March 16: A meeting was held in DMH where the preliminary results were reported.

March 17: Participants from Japan left Yangon.

4. Measurement Method and Corrections for Tides

According to the guidelines of Intergovernmental Oceanographic Commission (1998), following general procedure was adopted for the field survey.
(1) Collect relevant available data and information, existing maps, charts, tidal records (DMH, Local Authorities, etc.).
(2) Interview with local people.
(3) Take pictures of the present condition.
(4) Record the location by a portable GPS.
(5) Measurements of level and distance of maximum flood level.
(6) Measurements of level and distance of the wave front at the time of measurement.

In order to measure the tsunami heights, we used a handheld laser ranging instrument (Impulse 200LR; Laser Technology Inc.) and an auto-level equipment (Photo 1). In general, auto-level with the tripod provides more accurate heights than the laser instrument without the tripod, while the laser instrument provides quicker results for a long distance (>100 m). For measurements of a short distance, we used both instruments. The vertical difference between them is at most 20 cm. For measurements of longer distance, we used only laser instrument.

According to interviews from eyewitnesses, we recorded arrival time of the tsunamis (December 26, 2004) at each surveyed site, and measured height of tsunami traces (debris or watermarks) above the sea level at the time of measurement. Tsunami heights were calculated as follows:

Photo 1. Two kinds of measurements, using auto-level (left) and laser (right) instruments.

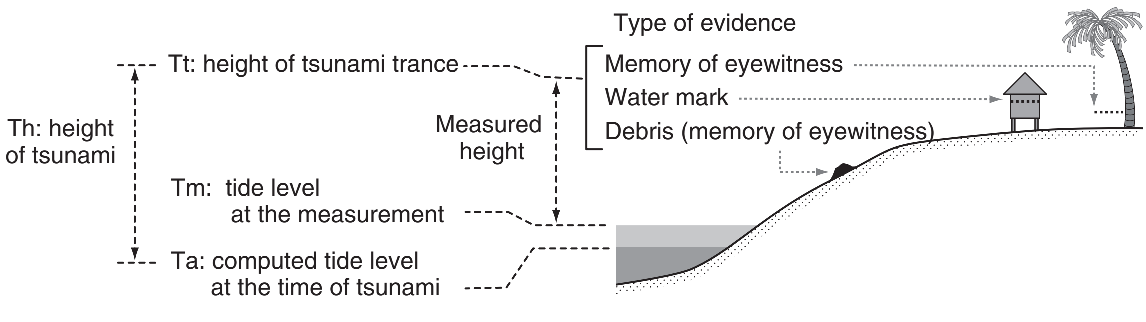


Fig. 3. Measurement of tsunami heights and corrections.

$$Th = (Tt - Tm) + (Tm - Ta)$$

where *Th* is the estimated tsunami height, *Tt* is the height of tsunami trace, *Tm* the tide level at the time of measurement, and *Ta* the computed tide at the time of Sumatra tsunami on December 26, 2004 (Fig. 3). We indicate the times in 24 hour system (e.g., 13:13) on Myanmar local time when it is accurate to the nearest minute.

The tide levels at the times of tsunami arrival and the measurement were computed on the basis of astronomical tides, by using computer program WXTide 32 release 4. The maximum differences of the predicted tides with a tide table (United Kingdom Hydrographic office, 2004) are within 70 minutes and 50 cm at ebb/flood times. For Ayeyarwaddy Delta coast, tide was calculated based on predicted tides at Bassein River, Diamond Island (15° 52.0' N, 94° 17.0' E). For Dawei coast, the tide was calculated at Heinze Bok, Long Island (14° 24.0' N, 97° 47.0' E). For Myeik measurements, the tide was calculated at Mergui (12° 26.0' N, 98° 35.9' E). For the measurements around Kawthaung, tide was calculated at Pulo Basin (9° 59.0' N, 98° 29.0' E) (Figs. 4 and 5).

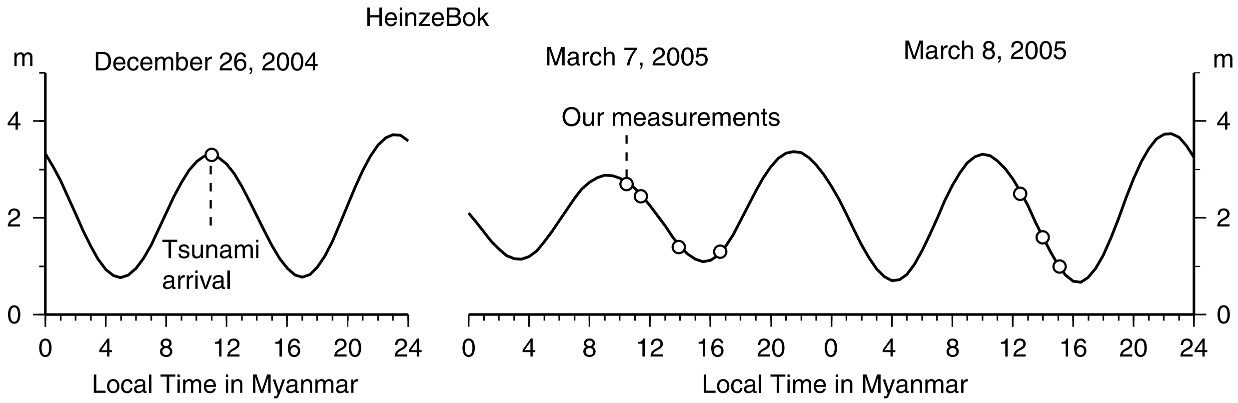


Fig. 4. Predicted astronomical tidal changes at Heinze Bok (Long Island), near Dawei. (a) Tidal change on December 26, 2004. An open circle on the curve shows the time of the tsunami arrival. (b) Tidal change on March 7-8, 2005. Circles on the curve show time of our measurements.

As described below, the tsunami arrival times from interview to coastal residents vary within the neighboring locations. We felt that such variation in arrival time is dependent on the interviewee, rather than the local effects of tsunami. We indicate the reported time to the nearest quarter hour with am or pm. We also assume that the tsunami arrival was 11:00 am for the Taninthayi coast and 11:30 am for Ayeyarwaddy Delta to make the corrections.

Figure 5 indicates the tidal levels for one year, from May 2004 through April 2005, including both dry and rainy seasons. In Myanmar, a year is divided into three seasons: summer from February through May, rainy season from June through September, and winter from October through January. As reported in more detail in each locality, many coastal residents compared the tsunami heights with the 'rainy season high tide level'. From the interviews, we had an impression that high tide levels are different from dry and rainy seasons. However, the seasonal change is very small, if any, compared to the amplitude of daily tidal change (Fig. 5).

The survey results are compiled in Table 2 with location numbers, location names, latitudes and longitudes, the corrected and measured heights (in meter), type of measurements (R for runup and I for inundation), type of evidence (D for debris, E for eyewitness accounts, W for watermarks), reliability (A is based on physical evidence supported by eyewitness accounts, B is based on eyewitness accounts only), tsunami arrival times based on interviews, measurement time, computed tide at the measurements, assumed tsunami arrival time and calculated tide for the corrections.

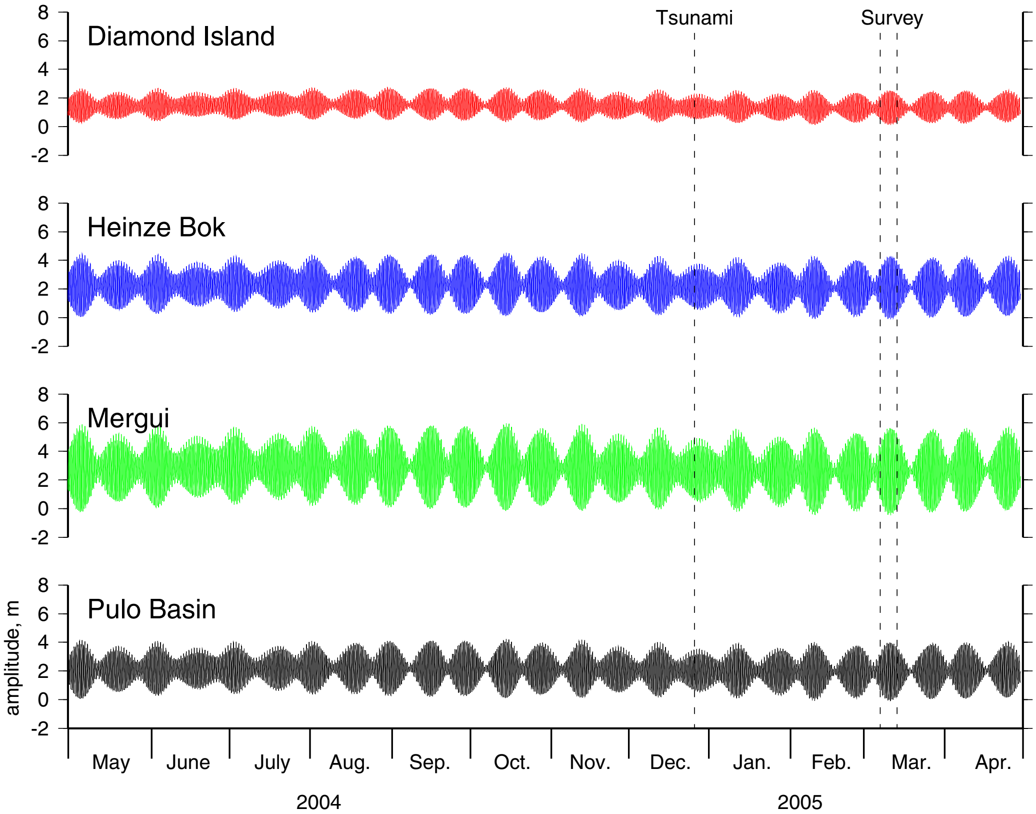


Fig. 5. Computed astronomical tidal changes at Diamond Island, Heinze Bok, Mergui and Pulo Basin for one year, starting May 2004. Note that tidal range is similar throughout the year, both dry and rainy seasons.

