

Some observations and considerations on the damage to structures and coasts induced by the tsunami of the 2004 Sumatra earthquake

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Abstract

The Sumatra earthquake of December 26, 2004 with a moment magnitude of 9.0 induced the most disastrous tsunami known in the history of mankind. The authors as the members of the reconnaissance team dispatched by Japan Society of Civil Engineers to Aceh Province of Indonesia visited the tsunami affected area and had the chance to observe the damage induced by the tsunami on various structures and the western and north-east coasts of Sumatra Island through land and aerial surveys. The tsunami wave height was 20m on the western coast and 10m in Banda Aceh City, which is the capital of the Aceh province. More than 220000 people were killed in countries neighboring Indian Ocean. The number of people killed in Aceh province was 160000 alone and some of towns and villages on the western coast were completely wiped away from the surface of the earth. The structures surveyed by the authors involve harbors, industrial facilities, airports, bridges, roadways, natural or cut-slopes, rivers and their embankments, buildings, coasts. Following the brief description of the characteristics of the 2004 Sumatra earthquake and induced tsunami, the damage on various structures, buildings and coasts is presented and their engineering implications are discussed on the basis of sub-classifications of structures. The sole purpose of this report is illustrate the actual situation of damage caused by the tsunami of this mega-thrust earthquake, which may be of useful for the design of the tsunami-resistant structures and minimizing casualties in future.

1. INTRODUCTION

Indonesia is a huge archipelagic country extending 5,120 kilometers from east to west and 1,760 kilometers from north to south. It encompasses 13,667 islands, only 6,000 of which are inhabited. There are five main islands (Sumatra, Java, Kalimantan, Sulawesi, and Irian Jaya), two major archipelagos (Nusa Tenggara and the Maluku Islands), and sixty smaller archipelagos. The Province of Aceh is located on the northwest part of Sumatra Island and covers an area of 57,365,57 sq km. It is the western most province of the Indonesia with the Indian Ocean to the west, the Strait of Malacca to the east. Bukit Barisan mountain ranges with Tangse, Gayo and Alas upland is located in the central part of this province.

The oldest rocks of Sumatra Island are gneiss, schist and quartzite. They probably belong to several geological periods, but all were folded and denuded

before the Carboniferous beds were deposited. They form the backbone of the island, and crop out on the surface at intervals along the mountain chain, which runs parallel to the west coast. They are penetrated by granitic plutons at several locations, which are also Pre-Carboniferous. The next series of rocks consist of slates below and limestones above. It lies unconformably upon the older rocks. Tertiary deposits are very widely spread over the plains and low-lying regions. They consist of breccias, conglomerates, sandstones, marls, and limestones, with seams of coal and lignite. Oil and gas deposits are found in Sumatra Island and its continental shelf and they are located in the eastern side of the island in Aceh province. Indonesia has some 400 volcanoes, of which approximately 100 are active. Peuet-Sague and Bur Ni-Telong active volcanoes are located in the province of Aceh.

Indonesia forms the southeastern extremity of the Euro-Asian lithospheric plate. It is bounded by the

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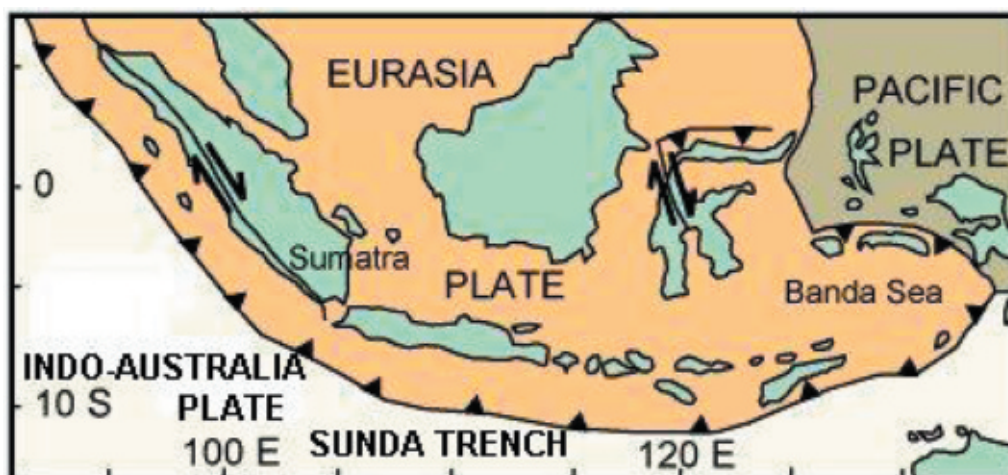


Figure 1 Plate tectonic model of Indonesia

northward-moving Indo-Australian and the westward-moving Pacific plates and it is certainly one of the most complex active tectonic zones on the earth (Figure 1). The subduction zone around the Euro-Asian plate is called the Sunda trench.

The earthquake occurred in the Sunda subduction zone nearby Sumatra Island at a depth of 10km and the ruptured fault was more than 1000km long and 100km wide with a relative displacement greater than 10m. Tsunami caused by this mega-thrust earthquake probably the most disastrous so far in the history of mankind and killed more than 220000 people in a region from Sumatra as far as to South Africa. Approximately 160000 people of Aceh province were killed by this tsunami. According to UN estimates, 655000 people are homeless and sheltering in scattered refugee camps across the province. Although the tsunami caused the great damage and the great loss of lives in countries neighboring Indian Ocean, the most severely hit region was the west and northwest coasts of Aceh province.

The all forms of damage expected from a tsunami were observed in this event. A wide band of the coastal zone was inundated and eroded by sea-water, the impact and drag forces of tsunami waves destroyed buildings, towns, cities, forests, fish farms, agricultural areas, infra-structures, industrial facilities, harbors and roadways, airports and killed both humans and animals.

The authors as the members of the reconnaissance team dispatched by Japan Society of Civil Engineers to Aceh Province of Indonesia visited the tsunami affected area in Aceh province of Indonesia and they made some observations on the tsunami damage induced on various structures and the western and north-east coasts of Sumatra Island through land and aerial surveys. The

observations and findings of this land and aerial surveys on the tsunami-affected area are presented and their implications are discussed in this article.

