Indonesian Journal on Geoscience Vol. 10 No. 2 Agust 2023: 167-179

INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Variation Parameters of The 2004 Indian Ocean Tsunami Model for Tsunami Prone Area Mapping in The Northern Part of Aceh Province

Siti Rohaya Syifa[1], Abdi Jihad[2]*, Muksin Umar[1], Vrieslend Haris Banyunegoro[2], and Andi Azhar Rusdin[2]

[1] Department of Physics, Universitas Syiah Kuala, Banda Aceh, Indonesia
[2]Meteorological, Climatological, and Geophysical Agency (BMKG), Geophysics Station of Aceh Besar, Indonesia

Corresponding author: abdi.jihad@bmkg.go.id
Manuscript received: March, 27, 2022; revised: January, 7, 2023; approved: May, 17, 2023; available online: July, 5, 2023

Abstract – A total of ten tsunami events occurred in Aceh Province from 1991 to 2012. This condition confirms that Aceh Province is very vulnerable to tsunami hazards. In 2004, a tsunami occurred due to the activity of the subduction zone on the west coast of Aceh with a magnitude of M_w 9.3. Since the 2004 tsunami, research on tsunamis has increased. The aim of this study is to reconstruct the 2004 tsunami models, to find out which models are suitable for the events of 2004. There are at least five models of earthquake source faults used for tsunami modeling in this study. The tsunami modeling was carried out numerically using the Tohoku University's Numerical Analysis Model Investigation (TUNAMI) programme. The maximum height obtained from the modeling is 58,05 m at the shoreline. The maximum height obtained from the best model is 17,73 m on land. The M5 fault model produced a tsunami height model that best matches the observation results validated by lowest RMS and highest correlation coefficient values.

Keywords: tsunami height, fault model, correlation coefficient, RMSE

How to cite this article:
Syifa, S.R., Jihad, A., Umar, M., Banyunegoro, V.H., and Rusdin, A.A., 2023. Variation Parameters of The 2004 Indian Ocean Tsunami Model for Tsunami Prone Area Mapping in The Northern Part of Aceh Province. *Indonesian Journal on Geoscience*, 10 (2), p.167-179. DOI: 10.17014/ijog.10.2.167-179

Introduction

Indonesia is located within three major tectonic plates, namely the Eurasian, Indian-Australian, and Pacific Plates. The border between the Eurasian Plate and Indian-Australian Plate in the western part of Indonesia forms Sunda Trench or commonly known as Sumatran Subduction Zone. Parallel to the subduction zone, in Sumatra there are several faults known as Sumatran Fault System that is created from the subduction movement (Hall, 2009). Sumatran Fault Zone traverses the hanging wall block of Sumatran Subduction Zone for 1900 km. Aceh-Andaman Megathrust segment has a slip-rate of 40 mm/year (Banyunegoro *et al.*, 2019). The results of earthquake relocation by Jihad *et al*. (2021) formed a pattern of the Sumatran Subduction Zone which tends to be gentle in the north, allowing deformation changes that induce large tsunami waves. Latief *et al*. (2000) divided six seismotectonic zones in Indonesia and explained tsunami occurrences by the zones (Figure 1). Zone A, Zone C, and Zone D are the three zones with the highest frequency of tsunami events due to earthquakes. Latief *et al*. (2000) mentioned since 1600 - 1999 there were fourteen tsunami events in West Sunda Arc or Zone A. As shown in Figure 1, out of a total of