5. Survey in Dawei Area (MM-01 ~ MM-07)

In the Dawei area, seven sites, MM01 through MM07, were visited. The measurement sites are shown in Fig. 6. The eyewitness accounts on the tsunami arrival time are variable. The difference seems to be dependent on interviewee rather than tsunami's local effects within the region. Hence we assume that the tsunami arrived at 11:00, when the tide was highest in the morning (3.3 m). If the tsunami arrival was 1.5 hours earlier (9:30), then the tide level was 3.0 m. If it was 1.5 hours later (12:30), then the tide level was 2.9 m. The corrected tsunami height would be higher by 0.3 m and 0.4 m, respectively.

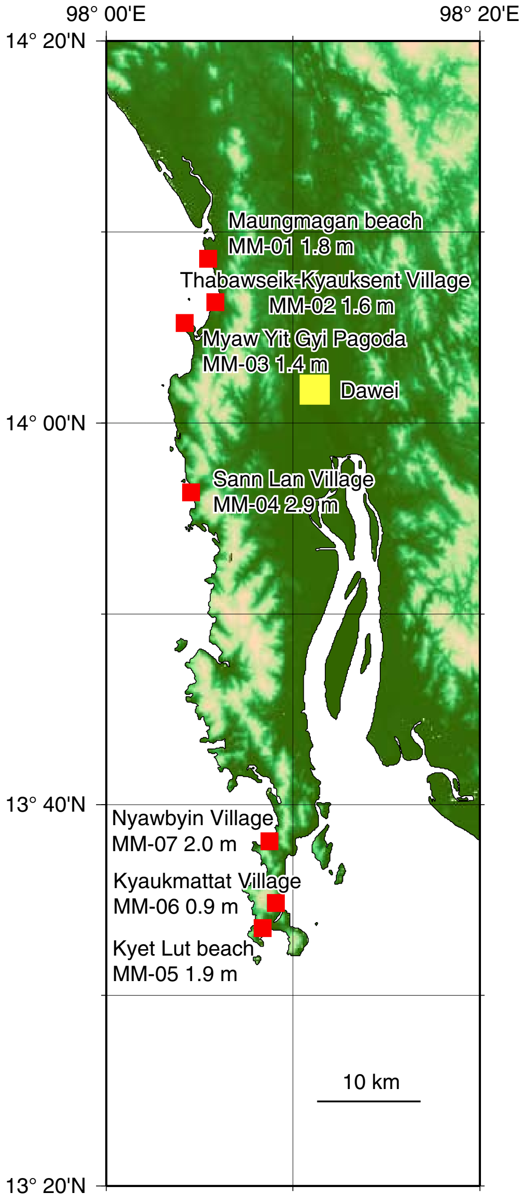


Fig. 6. Map showing tsunami measurement sites in Dawei area. Location numbers (in parenthesis) and corrected hights are shown at each location.

5.1 MM-01: Maungmagan beach (14°08’ 36.5”N, 98°05’ 26.8”E)

On this beach, two parallel lines of debris were observed (Photo 2). A local fisherman (36 years old male) told us that the lower debris line was formed by the December tsunami. He did not feel the earthquake but observed that the tsunami arrived at around 2 pm, in a total of four successive waves with 3 to 4 m height. The tsunami arrived at low tide and did not exceed the high tide level of the rainy season (the higher debris line). Another eyewitness indicated the tsunami arrival times were between 10 am and 12 noon.

Our measurement at 10:27 on March 7, 2005 indicates that the lower and higher debris lines are 2.4 m and 2.9 m above the sea level at the time of measurement (Photo 2). The dune, to which the tsunami did not reach, was 4.0 m high. The corrected tsunami height, assuming that the tsunami arrived at 11:00, becomes 1.8 m.

Photo 2. Group interviewing local people who had observed tsunamis at Maungmagan Beach, MM-01 (looking south).

5.2 MM-02: Thabawseik-Kyauksent Village (14°06' 20.3"N, 98°05' 51.4"E)

Thabawseik-Kyauksent Village is a coastal village of about 200 houses which builds up very close to the shore line. The peoples' stable earning is mainly fishery. The interview with a local person (51 year old male) confirmed that the tsunami reached up to 55 cm above the ground (Photo 3 left) and arrived between noon and 1 pm in three successive waves of 20 minute intervals but caused no severe damage. The tsunami height was lower than the rainy season high-tide level. The measurement at 11:25 on March 7 indicates that the tsunami height was 2.4 m above the sea level, while rainy season high tide level was 3.0 m. The corrected tsunami height becomes 1.6 m.

Photo 3. Survey measurement at Thabawseik-Kyauksent Village. Arrow indicates the height of tsunami (pointed by interviewee).

5.3 MM-03: Myaw Yit Gyi Pagoda (14°05’ 15.2”N, 98°04’ 12.6”E)

Myaw Yit Gyi Pagoda is situated on a small granite island and connected to the opposite bank by a concrete bridge (Photo 4). A Buddhist monk from the Pagoda told us that he did not feel the earthquake shaking. Between 9:30 and 11:30 am, he observed that three waves coming from different directions reached at the base of the bridge. The height of tsunami was larger than the high tide of the rainy season. When receded, the seafloor was exposed about 200 m from the shore line.

The measurement at 13:56 on March 7, 2005 indicates that the tsunami height was 3.3 m above the sea level. The corrected tsunami height becomes 1.4 m.

Photo 4. Interview with a Buddhist monk at Myaw Yit Gyi Pagoda (left) and view of Myaw Yit Gyi pagoda in seaward (westward) direction (right).

5.4 MM-04: Sann Lan Village (13°56’ 22.3”N, 98°04’ 32.7”E)

Sann Lan Village is also situated on the same shore line, and constituted of almost wooden houses. The major earning is fishery. A fisherman told that the tsunami arrived at 11 am in four times with 15 minute intervals and it was coincidence with low tide (Photo 5).

Measurement at 16:40 on March 7, 2005 indicates that the tsunami height was 4.9 m above the sea level, while the high tide of the day was between 1.9 and 2.3 m. The corrected tsunami height becomes 2.9 m.

Photo 5. Survey at Sann Lan Village. Yellow dotted line is tsunami height (left). Measurement at Sann Lan Village (right).

5.5 MM-05 Kyet Lut beach (13°33’ 32.4”N, 98°08’ 22.7”E)

Kyet Lut beach is situated on the southern tip of the peninsula, 60 km from the Dawei. Two parallel debris lines were observed on the beach (Photo 6 left). A 19-years old male who live in a cottage where a group of farmers living seasonally reported that the tsunami entered after lunch (normally, local people take lunch about 10 am), and observed three times with 3 to 5 minute intervals. In addition, the lower debris was brought by the tsunami, while the upper one was by rainy season high tide.

Measurement at 12:30 on March 8, 2005 indicates that the lower debris line was 2.7 m above the sea level, while the upper line was 3.2 m. The corrected tsunami height becomes 1.9 m.

Photo 6. Survey at Kyet Lut Beach. Debris line indicates the maximum reach of tsunami (left) and a small seasonal hut where the interviewee lives (right).

5.6 MM-06: Kyaukmattat Village (13°34’ 51.5”N, 98°09’ 04.9”E)

Kyaukmattat Village is situated on the west bank of the Dawei River and the major earnings of the people are farming and fishery. A fisherman mentioned that a receding wave firstly came around 1 pm and then another high tide appeared at 8 pm. He indicated that the tsunami height was about 20 cm above ground on the wooden structure (Photo 7 right).

Measurement at 14:00 on March 8, 2005 indicates that the tsunami height was 2.6 m above the sea level. The indicated high tide levels of the day and rainy season were 2.3 m and 3.8 m, respectively. The corrected tsunami height becomes 0.9 m.

Photo 7. Survey at Kyaukmattat Village on the west bank of the Dawei River.

5.7 MM-07: Nyawbyin Village (13°38’ 05.3”N, 98°08’ 45.3”E)

Nyawbyin Village is situated on the western coast of the peninsula in Longlon Township and its curve shape beach profile is surrounded by two ridges. Most people did not feel the earthquake but noticed that the tsunami arrived there around noon.