2. THE CHARACTERISTICS OF THE 2004 SUMATRA EARTHQUAKE

Sumatra Island as a part of Indonesia experienced very large earthquakes in the past and this high seismic activity has been still continuing. Seismic events with a magnitude greater than 8 took place in the Sumatran section of the Sunda subduction zone before the 26 December 2004 earthquake. For example, the seismic events with a magnitude of 8.5 and 9.0 in 1861 and 1833, respectively, resulted in the uplifts of corals ranging between 70cm to 230cm. However, the tsunamis caused by these earthquakes were limited to the south of the location of the 26 December 2004 event. Furthermore inland earthquakes also took place along the Sumatran fault system as shown in Figure 2. The pre-post seismicity of a region bounded between Latitudes 2°N to 6°N and Longitudes 95°E and 98°E is shown in Figure 3(a). The earthquake catalog of NEIC is used for this purpose and the magnitude of the earthquakes is set to be greater than 3. Figure 3(b) shows the seismicity projected onto a cross-section along the direction A-A shown in Figure 3(a), which is perpendicular to the strike of the subduction zone in the region of the earthquake. The pre-shocks occurred over a wide area. However, the distributions clearly indicate the existence of a subducting plate. Aftershocks are shallow and distributed along a gently inclined plane.

The magnitude, location and fault plane parameters of the earthquake are listed in Table 1. Some of fault plane solutions computed by various institutes listed in