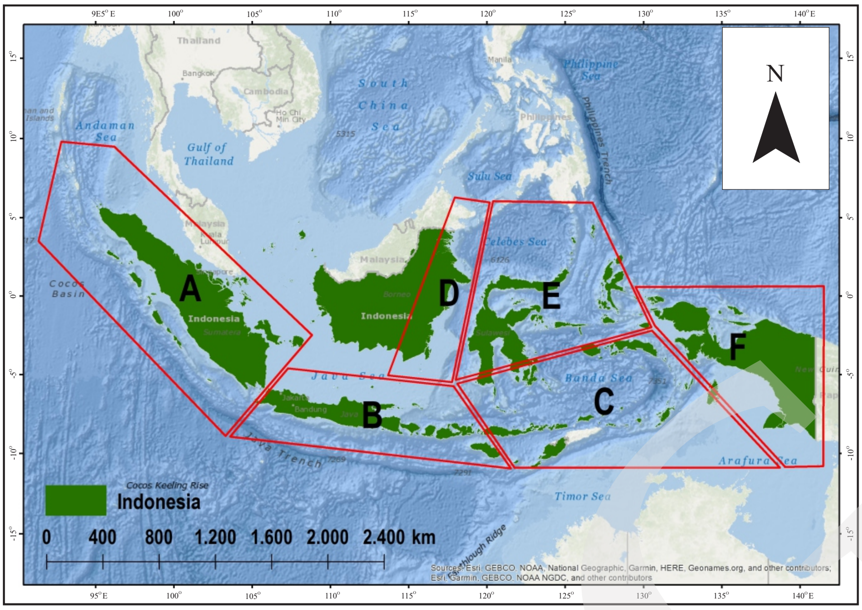

Figure 1. Division of the seismotectonic zone boundaries of Indonesia (Latief *et al*., 2000). Zone A is the West Sunda Arc area.

fourty-nine tsunami events, there were fourteen tsunami events caused by earthquakes, while others are caused by other generating sources such as volcanic eruptions and terrestrial slides (Latief *et al*., 2000). Pribadi (2013) explained that in the period of 1991−2012 there were twenty-seven tsunamis in Indonesia, ten of which were located in Sumatra and impacted Aceh Province.

The 2004 Sumatra-Andaman earthquake was an earthquake located off the west coast of Sumatra at a depth of 30 km with a magnitude of M_w 9.3 (Stein and Okal, 2005; USGS, 2020). The earthquake had an intensity of up to IX MMI, which translated into violent shocks causing heavy damage in the affected area (USGS, 2015). The earthquake generated a tsunami that affected various countries, including Indonesia with the worst impact, Sri Lanka, southern India, and Thailand. The tsunami disaster also caused the deaths of around 200,000 to 300,000 people (Poisson *et al*., 2011). Koshimura *et al*. (2009) stated that the release of stress along the Sunda megathrust or subduction zone is believed to be still very active, and has caused various significant earthquakes after the 2004 Sumatra-Andaman earthquake. Thus, tsunami generated by the earthquake has potential to be repeated in the future (Jihad and Banyunegoro, 2017).

Since the 2004, Indian Ocean tsunami, where a number of tsunami modeling research has increased, and efforts have been made to investigate the potential for subsequent events. Various studies were developed to reconstruct the fault model of the earthquake source as a tsunami generating scenario. The methods used include inversion of slip distribution from the GPS offset (Vigny *et al*., 2005; Subarya *et al*., 2006; Banerjee *et al*., 2007), from seismic waves (Ammon *et al*., 2005; Song *et al*., 2005; Tsai *et al*., 2005; Vallée, 2007), tidal recordings (Tanioka *et al*., 2006; Piatanesi and Lorito, 2007), and satellite altimetry data (Hirata *et al*., 2006; Sladen and Hébert, 2008). Several studies have also been carried out by combining two or more different data sets to create a better model. Several studies are also equipped with an inverted tsunami generator source analysis by conducting tsunami simulations.

Poisson *et al.* (2011) conducted a comparison on five fault models of tsunami generator sources, and simulated tsunami inundation in Sri Lanka using the GEOWAVE programme. The five models used include models proposed by Banerjee *et al.* (2007), Fujii and Satake, (2007), Piatanesi and Lorito, (2007), Rhie *et al.* (2007), and Chlieh *et al.* (2007). They obtained seismic inversion by Rhie *et al.* (2007) is the most suitable for the JASON-1 satellite data particularly around Sri Lanka. Then, Suppasri *et al.* (2011) studied the character of the 2004 tsunami in Thai terrestrial using the fault model of Koshimura *et al.* (2009) which is a modification of the fault model by the Disaster Control Research Centre (DCRC). The DCRC fault model is the best model for modeling the tsunami in a Thai terrestrial area (Suppasri *et al*., 2008).

In contrast to previous research, this study aims to determine the earthquake source model producing a tsunami height that most closely matches the results of tsunami observations by the National Oceanic and Atmospheric Administration (NOAA) for Banda Aceh City and Aceh Besar District, Aceh Province. The height of the tsunami modeling results with the closest value to the tsunami height from NOAA is considered the best source model for analyzing the tsunami hazard in the Banda Aceh-Aceh Besar region. A comparison of the modeled tsunami height values with the tsunami height records from NOAA was carried out based on the calculation of the root mean square error (RMSE) value and the correlation coefficient. The research results are expecd to be a reference for determining tsunami disaster mitigation measures and infrastructure development plans for Banda Aceh City and Aceh Besar District. Additional, a strength-weakness-opportunity-threat (SWOT) analysis as an appropriate policy has to be carried out to mitigate a negative impact of tsunami (Hidajat *et al*. 2023)

Furthermore, this study was carried out by modeling tsunami propagation based on five models of the 2004 Sumatra-Andaman earthquake source for generating tsunami. Fault geometry or segment for each model can be seen in Figure 2. Characteristics of each model are briefly listed in Table 1.