The measurement at 15:07 on March 8 indicates that the tsunami height was 4.3 m above the sea level. The indicated high tide levels of the day and rainy season were 3.2 m and 4.8 m, respectively. The corrected tsunami height becomes 2.0 m.

Photo 8. Survey at Nyawbyin Village in Longlon Township.

6. Survey in Kawthaung area (MM-08 ~ MM-14)

Kawthaung City is located at the southern tip of Myanmar, and its surrounding islands are affected by tsunami according to the report of the Department of Meteorology and Hydrology. Total of seven localities along coastal areas of Kawthaung Township, including three islands and western coast of Kawthaung were surveyed (Fig. 7).

The eyewitness accounts of tsunami arrival were also variable, though the difference among the site locations is small, between 10:30 and 11:45 am. We assume that the tsunami arrival was 11:00 (when tide level was 2.9 m) throughout the Kawthaung area. If the tsunami arrival was earlier or later by half an hour, i.e., at 10:30 and 11:30 when the tide levels were 3.0 m and 2.7 m, then the corrected tsunami heights would be either 0.1 m lower or 0.2 m higher, respectively.

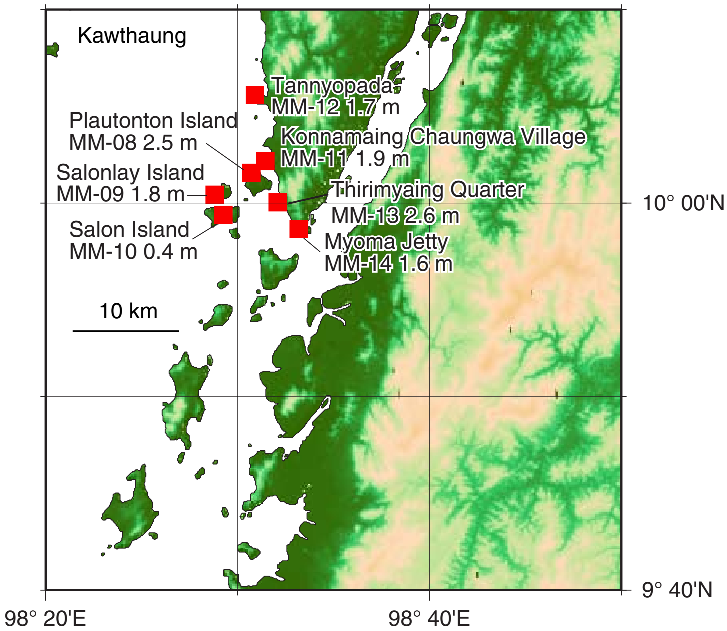


Fig. 7. Survey locations in Kawthaung area. Location numbers (in parenthesis) and corrected hights are shown at each location.

6.1 MM-08: Plautonton Island (10°01' 34.5"N, 98°30' 43.9"E)

Plautonton Island is a small island close to the west coast of Kawthaung City, connected by a 600 meter long wooden bridge. The central part of the bridge was destructed by the tsunami (Photo 9). Field survey was taken at Plautonton Village on the island. Most houses of the village are built on a mudflat, raising floor level up to one or two meters above the sea surface (Photo 10 left). Watermarke was observed at the interviewee's house (Photo 10 right). A 37 year old housewife told that the tsunami arrived at 10:30 am in three waves with 15 minute intervals. A 62 year old male, owner of a grocery store, said that two waves with 10-15 minute intervals arrived. Because the tsunami arrived during low tide, there was no severe damage to buildings, but some household wares (rice bags, cloths and TV sets, etc) were flooded. One person died in this village.

Measurement at 9:30 on March 10, 2005 indicates that the tsunami height was 1.8 m above sea level, while that of the rainy season high tide was 0.7 m. By assuming that the time arrived at 11:00, the corrected height becomes 2.5 m.

Photo 9. Destruction of wooden bridge to Plautonton by the tsunami.

Photo 10. Houses above water (left) and the watermark on the wall of a house (right).

6.2 MM-09: Ywarthaya Village, Salonlay Island (10°00’ 25.8”N, 98°28’ 49.4”E)

At the Ywarthaya Village of Salonlay Island, situated to the west of the Plautonton Island, there was no damage at all by the tsunami (Photo 11). A 23 year old male told us that the tsunami arrived at 11:15 am. Three to four waves arrived with 5 minute intervals. Measurement (at 10:50 March 10) indicates that the tsunami height was 1.0 m above the sea level, while the rainy season high tide level was 0.6 m. The corrected height is 1.8 m.

Photo 11. Field survey at Ywarthaya Village, Salonlay Island.

6.3 MM-10: Dolphin Club, Salon Island (9°59’ 23.7”N, 98°29’ 15.9”E)

The Dolphin Club of Salon Island, a few kilometers south of Salonlay Island, has a flat shore line. An interview was made to an eyewitness from the Dolphin Club. A 27 year old male told us that tsunami arrived at 11:45 am, in four waves with 5 minute intervals, and the height was the same as the sea level at the time of our visit at 11:40 on March 10. The high tide level in rainy season is 1.1 m above the sea level. The corrected height is 0.4 m (Photo 12).

Photo 12. Survey at the Dolphin Club, Salon Island.

6.4 MM-11: Konnamaing Chaungwa Village (10°02’ 10.2”N, 98°31’ 27.6”E)

Konnamaing Chaungwa is a small village located on the western coast, northwest of Kawthaung City. A bridge over a stream connected to the village was partly damaged during the incoming tsunami (Photo 13).

Photo 13. Destruction of bridge to Konnamaing Chaungwa Village by tsunami (narrow flat portion in the right far site of photo).

There were some damages by the tsunami: one death and destruction of eight houses. There is a clear watermark on a wall of a house indicating the tsunami height (Photo 14 right). Furthermore, the tsunami brought up some fishing boats along the stream course and then onto the paddy field (Photo 15 left). Some traces of marine mud on telephone post indicated the height of splash from the tsunami (Photo 15 right). According to eyewitness account, the tsunami arrived at 10:45 am.

Systematic measurement at 14:40 on March 10, 2005 indicates that the two watermarks were 1.4 and 1.2 m above the ground level, and 3.9 m and 4.0 m above the sea level. The corrected tsunami height is 1.9 m.

Photo 14. Watermark (right) at the wall of the interviewee’s house (left).

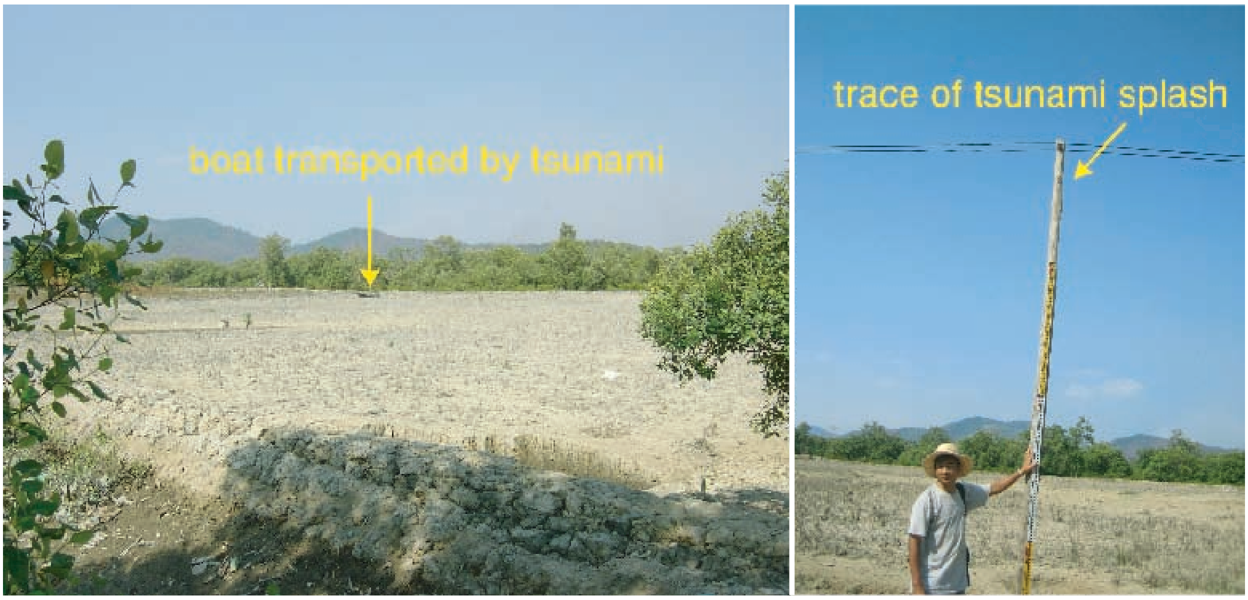


Photo 15. Traces of mud brought by tsunami at the top of the telephone post (right) and a boat and tsunami deposit in a paddy field (left).

6.5 MM-12: Tannyopada Village (10°05’ 35.3”N, 98°30’ 54.2”E)

Tannyopada is a small village of 40 houses located along the shore line northwest of Kawthaung City. A 40 year old man told that the tsunami arrived between 10:30 and 11:00 am, in three times with 10 minute intervals (Photo 16).