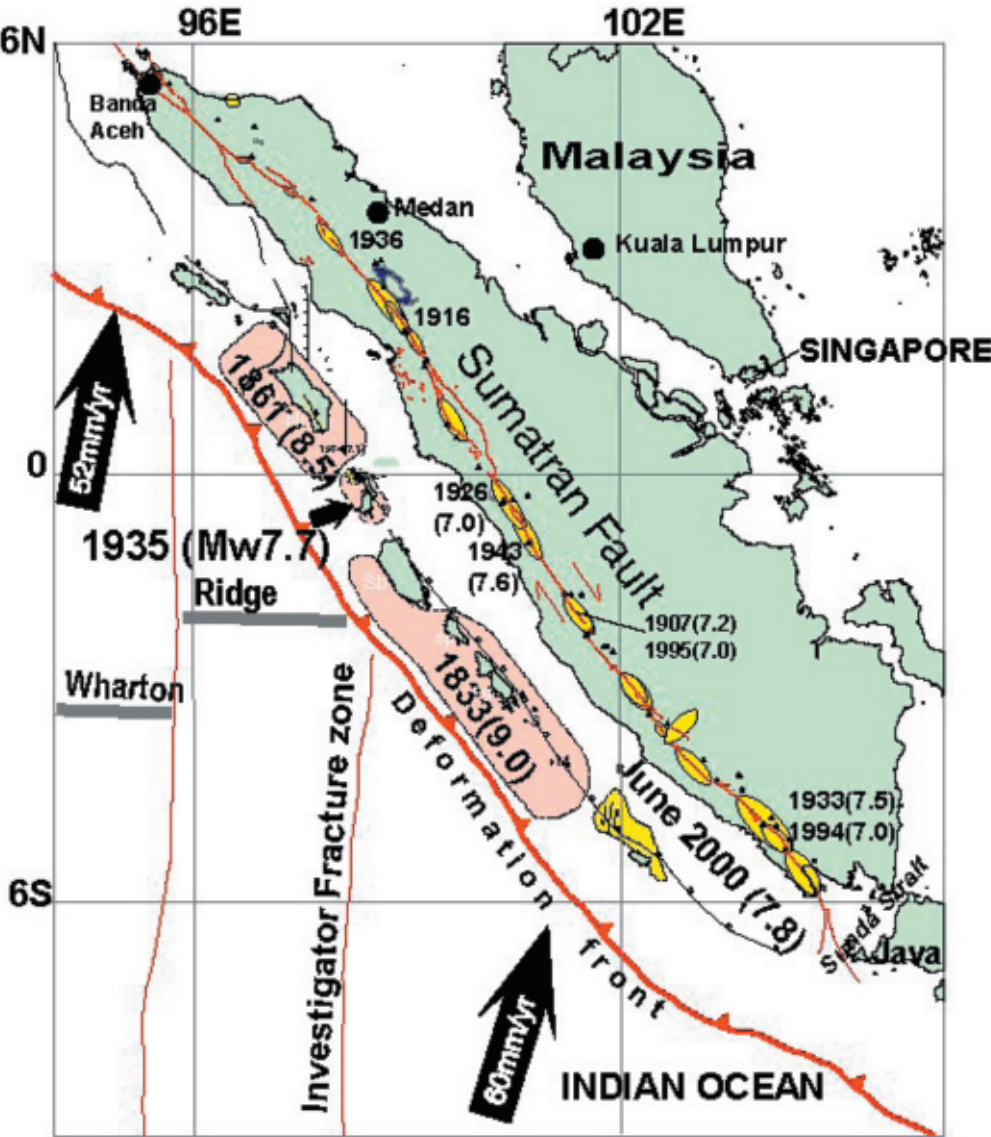


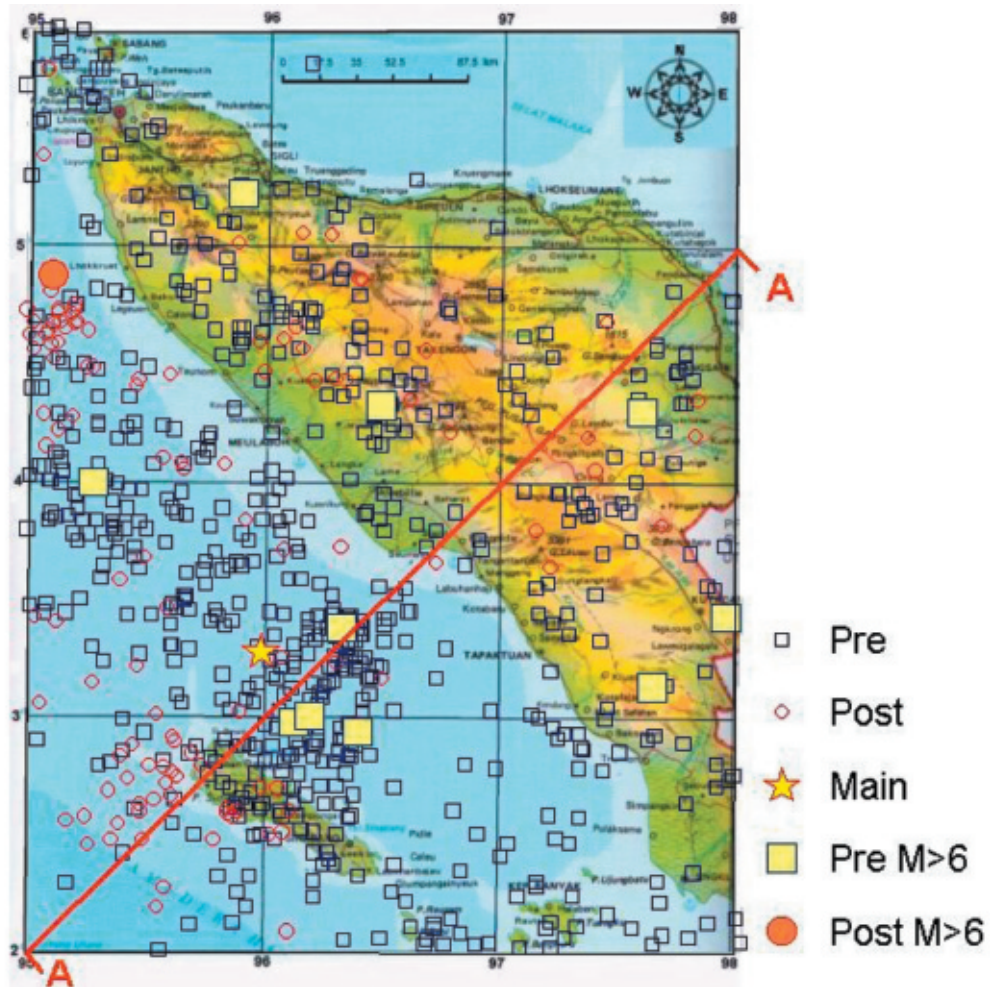
Figure 2 Seismo-tectonics of Sumatra Island (from Natawidjaja, 2005)

Table 1 and some of them are illustrated in Figure 4. The earthquake magnitude was estimated to be ranging between 8.2 and 9, and the fundamental faulting mode was thrust-type with a dextral sense. However, the solution obtained by the USGS indicated that strike-slip component of the faulting was sinistral, which is contrary to those of the solutions reported by other institutes. The causative fault was gently inclined. Furthermore, the depth of the earthquake was shallow and it seems that it took place along the upper surface of the Indo-Australian plate in contact with Euro-Asian plate. The faulting mechanism of this earthquake has the characteristics of a subducting plate-boundary earthquake as illustrated in Figure 5.

The rupture and slip characteristics estimated by several researchers are given in Table 2. Assuming that

the inclination of the fault plane is about 10°, the vertical component of the relative displacement should range between 1.5 and 3.5m. The measurements of the coastal line in Simeulue Island nearby the earthquake epicenter by Sieh confirmed these estimations. Several researchers estimated the rupture propagation of the causative fault, and the results obtained by ERI are shown in Figure 6. It seems that the causative fault was segmented. Depending upon the solutions, the segment number ranges from 2 to 5. The longest segment was very close the Banda Aceh and the distance between highest energy release point and Banda Aceh is about 80 –100km.

(a)



(b)

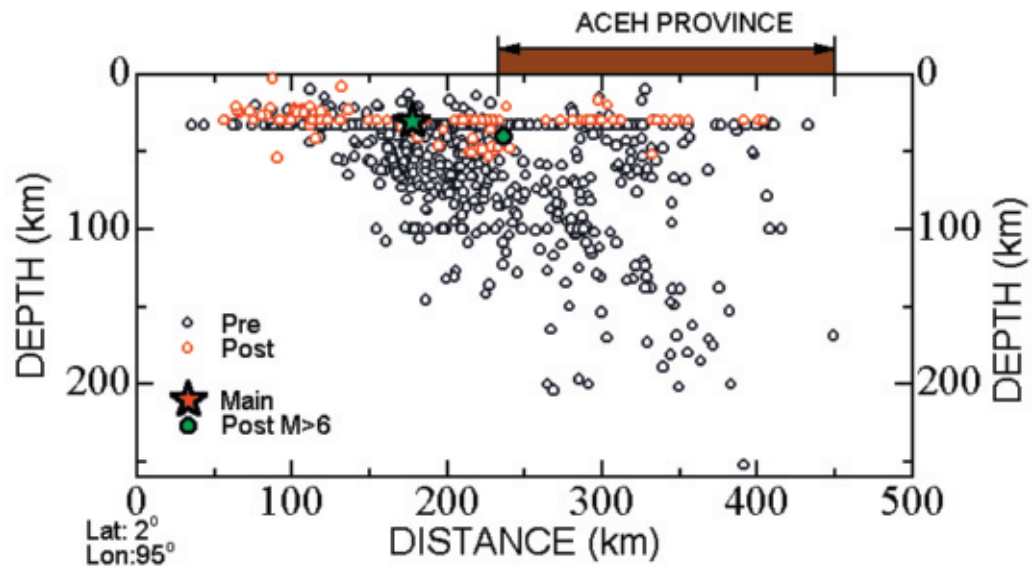


Figure 3 Pre-post seismicity of the region of the 26 December 2004 earthquake

Table 1 Main characteristics of the earthquake inferred by various Institutes

Institute	Mw	LAT (N)	LON (E)	DEPTH (km)	NP1 strike/dip/rake	NP2 strike/dip/rake
USGS	8.2	3.32	95.85	30	274/13/55	130/79/98
HARVARD	9.0	3.09	94.26	29	329/8/110	129/83/87
ITU (Turkey)	9.0	—	—	25	320/15/95	135/75/89

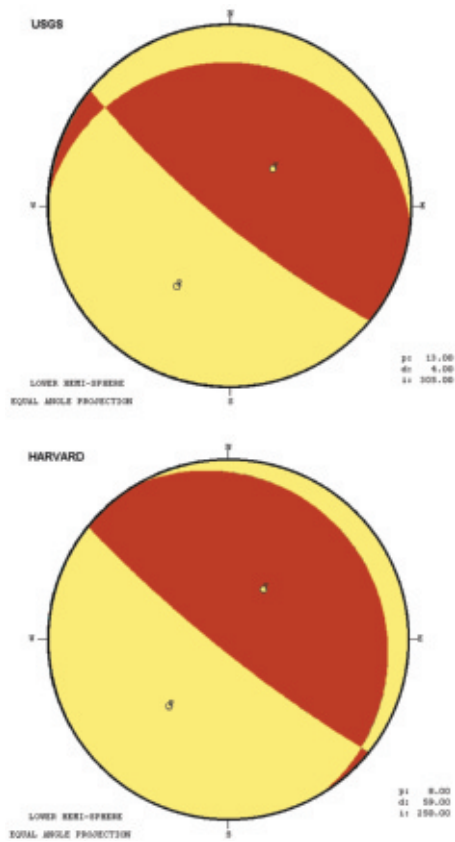


Figure 4 Fault plane solutions

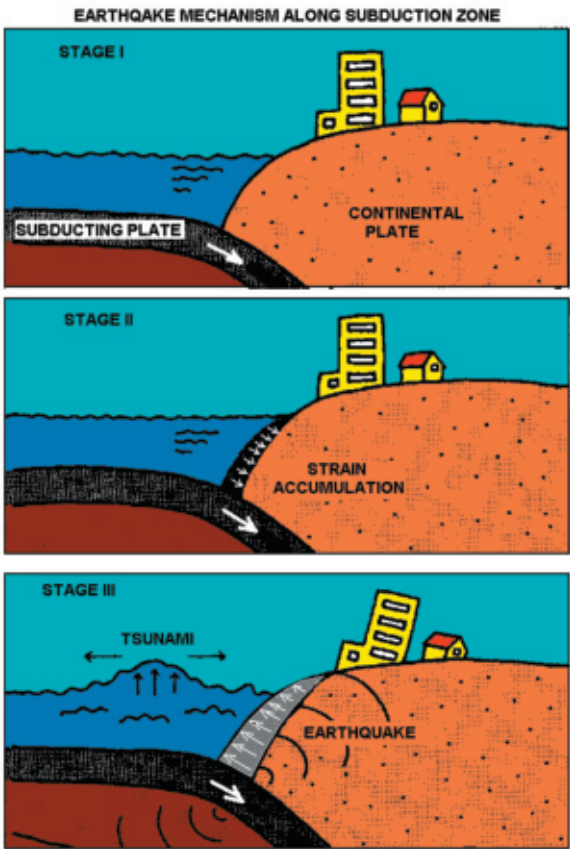


Figure 5 The mechanism of the 2004 Sumatra Eq.

Table 2 Rupture and slip characteristics of the earthquake fault

Reference	Magnitude	Length (km)	Slip (m)	Area (km ²)
Yamanaka (ERI)	9.0	850	8.9	850×200
Borges et al.	9.0	1000	9.0	1000×150
Dasgupta (India)	9.0	1000	15.0	1000×100
Aydan	8.6 (Ms)	975	9.75	975×45

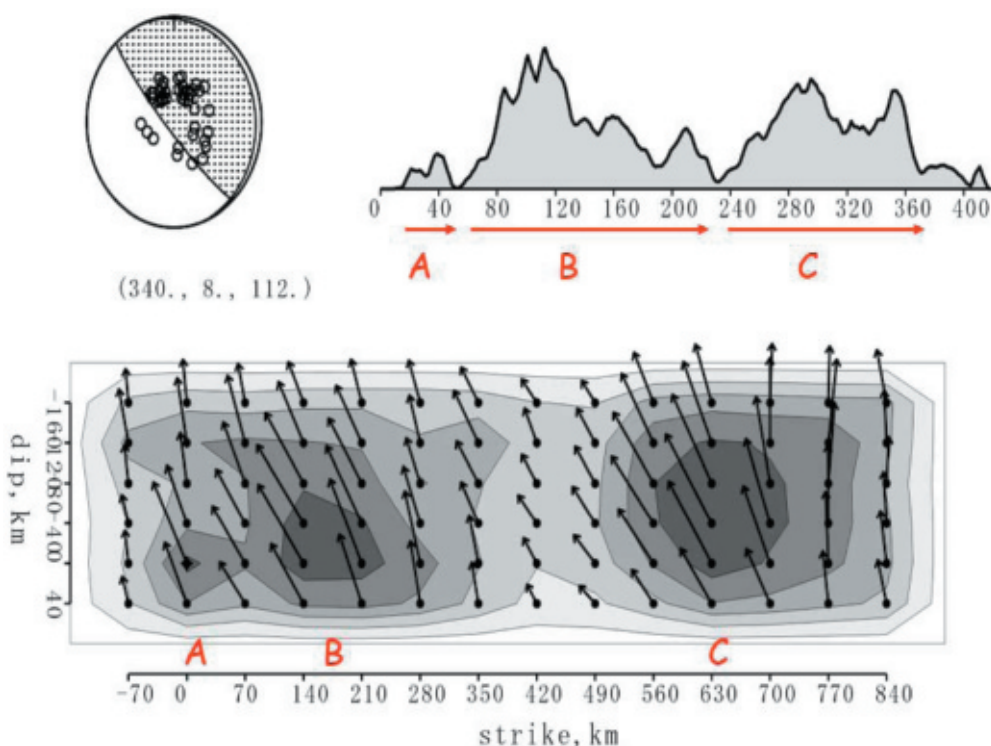


Figure 6 Inferred fault mechanism and slip distributions by Yamanaka (ERI)

3. THE CHARACTERISTICS OF THE TSUNAMI

The tsunami caused the great damage and the great loss of lives in countries neighboring Indian Ocean and the most severely hit region was the west and north coast of Aceh province. Out of 10000 original population of Leupung town, the estimated number of survivors was only several hundreds. According to official estimates, 8000 of the 18000 population of town Teunom were dead. 40000 people of Meulaboh city with a population of 120000 were killed by the tsunami. Surprisingly only 7 people out of 70000 people of Simeulue Island nearby the epicenter of the earthquake were killed, thanks to the saying of their ancestors “if there is an earthquake run for your life”.