The measurement at 15:50 on March 10 indicates that the tsunami height was 4.4 m above the sea level. The sea level was very low at the time of measurement and the current water front was more than 200 m offshore, hence the height measurement was less reliable. The corrected tsunami height becomes 1.7 m.

Photo 16. Field survey at Tannyopada.

6.6 MM-13: Thirimyaing Quarter of Kawthaung City (10°00' 2.8"N, 98°32' 06.3"E)

The locality is the west part of Kawthaung city with coast line facing to west. Survey measurement and tsunami information were taken by interviewing local people. A 25 year old female told us that the tsunami arrived at 10:30 am, in five times with 5 minute intervals (Photo17).

Measurement at 16:54 on March 10 indicates that the tsunami height was 3.3 m above the sea level. The calculated tide levels at the time of measurement and 11:00 of December 26 are 0.2 m and 2.9 m, respectively, hence the corrected height would be 0.6 m. However, the sea level at the time of measurements was very low, and the measured heights are not reliable. Alternatively, we estimate the tsunami heights using the differential levels at this location. We also measured, on the basis of eyewitness accounts, the high tide levels of the rainy season, evening and morning of the day as 2.0 m, 1.8 m and 1.5 m, respectively, above the sea level. The tsunami height was 1.8 m higher than the high tide level of the morning of March 10. The calculated high tide is 3.7 m, or 0.8 m higher than 11:00 of December 26. From these, the tsunami height is estimated as 2.6 m. We consider that this estimate is more reliable.

Photo 17. Field measurement was carried out in Thirimyaing Quarter of Kawthaung City. A large coverage of mud flat in connection with low tide and a barrier of Island in the seafront lead to less tsunami effect on the shore.

6.7 MM-14: Myoma Jetty of Kawthaung City (9°58' 39.9"N, 98°33' 11.6"E)

Myoma Jetty is a harbor for domestic transportation near the center of Kawthaung City. Many people noticed the abnormal rise of sea level and reported that the highest tsunami level was about 30 cm below the top of the quay wall (Photo 18).

Measurement at 17:30 March 10 indicates that the tsunami height was 4.1 m above the sea level. The estimated tsunami height becomes 1.6 m.

Photo 18. Survey at Kawthaung Myoma Jetty.

7. Survey in Myeik area (MM-015 ~ MM-16)

Myeik is the capital of Taninthayi division and situated a half way between Dawei and Kawthuang cities. A chain of small islands called Myeik archipelago trending in a north-south direction is situated to the west of Myeik City. Two localities, Thandar Kyun Village (MM-15) and Pahtaw Village (MM-16) were surveyed (Fig. 8).

As in the Dawei and Kawthaung areas, the tsunami arrival times by eyewitness accounts differ by an hour. We assume that the tsunami arrival time was 11:00, when the calculated tide was 4.2 m. If the tsunami arrival was 12:00 (noon), when the tide level was 3.7 m, then the corrected tsunami height would be higher by 0.5 m.

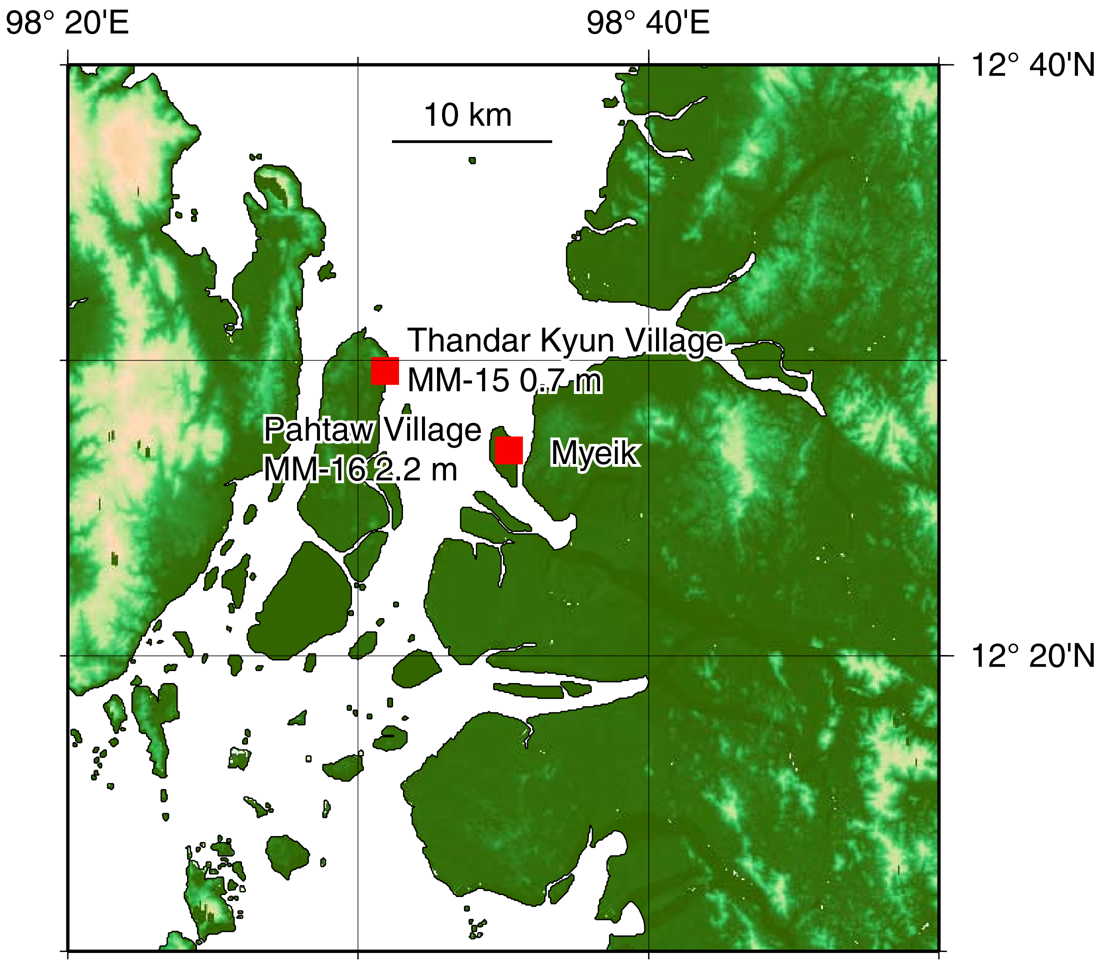


Fig. 8. Map of surveyed localities at Myeik area. Location numbers (in parenthesis) and corrected hights are shown at each location.

7.1 MM-15: Thandar Kyun Village (12°29' 39.2"N, 98°30' 55.5"E)

Survey was taken at Thandar Kyun Village about 10 km west of Myeik City (Photo 19). A 27 year old male told that the tsunami arrived at 11 am, in two waves with 20 minute interval.

Our measurement (at 16:10 March 11) of the tsunami levels of two accounts are 2.2 m and 4.4 m, and the high tide level of the rainy season is 5.1 m. Assuming that the higher level (4.4 m) represents the maximum tsunami height and the tsunami arrival time as 11:00 am, the corrected height becomes 0.7 m.

Photo 19. Field survey at Thandar Kyun Village.

7.2 MM-16: Pahtaw Village (12°26' 57.4"N, 98°35' 11.4"E)

Pahtaw Village is located on a small island, a few kilometers west of Myeik City. An eyewitness reported that the tsunami arrived at 12 noon in three waves (Photo 20 right).

Measurement (at 18:00 March 11) indicates that the tsunami height was 6.7 m above the sea level, while the high tide in the rainy season was 6.3 m. Assuming that the tsunami arrival time was 11:00, the corrected tsunami height becomes 2.2 m. An eyewitness indicated that the tide level just before the tsunami arrival was 4.6 m, making the tsunami height 2.1 m, very similar to the corrected height.

Photo 20. Field survey at Pahtaw Village.

8. Survey in Ayeyarwaddy Delta (MM-017 ~ MM-22)

A total of six localities (MM-17 to MM-22) near Pyinsalu were surveyed (Fig. 9) in Ayeyarwaddy Delta. In this region, 25 people lost their lives and 1,130 people were affected. For the Ayeyarwaddy Delta, the tsunami arrival times were between 11:00 and 11:45 am, according to eyewitness accounts. We assume that the tsunami arrival was 11:30, when the tide level was 1.9 m, for the entire region for the correction of tsunami heights. If the tsunami arrival was 11:00 or 11:45, when the tide levels were 2.0 m and 1.8 m, the corrected heights would be lower or higher by 0.1 m, respectively.