Following the earthquake, many researchers at different institutes tried to simulate the arrival time, inundation distance and run-up height and also to measure the distribution of areas affected by the tsunami using satellite images, aerial photography and land surveying (Figure 7). The first tsunami waves arrived on the land within 20 minutes following the ground shaking, which lasted more than 400s.

The first computational estimations (Figure 8) for propagation and wave height of tsunami induced by this earthquake were done by K. Satake of (National Insti-

tute of Advanced Industrial Sciences and Technology (AIST, Japan)). Because of the fault geometry, the waves propagating to the East begin with a receding wave before flooding the coast. On the opposite, to the West a large wave suddenly hit the coast without warning. 10 hours later, the tsunami reached the African coast. Following the estimations by Satake, several researchers and institutes did similar type of simulations with better seabed topography and longer computation times.

The tsunami run-up height and inundation distance measured by several local and international groups in the tsunami-affected regions neighboring Indian Ocean. The maximum run-up height was measured as 34.5m in Lhonga in Aceh province by the group led by Tsuji of ERI of Tokyo University and the maximum inundation distance was about 7km according to UN reports (Figure 9).

No tsunami warning was issued in any country neighboring Indian Ocean although the scale and possibility of the tsunami was estimated by US Pacific Tsunami Warning Center, Japan and Australia. The officials at US Pacific Tsunami Warning Center seem that they tried to get in touch with authorities in the countries to be the affected by the possible tsunami. However, they could not find anybody to inform. Although there could be no or very limited time for such

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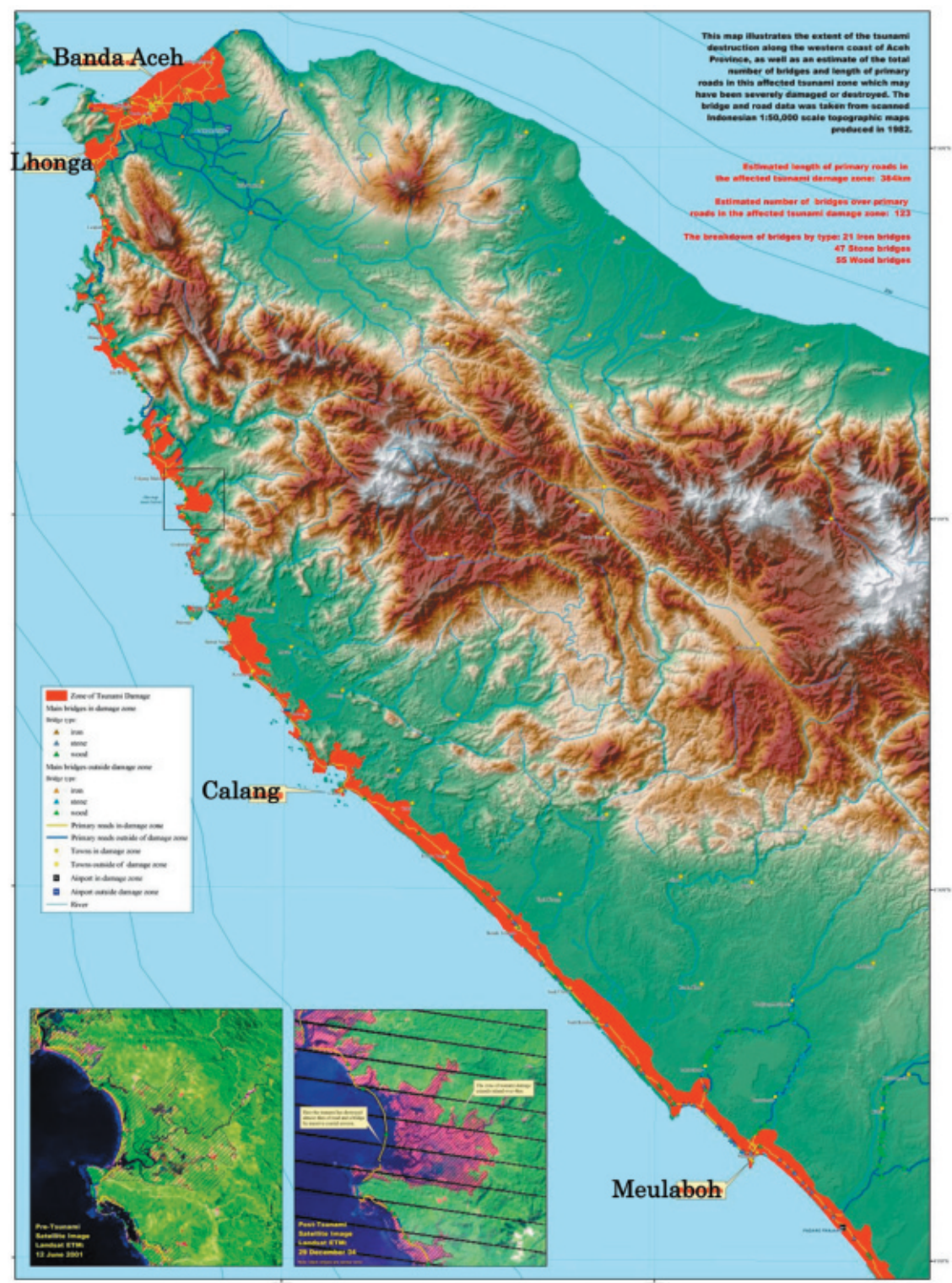


Figure 7 Inundated areas (red zone) in Aceh Province (from UNOSAT, 2005)

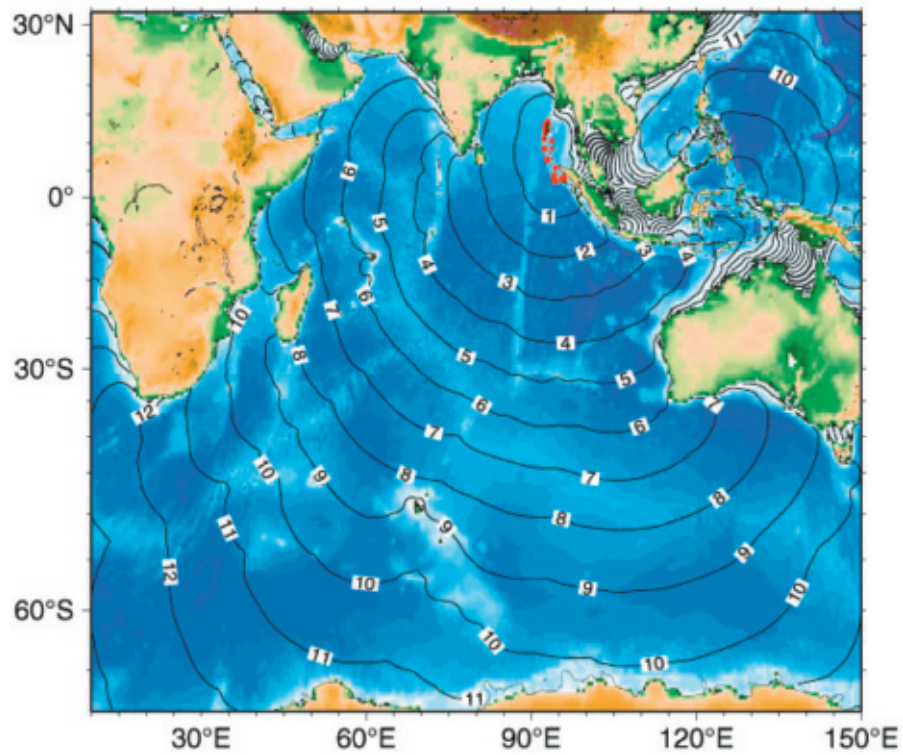


Figure 8 Estimated travel time by Satake (2005)

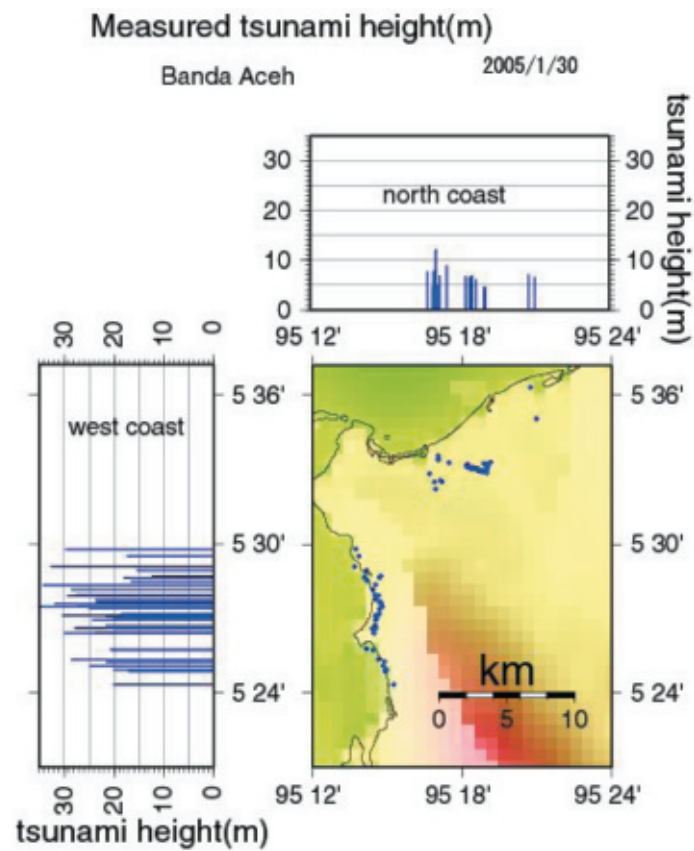


Figure 9 Run-up heights measured by the group led by Tsuji of ERI (2005)

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a warning for Aceh province, it is unbelievable that some warnings could not have been issued to other countries in spite of the availability of advanced communication options of this century.

4. TSUNAMI DAMAGE ON STRUCTURES AND COASTS

4.1 Tsunami Damage to Industrial Facilities

Aceh province is one of the major oil and natural gas producing regions in Indonesia. These facilities are on the east coast of province. None of these facilities were damaged either by ground shaking or induced tsunami. However, the cement plant at Lhonga was heavily damaged by tsunami waves. A French company originally built the plant and an Indonesian company now operates it. The steel structure sections, kiln and fuel storage tanks were heavily damaged by tsunami while RC silos remained intact (Figure 10(a)). It seems that tsunami waves reached a height of 15–20m in some sections and the steel beams and columns were either bended or buckled by the impact of tsunami waves and dragged objects. There were two cylindrical fuel tanks in the plant. One of them was completely destroyed while the other one was buckled and it was offset from its original location. Storage tanks from an oil tank farm in the eastern part of Banda Aceh city were displaced by the tsunami waves for a considerable distance from their original position as seen in Figure 10(b). The tanks were not fixed to the ground and some damage to piping did occur. An oil tank along the seashore in Meulaboh was hit by tsunami waves and that side of the tank was buckled. Furthermore, the settlement of the base of the tank occurred probably due to the liquefaction of foundation ground.