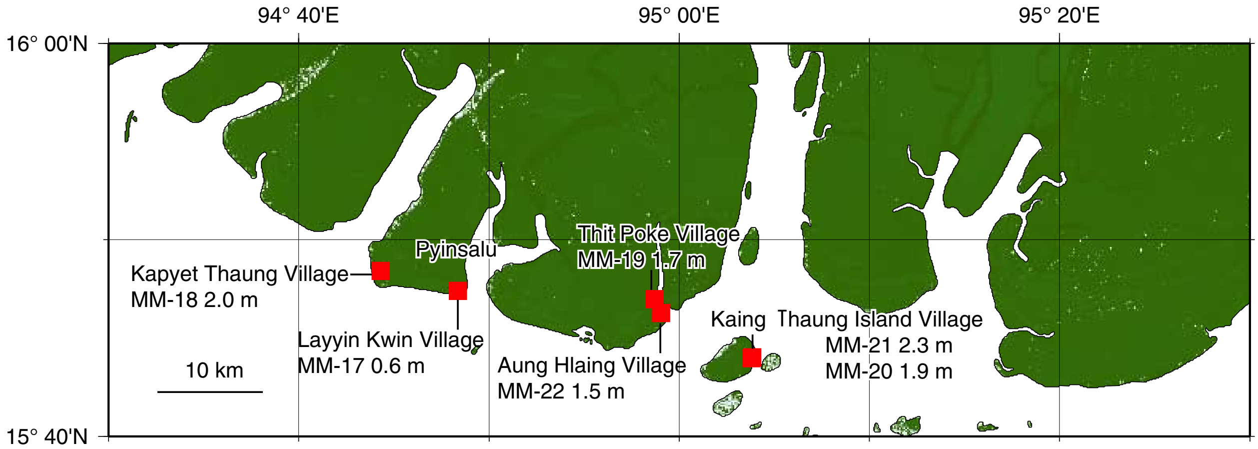


Fig. 9. Map of surveyed localities at Ayeyarwaddy Delta. Location numbers (in parenthesis) and corrected hights are shown at each location.

8.1 MM-17: Layyin Kwin (Airfield) Village (15°47’ 25.0”N, 94°48’ 22.9”E)

At Layyin Kwin Village, 16 huts out of 20 were washed away and one person was perished by the tsunami. According to an eyewitness, the tsunami arrived at 11:45 am, when the tide was low, in four waves. The inundation depth was about 20 cm.

Measurement at 14:46 on March 13, 2005 indicates that the tsunami level was 0.7 m above the sea level. Assuming that the tsunami arrived at 11:30, the corrected tsunami height becomes 0.6 m.

Photo 21. Field survey at Layyin Kwin (Airfield) Village near Pyinsalu.

8.2 MM-18: Kapyet Thaung Village (15°48' 22.0"N, 94°44' 19.3"E)

Kapyet Thaung Village is highly affected by the tsunami. Almost all of 130 huts were washed away and 17 casualties were reported (Photo 22). Some ships were dragged over inland. According to an eyewitness account, the tsunami arrived at 11 am in three waves with 15 minute intervals. Measurement at 17:51 on March 13 indicates that the tsunami height was 3.5 m above the sea level. Assuming that the tsunami arrived at 11:30, the corrected height becomes 2.0 m.

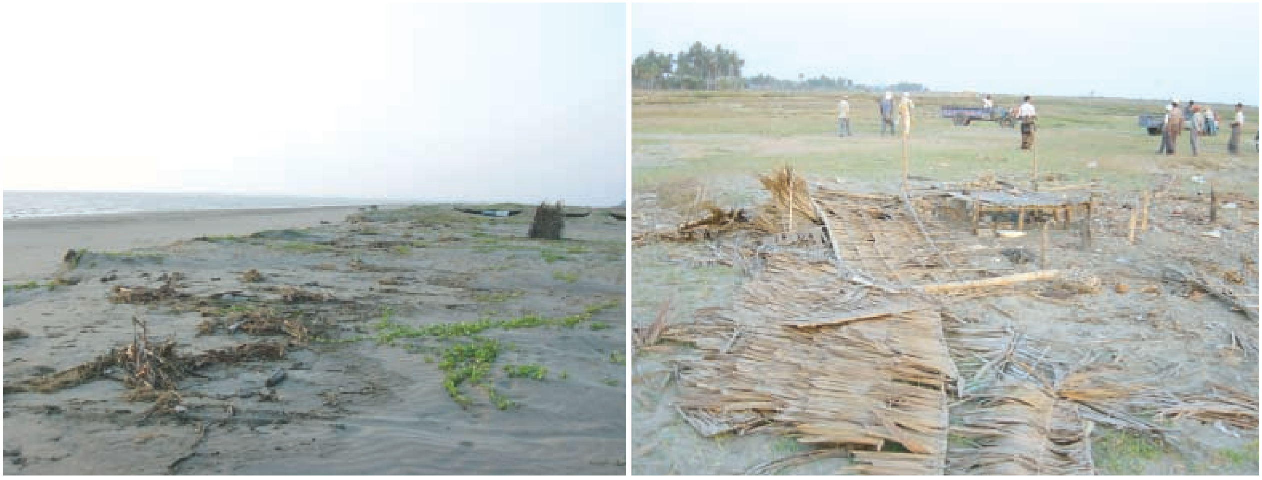


Photo 22. Field survey at Kapyet Thaung Village, Pyinsalu. Small huts were damaged by the tsunami (right photo) and the situation of ocean at the time of measurement (left).

8.3 MM-19: Thit Poke Village (15°46' 59.9"N, 94°58' 42.1"E)

Thit Poke Village is a small one with 332 houses and located at about 20 km from Pyinsalu. Two houses were damaged, but the tsunami caused no injuries or casualties. Interview with local people indicated that the tsunami inundated about 50 cm above the ground at 11:40 am. Measurement at 8:57 on March 14 indicates that the tsunami height was 2.9 m above the sea level. Assuming that the tsunami arrived at 11:30, the corrected height becomes 1.7 m.

Photo 23. Field survey at Thit Poke Village.

8.4 MM-20: Kaing Thaung Island Village, Pagoda (15°44’ 01.2”N, 95°03’ 51.2”E)

In Kaing Thaung Village, a pagoda built near the shore line was damaged by the tsunami. Part of the outer wall was knocked down (Photo 24 left) and watermark was clearly observed at 50 cm above the ground level (Photo 24 right). A Buddhist monk told us that the tsunami arrived at 11:30 am. Our measurement at 11:46 on March 14 indicates that the tsunami height was 1.8 m above the sea level. Assuming that the tsunami arrived at 11:30, the corrected height becomes 1.9 m.

Photo 24. Field survey at Kaing Thaung Island Pagoda. Walls of Pagoda are destructed by Tsunami (left) and Watermark at the wall (right).

8.5 MM-21: Kaing Thaung Island Village (15°43’ 59.6”N, 95°03’ 48.4”E)

In the village, 8 casualties and 16 damaged houses are reported by Department of Meteorology and Hydrology. An eyewitness account indicated that the tsunami height was 1.35 m above the ground (Photo 25). Measurement at 12:05 on March 14 indicates that the tsunami height was 2.0 m above the sea level, and the corrected tsunami height is 2.3 m.

Photo 25. Field survey at Kaing Thaung Island Village. Local people showed the inundation height of tsunami wave (right).

8.6 MM-22: Aung Hlaing Village (15°46’ 17.3”N, 94°59’ 02.3”E)

In Aung Hlaing Village, an eyewitness account indicated that the tsunami arrived at 11:45 am in two waves. The tsunami inundated about 60 cm above the ground (Photo 26 right). The second wave caused damage to 55 houses without any fatalities. Measurement at 14:06 on March 14 indicates that the tsunami height was 1.2 m above the sea level. Assuming that the tsunami arrived at 11:30, the corrected height becomes 1.5 m.

Photo 26. Survey at Aung Hlaing Village.

9. Discussion and Conclusions

9.1 Summary of tsunami heights

Survey data at the 22 localities (MM-01 to MM-22) from Myeik Archipalegos, Taninthayi Division and Ayeyarwaddy Delta reveal that tsunami heights along the Myanmar coast were not more than 3 m and the affected time was mostly between 9:30 and 13:00, that is 2 to 5.5 hours after the Sumatra-Andaman earthquake (Fig. 10). The arrival times vary at small distance in the same area, indicating that the reported times depend on the interviewees. Among the eyewitness we interviewed, nobody felt the earthquake shaking, making it difficult to estimate the time between the earthquake and tsunami arrival.

The tsunami height was much smaller than those of the neighboring Thai coast, where the heights were reportedly 5 to 20 m (Fig. 11). The tsunami heights along the Thai coasts were measured by three Japanese parties: Matsutomi *et al*. (2005) in December 30 – January 4, Satake *et al*. (2005) in January 28– 29, and Tsuji *et al*. (2005) in February 24 – March 4. The relatively smaller tsunami heights explain why the tsunami casualties, as reported as 71, were much smaller than those of other countries. One of the reasons for the smaller tsunami is due to the fact that the coast of Taninthayi Division is protected by offshore islands of the Myeik Archipelago trending north-south direction.

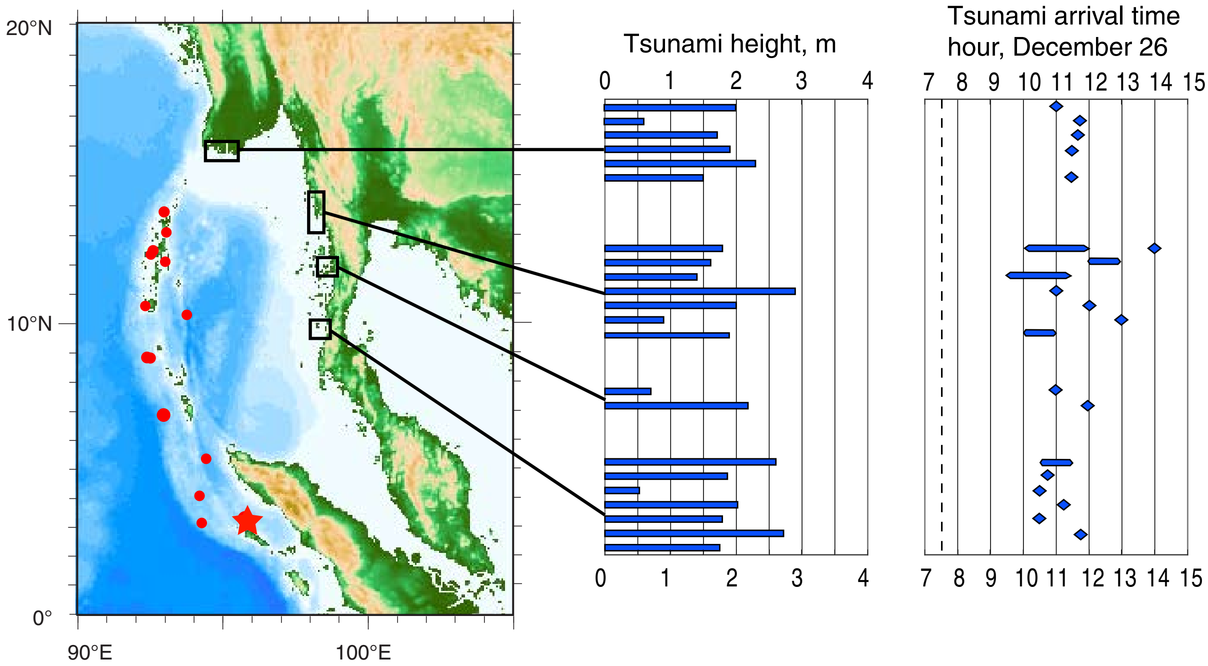


Fig. 10. Summary of tsunami survey. The left map shows the epicenter of the mainshock (star) and 1-day aftershocks (circles) according to U.S.G.S. The center panel is the corrected tsunami heights. The right panel indicates the tsunami arrival times according to eyewitness accounts. The vertical dashed line shows the earthquake origin time..

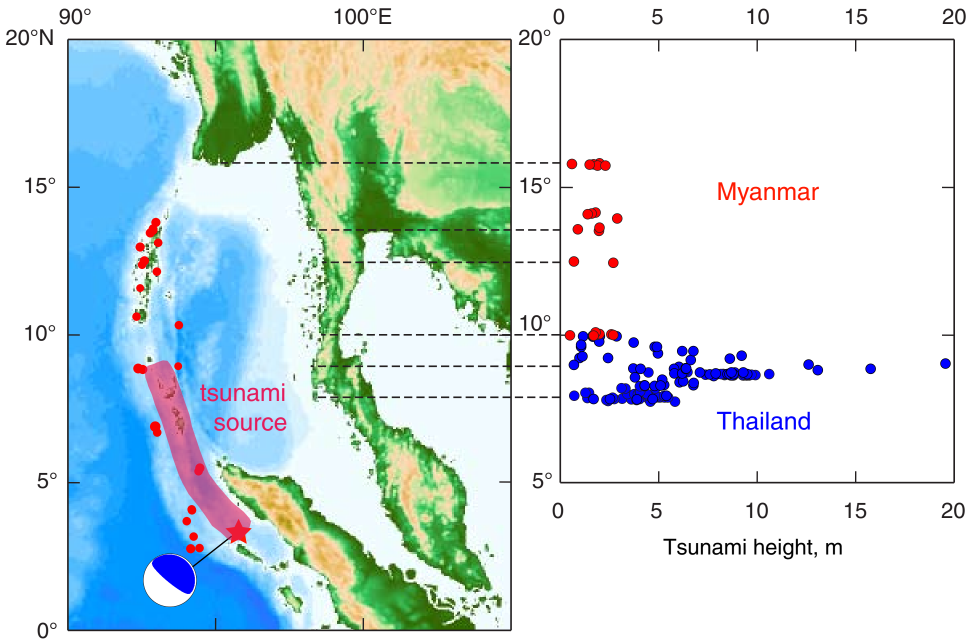


Fig. 11. Comparison of tsunami heights along the Myanmar and Thai coasts. The tsunami heights along the Thai coasts were surveyed by Matsutomi *et al*. (2005), Satake *et al*. (2005), and Tsuji *et al*. (2005). Inferred tsunami source area is shown.

9.2 Possible origin of rainy season high tide

Eyewitness often compared the December tsunami heights with the 'rainy season high tide'; at most locations, the tsunami height was similar or smaller than the 'rainy season high tide' level. As shown in Fig. 5, however, the calculated high tides are more or less similar throughout the year.

Seasonal change in sea level may be due to seasonal change in wind direction. In Andaman Sea, the SW wind toward land is dominant in rainy (Monsoon) season (from June through September), while the NE wind toward ocean is dominant in other seasons (Fig. 12). The sea level change due to the Monsoon wind is about 20 cm according to a Global Circulation Model, and the sea level change due to atmospheric pressure change is estimated as about 10 cm (M. Hirabara, Meteorological Research Institute, personal communication). The observed seasonal change in Sea Surface Height by a satellite in the central Andaman Sea is about 10 cm (N. Usui, Meteorological Research Institute, personal communication). Hence the amplitudes of sea level change due to Monsoon wind are smaller than the daily tidal changes.

A possible cause for the sea level change and the observed debris deposition may be caused by storm surge associated with Cyclones before and after the rainy season. In fact, during May 17 – 19, 2004, wind speed for more than 20 m/s was observed along the Andaman Sea coast (Fig. 13), and such a wind might have caused storm surges.

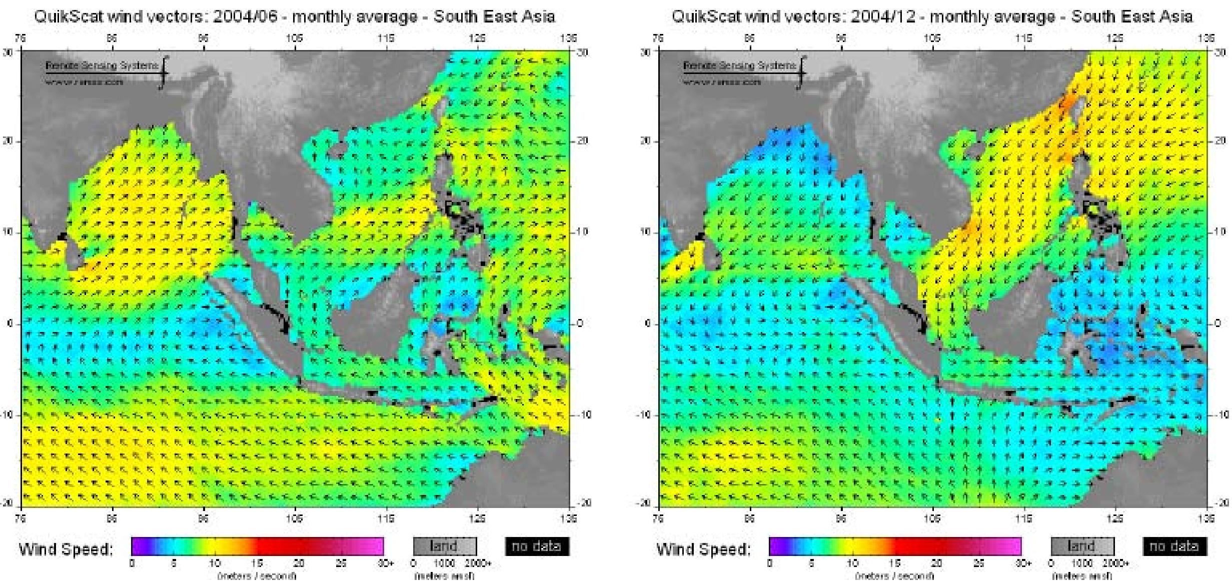


Fig. 12. Monthly-averaged wind direction and speed in South East Asia observed by QuickScat. http://www.ssmi.com/qscat/