4.2 Tsunami Damage to Ports and Coastal Facilities

Tsunami induced heavy damage to ports and coastal facilities along the west and north coast of Sumatra Island. Figure 11 shows satellite views of Banda Aceh harbor before and after the earthquake. As noticed from the comparison of two satellite views, a huge area was damaged by the tsunami as a result of settlement and erosion due to probably ground liquefaction induced by ground shaking as well as due to the tsunami. The ground consists of sandy soil in this area. It is also of great interest that some parts of the dykes of the harbor disappeared. Besides the effects of liquefaction, the flow direction of tsunami waves might have some damaging effects on the missing section of the dykes.

The RC building of the port facility collapsed at the ground floor. However, the main cause of collapse was ground shaking rather than the tsunami waves. Large stone blocks were thrown by the tsunami waves over the wharf of the port. Although the wharf of a barge with a power generator was not damaged by the tsunami as seen in Figure 12, the barge was displaced from the wharf to a distance of 3km inland.

The port facility for the cement factory was also damaged by the tsunami. The piles of the wharf of the port were fractured by the impact forces of the capsized ship moored to the wharf as seen in Figure 13(a). Furthermore, the tetrapods of the wave-break were displaced for a considerable distance due to whirling of the tsunami waves (Figure 13(b)).

4.3 Tsunami Damage to Transportation Facilities

The damage of transportation facilities were mainly associated with roadways and bridges along the west coast between Banda Aceh and Meulaboh cities in Aceh



(a) Damaged cement factory



(b) Damaged oil tank farm and displaced tanks

Figure 10 Damage by the tsunami on industrial facilities



Figure 11 Satellite views of Banda Aceh port before and after the earthquake



Figure 12 Displaced barge with a power generator and its wharf (JSCE, 2005)



Figure 13 Damaged wharf and displaced tetrapods of wave-break at Lhonga port



(a) Collapsed truss bridge (b) Collapsed concrete bridge

Figure 14 Some examples of collapsed truss and concrete bridges

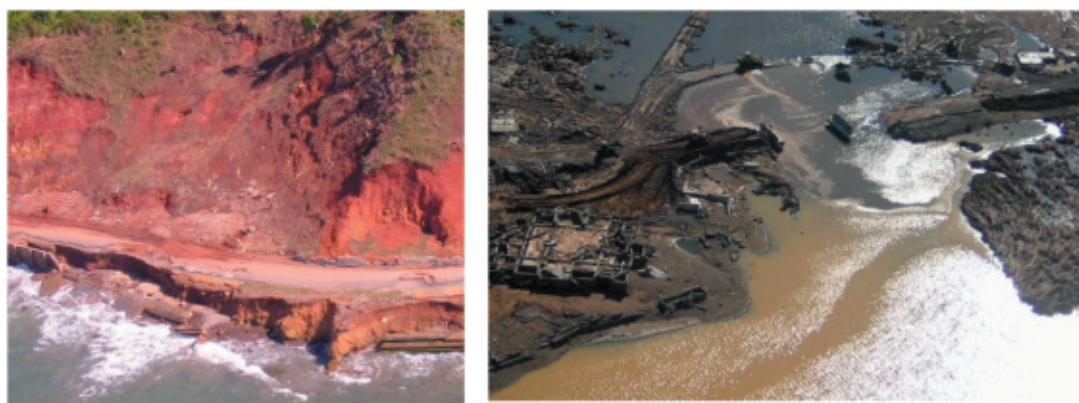


Figure 15 Roadway damage due to erosion and failures of embankments

province and caused by tsunami waves. The road between Banda Aceh and Meulaboh cities for a length of 384km was disrupted at 123 locations according to UN records. The only airport in the earthquake-affected region is Iskandar Muda airport.

Bridges are either of truss or reinforced concrete type. 21 truss type steel bridges were mainly uprooted from their bearings and 47 concrete bridges were collapsed or heavily damaged. The causes of the damage were the impact, drag and uplift forces of the tsunami as well as the impact of dragged objects by the tsunami waves. Figure 14 shows some examples of bridge failures. The following statements can be made on the damage of bridges:

- * When bridges have no shear keys, the girders are easily displaced due to horizontal forces.
- * When the bridges are sufficiently elevated for the unobstructed passage of tsunami and dragged materials, they are not damaged
- * When there are some obstructions such as small hills next to the bridges against tsunami waves, there is almost no damage or very limited damage to bridges

Damage to roadways was mainly due to the erosion resulting from tsunami waves, ground liquefaction or embankment failure (Figure 15). The damage was quite extensive in lowland area, nearby rivers and seashores next to steep slopes.

The only airport in the region of the earthquake was Iskandar Muda Airport to which commercial flights are in operation. This airport was not damaged either by ground shaking or by tsunami waves. However, the airstrip nearby Meulaboh was damaged by tsunami waves and by ground shaking.

4.4 Tsunami Damage to Buildings

The building stocks in the region of the earthquake can be broadly classified as follows: a) Wooden houses, b) Masonry (brick) houses, c) Reinforced Concrete buildings, and d) Mosques and Minarets. The causes of damage to buildings were ground shaking, tsunami or both. While the story number of buildings in the populated cities such as Banda Aceh and Meulaboh could be greater than 3, most of the buildings along the west coast of Sumatra were mainly single story or two story buildings.

Wooden houses are generally single story or two story buildings. These buildings were almost non-damaged in the regions, which were not affected by the tsunami. Therefore the main cause of the damage was tsunami. The tsunami may impose at least four types of loading, namely, impact force, drag force, hydrostatic water loading and buoyancy (uplift) force on wooden buildings. While impact and drag forces directly related to the velocity of tsunami, the hydrostatic and buoyancy forces depend upon the tsunami height and relative density differences between the building material and tsunami waves. Figure 16 shows some examples of damage to wooden houses.