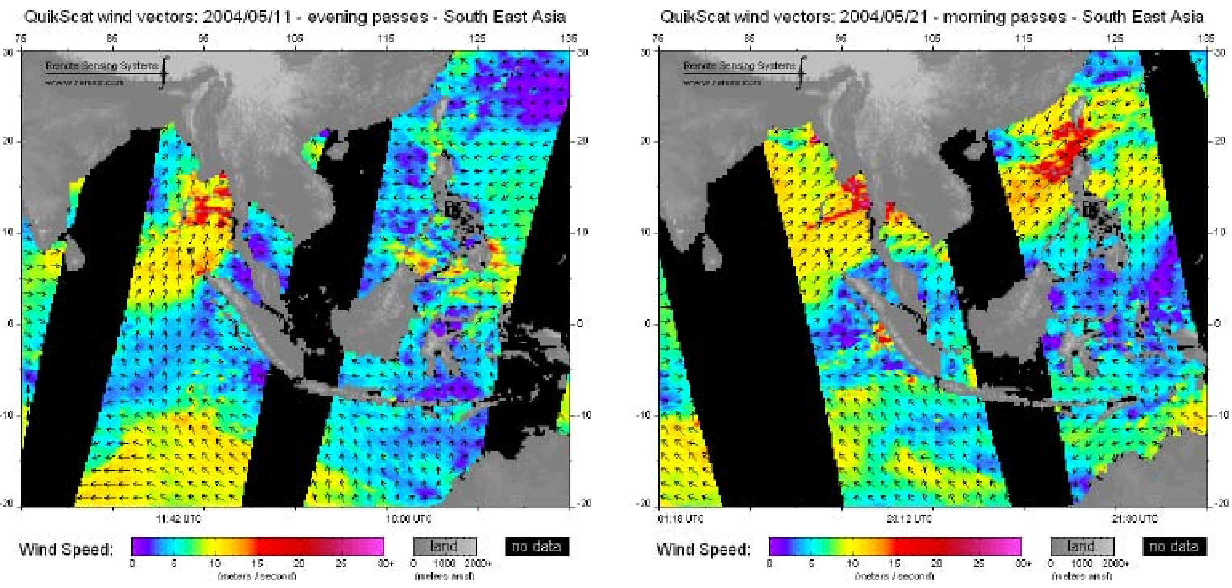
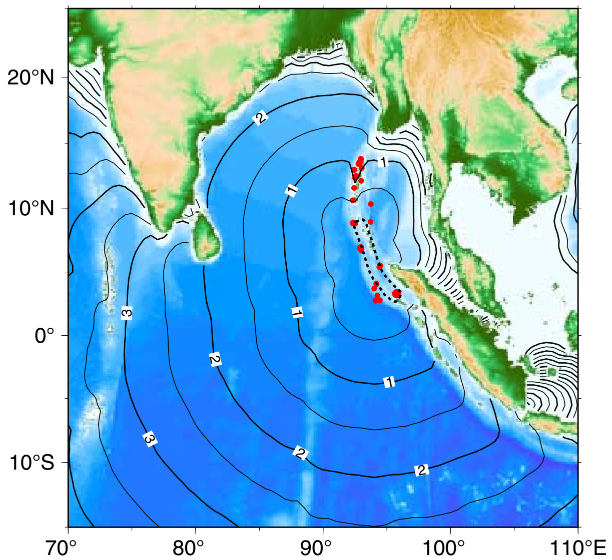


Fig. 13. Wind direction and speed in the evening of May 11, 2004 and morning of May 21, 2004, observed by QuickScat. http://www.ssmi.com/qscat/

9.3 Computed tsunami arrival times and height distribution

The tsunami source was estimated to be about 700 km long from analysis of tide gauge records (Lay *et al*., 2005). Tsunami travel times are computed from this source (Fig. 14). It shows that the tsunami travel times to Myanmar coast is 2.5 hours or more, indicating that the first tsunami was expected at around 10 am. Because of lack of ground shaking and the relatively small size of tsunami, coastal residents might not have noticed the tsunami at the first arrival.

The tsunami source extending in the north-south direction affects the amplitude distribution. Figure 15 shows the distribution of computed maximum amplitudes. The tsunami amplitudes are larger in the NE (toward Phuket) direction and SW (toward Maldives) direction. The computed tsunami amplitudes are relatively smaller along the Myanmar coast. The amplitudes are slightly large off Ayeyarwaddy Delta, because the shallow delta extends offshore to cause concentration of tsunami energy.



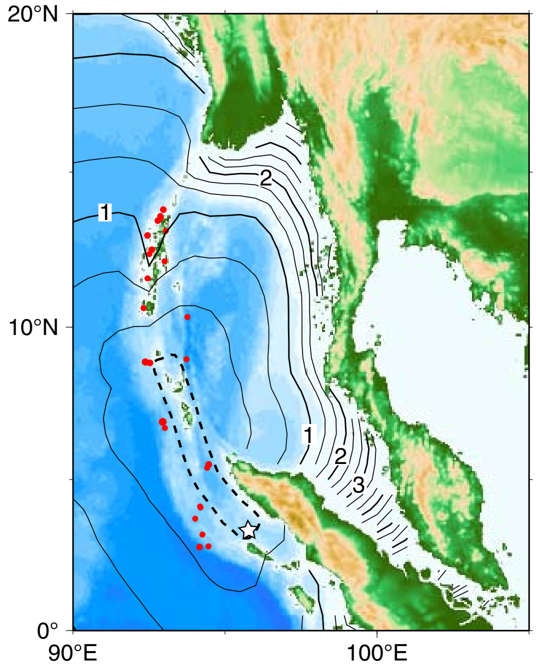


Fig. 14. Tsunami arrival times computed from a 700 km long tsunami source. Counter interval is 20 minutes with labels at each hour. The one-day aftershocks (circles) and the assumed tsunami source (dotted curve) are also shown.

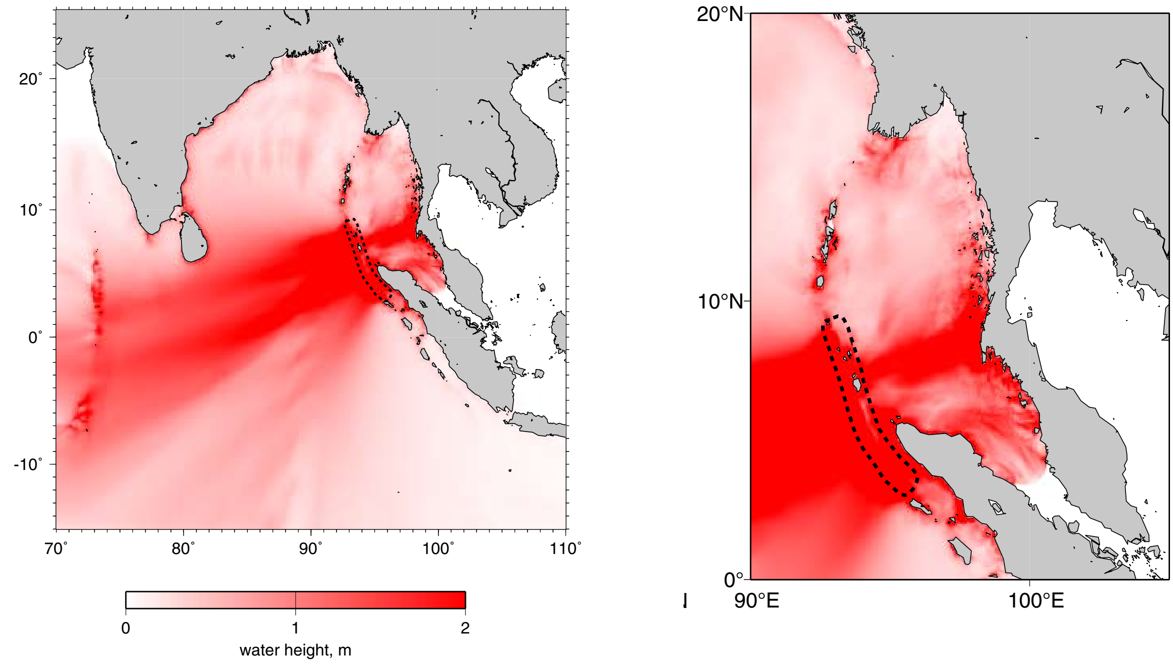


Fig. 15. Distribution of maximum tsunami heights computed from a 700 km long tsunami source. The assumed source region is also shown.

9.4 Vulnerability of the Myanmar Coast for tsunamis

In 2004, tsunami damage in Myanmar was relatively slight, compared to other countries such as Indonesia, Thailand, Sri Lanka and India. Numerous houses, including seasonal huts, are built along the Myanmar coasts without any protection for tsunamis. Our interviews indicate that the people did not feel earthquake in Tanintharyi Division or in Ayeyarwaddy Delta. The only way to notify people about the tsunami danger is through Tsunami Warning System. However, the infrastructure to disseminate the warning information is rather poor in Myanmar. In addition, coastal residents in most surveyed localities live the flat land, along the coast, especially in the Ayeyarwaddy Delta, and there is no higher elevation to evacuate. In order to prevent future tsunami hazards, evaluation of earthquake and tsunami potential in the northern extension of the Sunda subduction zone is needed. Study of historic and prehistoric tsunami events would be necessary for such evaluation.

Acknowledgements

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About the seasonal change in wind in Myanmar, Drs. Yamasaki, Nakazawa, Hirabara and Usui at Meteorological Research Institute provided us valuable information.

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Table 2. Summary of Survey.