Masonry (brick) houses are generally single story buildings and some of them could be 2 story buildings. Solid red clay bricks or hollow concrete blocks were used for constructing the masonry (brick) houses. Although concrete columns and slabs are utilized during the construction, they are merely used for achieving structural integrity. These buildings were not damaged in non-tsunami affected area. However, they were completely destroyed when the tsunami waves hit these structures. It seems that the impact force of the tsunami waves were quite high from the state of debris and the fallen tree trunks. The other force components of the



Figure 16 Damage to wooden houses



Figure 17 Damage to masonry (brick) buildings

tsunami waves could be drag forces and hydrostatic water loads. When the masonry (brick) houses are still standing, their walls were punched out. Figure 17 shows some example of damage to masonry (brick) houses.

Most of RC buildings have 2 to 3 stories. Nevertheless, new buildings for governmental offices and shopping malls have more than 3 stories. Commonly their story number is 5. Almost all new buildings in non-tsunami affected area were collapsed or heavily damaged by ground shaking. In addition, the collapsed or heavily damaged RC buildings were constructed nearby rivers or swampy areas. The RC structures in

tsunami-affected areas have stories ranging between 2 and 3. Some of columns were broken and in-fill walls were punched out by the impact forces of tsunami waves and tsunami-dragged objects (Figure 18). Nevertheless, they survived against the ground shaking and also the forces resulting from tsunami waves. The columns were generally ruptured or fractured at their mid-height, which implies that they were subjected to high bending forces. Furthermore, the broken columns and punched-out walls were facing the flow direction of the in-coming tsunami waves.

Mosques are generally built as single story RC



Figure 18 Damage to RC buildings in tsunami-affected area



Figure 19 Damage to mosques

structures without infill-walls. Mosques survived against the ground shaking and tsunami waves even in the severely hit areas (Figure 19). The possible reason for such a good performance against tsunami may be associated with its columnar structure without in-fill walls. The only mosque damaged in this earthquake is in Ulee Lheue district and the central RC column of the wall facing the sea was fractured by bending at mid-height. Many mosques built as masjid having no minarets. The grand mosques in Banda Aceh and Meulaboh have only minarets. Their minarets were lightly damaged, as they are slender structures.

CONCLUSIONS

The damage to civil engineering structures and buildings caused by the tsunami have been presented and the causes of damage were discussed. The outcomes of this investigation may be summarized as follows:

- * Impact, buoyancy, and dragging forces of the tsunami waves were the primary factors for the damage to bridges.
- * The roads built on the soft or sandy soils seemed to be completely washed away. Such sandy soils sections are generally located closed to the shore, or the present or past river courses.
- * Bridges with shear keys at bearing supports performed better against various forms of forces imposed by the tsunami waves.
- * Elevated bridges without obstructing the passage of tsunami waves and dragged objects performed well.
- * The port facilities were heavily damaged by ground liquefaction and erosion caused by shaking and tsunami.
- * Missing of the central part of small peninsula nearby Banda Aceh harbor could be due to liquefaction or landslide in addition to tsunami.

- * The RC buildings having story number less than 3 were in tsunami affected areas were destructed by impact force of tsunami waves and objects dragged by tsunami.
- * Wooden houses were mainly damaged by the uplift force of seawater and impact force of tsunami waves and objects dragged by tsunami.
- * Masonry (brick) houses were mainly damaged by the impact force of tsunami waves and objects dragged by tsunami.
- * Mosques performed well during ground shaking and tsunami and they can have a function as tsunami evacuation buildings.
- * International collaborations and an information sharing protocol on tsunami warning must be established.

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要 旨

2004年度スマトラ島沖地震・津波による構造物および海岸の被害について

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2004年12月26日午前8時7分(現地時間), スマトラ島北西部沖を震源とする M9.0 の巨大地震が発生した。地震による揺れは最も近い都市バンダアチェで気象庁震度の5程度と推定されたが, スマトラ島北西部沖合からマレー半島沖合のアンダマンニコバル諸島付近にいたる 1,000km 以上のプレート境界が動き, 20m を超える大津波が発生した。津波の被害はインド洋全域に及び, 死者・行方不明者合わせて20万人を超える人類史上まれにみる自然災害となった。国連の協力を得て, 特に陸路ではアプローチが難しい西海岸の様子をヘリコプターから観察する機会を得た。津波の高さは, バンダアチェ市北海岸で 10m 超, 震源断層線に面する西海岸で 20m 超である。バンダアチェ市内では, 北部海岸線からおおよそ 2 km までの家屋は RC 造も含めほぼ消滅, 4 km までは次第に建物が残存するが津波に運ばれた大量のヘドロと瓦礫で埋まった。西海岸では海岸平野にあった集落が完全に消滅, 風景が一変した。西海岸から駆け上った津波は標高 20m 弱の鞍部を越えてバンダアチェ市北海岸からの津波遡上域に達していた。大部分の建物が流された地域においても, モスクは残る所が散見された。モスクは丁重に作られ, かつ 1F はピロティ形式で津波が透過しやすいためと考えられる。バンダアチェからムラボーに至る西海岸沿いの道路で80橋近くが落橋した。桁の横ずれに抵抗するシアキーが有るものは津波高が高い地域においても流失を免れた。一方, 多数の橋梁でアバットメント背後の取り付け盛土が洗掘されていた。また, 元々脆弱な地盤に作られたと推定される区間の道路が選択的に洗掘されていた。バンダアチェ市北海岸の Ulee Lheue 港では大きな防波捨て石(約3トン)が岸壁上に打ち上げられていたが, 直杭棧橋やドルフィンに大きな被害は認められなかったとのこと。西海岸のセメント工場の岸壁では防波堤と岸壁の一部が損傷し, 停泊中の船舶が転覆していたが, 岸壁は使える状態だった。バンダアチェ市東方 25km の Krueng Raya 港に石油類の供給ターミナルがあり, 9 基のタンクの内, 空の3基が高さ 3~5 m の津波で浮き上がり, 最大で約 300m も移動した。バンダアチェ市西方西海岸のセメント工場では3基のタンクすべてが移動し押し潰された。同工場の鉄骨構造物も浮遊瓦礫の衝突などで大きな被害を受けたが, サイロ状のコンクリート構造物は目視する限り無被害だった。