No	Locality	Lat.	Long.	Tsunami	Measured	Type	Based	Reliability	Reported time	Measured at	Tide	Arrival	Tide
MM-01	Maungmagan Beach	14.1435	98.0908	1.8	2.4	R	D	A	10-12, 14	2005/3/7 10:27	2.7	11:00	3.3
MM-02	Thabawseik-Kyauksent Village	14.1056	98.0976	1.6	2.4	I	E	B	12-13	2005/3/7 11:25	2.5	11:00	3.3
MM-03	Myaw Yit Gyi Pagoda	14.0876	98.0702	1.4	3.3	R	E	B	9:30-11:30	2005/3/7 13:56	1.4	11:00	3.3
MM-04	Sann Lan Village	13.9395	98.0758	2.9	4.9	R	E	B	11	2005/3/7 16:40	1.3	11:00	3.3
MM-05	Kyet Lut Beach	13.559	98.1396	1.9	2.7	R	D	A	10-11	2005/3/8 12:30	3.0	11:00	3.3
MM-06	Kyaukmattat Village	13.581	98.1514	0.9	2.6	I	E	B	13, 20	2005/3/8 14:00	1.6	11:00	3.3
MM-07	Nyawbyin Village	13.6348	98.1459	2.0	4.3	R	E	B	12	2005/3/8 15:07	1.0	11:00	3.3
MM-08	Palautonton Island	10.0263	98.5122	2.5	1.8	I	W	A	10:30	2005/3/10 9:30	3.6	11:00	2.9
MM-09	Ywarthaya Village, Salonlay Island	10.0072	98.4803	1.8	1.0	R	E	B	11:15	2005/3/10 10:50	3.7	11:00	2.9
MM-10	Dolphin Club, Salon Island	9.9899	98.4878	0.4	0	R	E	B	11:45	2005/3/10 11:40	3.3	11:00	2.9
MM-11	Konnamaing Chaungwa Village	10.0362	98.5243	1.9	4.0	I	W	A	10:45	2005/3/10 14:40	0.8	11:00	2.9
MM-12	Tannyopada Village	10.0931	98.5151	1.7	4.4	R	E	B	10:30-11:00	2005/3/10 15:50	0.2	11:00	2.9
MM-13	Thirimyaing Quarter, Kawthaung	10.0008	98.5351	2.6	1.8	R	E	B	10:30	2005/3/10 16:54	0.2	11:00	2.9
MM-14	Myoma Jetty, Kawthaung	9.9778	98.5532	1.6	4.1	R	E	B		2005/3/10 17:30	0.4	11:00	2.9
MM-15	Thander Kyun Village	12.4942	98.5154	0.7	4.4	R	E	B	11	2005/3/11 16:10	0.5	11:00	4.2
MM-16	Pahtaw Village	12.4493	98.5865	2.2	6.7	R	E	B	12	2005/3/11 18:00	-0.3	11:00	4.2
MM-17	Layyin Kwin (Airfield) Village	15.7903	94.8064	0.6	0.7	I	E	B	11:45	2005/3/13 14:46	1.8	11:30	1.9
MM-18	Kapyet Thaung Village	15.8061	94.7387	2.0	3.5	R	E	B	11	2005/3/13 17:51	0.4	11:30	1.9
MM-19	Thit Poke Village	15.7833	94.9784	1.7	2.9	I	E	B	11:40	2005/3/14 8:57	0.7	11:30	1.9
MM-20	Kaing Thaung Island, Pagoda	15.7337	95.0642	1.9	1.8	I	W	A	11:30	2005/3/14 11:46	2.0	11:30	1.9
MM-21	Kaing Thaung Island Village	15.7332	95.0634	2.3	2.0	I	E	B		2005/3/14 12:05	2.2	11:30	1.9
MM-22	Aung Hlaing Vllage	15.7715	94.984	1.5	1.2	I	E	B	11:45	2005/3/14 14:06	2.2	11:30	1.9

要　旨

2004年スマトラ島沖巨大地震による津波は，インドネシア（約160,000人），タイ（約8,300人）などで多くの犠牲者を出したが，ミャンマーからは，71人という極端に少ない数字が報告された．余震域は震源から1,000 km以上離れたアンダマン諸島まで達し，アンダマン諸島では地殻変動も報告された．津波の波源域を推定するためには，周辺での津波の高さならびに到達時刻データが重要であることから，ミャンマーのタリンダーリ海岸ならびにイラワジ川河口の22ヶ所において，津波の現地調査を行った．

現地調査では，沿岸の住民への聞き込み，写真撮影，携帯型GPSによる位置測定，津波痕跡の高さならびに水平距離の測定（測定時の海面から）を行なった．津波の痕跡はさまざまな形で残されており，その種類によって信頼度が異なる．建物の内外の壁や海岸に痕跡が残っており，住民の証言と一致する際には信頼度は高いが，物的証拠がなく，証言だけに頼る際には信頼度は低い．津波の高さは，レーザー測距儀とオートレベルを用いて調査時の海面から測定した．津波到達時の高さを計算するため，測定時との潮位差を計算し，補正した．津波の到達時刻についての聞き込み結果は場所ごとに大きく異なるので，潮位補正のためには，タリンダーリ海岸では現地時刻の11:00に，イラワジ川河口では11:30に統一した．なお，地震発生は現地時刻で7:29頃である．

ダーウエイ（Dawei）周辺では7ヶ所において0.9〜2.9 mという津波高さを得た．証言による津波到達時刻は10:00〜14:00と大きくばらついた．Maungmagan beachでは，海岸に2本の痕跡が残っており，住民によると，低い方が12月の津波によるものであるとのことである．Thabawseik- Kyauksent村では，津波の高さは雨季の高潮位よりも低かった．Myaw Yit Gyiのパゴタでは僧侶が津波の来襲を観察しており，9:30〜11:30にかけて3回の波が押し寄せてきたこと，引き波の際には海岸から約200mにわたって海底が露出したこと，津波の高さは雨季の高潮位よりも高かったことを証言した．Sann Lan村，Kyaukmattat村，Nyawbyin村においても，津波の到達時刻と高さに関する証言を得た．Kyet Lut beachでも海岸に2本の痕跡が残っており，低い方が12月の津波，高い方は雨季の高潮位であるとのことである．

タイ国境に近いコートーン(Kawthaung)周辺では，7ヶ所で津波高さを測定し，0.4〜2.6 mという値を得た．証言による津波の到達時刻は10:30〜11:45とばらついた．Plautonton島へ渡る橋（全長600 m）が津波によって破損した．この島の民家はほとんどが水上に建設されており，津波によって床上数十cmまで浸水し，家財道具などに被害が出た．Salonlay島及びSalon島でも津波到達時刻と高さに関する証言を得たが，津波による被害はなかった．Konnamaing Chaungwaでは村の入り口の橋や数軒の家屋が津波による被害を受けた．家屋の内壁には津波の痕跡が残っていた．Tannyopada，Thirimyaing Quarterにおいても津波到達時刻と高さに関する証言を得たが，測定時の潮位が非常に低かったため，津波の高さの推定に関する誤差は大きい．Myoma Jettyでは津波の高さに関する証言のみが得られた．

ミャイック（Myeik）周辺では2ヶ所で津波高さを測定し，0.7，2.2 mという値を得た．証言によると津波の到達時刻はThandar Kyun村では11:00, Pahtaw村では12:00であった．後者では津波到達時の水面に関する証言も得られた．

イラワジ川河口付近では6ヶ所で津波高さを測定し，0.6〜2.3 mという結果を得た．この周辺では25名の犠牲者が出た．証言によると，津波の到達時刻は11:00〜11:45であった．Layyin Kwin村では約20軒の家屋のうち16軒が津波で流失し，1名が犠牲となった．Kapyet Thaung村では海岸の130軒の家屋がほとんどすべて流失し，17人の犠牲者が出た．Thi Poke村では2軒が被害を受けたが，人的被害はなかった．Kaing Thaung村では，パゴタの外壁が津波によって破損し，地上50 cmに津波の痕跡が残っていた．この村では，8名の犠牲者と16軒の家屋被害が報告されている．Aung Hlaing村では55軒に被害が生じたが，人的被害はなかった．

津波調査結果をまとめると，津波の高さは0.4〜2.9 m，到達時刻は9:30〜13:00となる．地震発生後，津波の到達まで2〜5.5時間という結果が得られたが，地震を感じた人はいなかったため，津波第1波の到達時を正確に見積もるのは困難である．津波の高さに関しては，住民の多くが雨季の高潮位と比較して同程度かやや低かったと証言した．天文潮汐による水位は一年を通じてほぼ一定であるが，乾季と雨季とでは季節風の向きが異なる．ただし，季節風により海水面の上昇は数十cm程度と推定されるため，「雨季の高潮位」はサイクロンに伴う高潮の可能性が高い．

波源の大きさを長さ700 km，幅100 kmと仮定し，津波の到達時間と最高水位分布を計算した．ミャンマー沿岸までの走時は約2.5時間以上であり，津波到達時刻は10:00以降と推定される．最高水位分布をみると，タイの海岸へ向けては水位が大きいが，ミャンマーでは比較的小さいこと，イラワジ川河口付近で津波の高さがやや大きくなることがわかる．

スマトラ島沖地震の津波の高さはタイのプーケット周辺で5 m程度，カオラク周辺で10 m以上，最大20 m近くであった（松富ほか，2005；都司ほか，2005；佐竹ほか，2005）が，その北のミャンマーでは3 m以下と急激に低くなる．ミャンマーにおける犠牲者数が少なかったのは，津波が小さかったことが原因であろう．

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