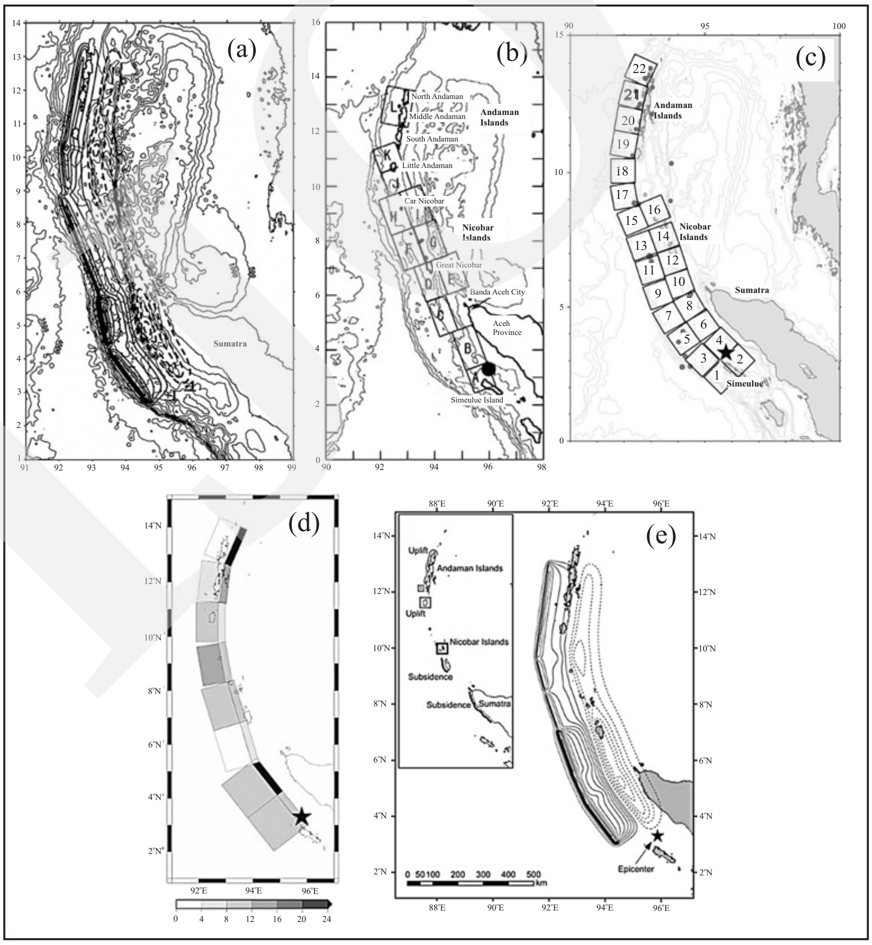

Figure 2. Fault model developed by: (a) Grilli *et al*. (2007), (b) Tanioka *et al.* (2006), (c) Fujii and Satake (2007), (d) Piatanesi and Lorito (2007), and (d) Koshimura *et al.* (2009).

Table 1. Details of Grid Sizes Used in Tsunami Inundation Modeling

Layer	N (sub fault)	Spatial Grid Size (°)	Map	Manning Coef.	Method
1	91.874 – 96.874, 9.774 – 4.774	1	GEBCO	0.025	Linear
2	93.084 – 96.084, 8.070 – 5.070	0.33333	GEBCO	0.025	Linear
3	94.198 – 95.698, 6.819 – 5.319	0.11111	GEBCO	0.025	Nonlinear
4	95.057 – 95.557, 5.893 – 5.393	0.037037	GEBCO + DEMNAS	0.06	Nonlinear

Tanioka *et al.* (2006) estimated the fault process of the 2004 Sumatra-Andaman earthquake using the tsunami waveform observed at five tide gauge stations and coseismic vertical deformation along the coastline. As a result, it is known that the fault is divided into twelve segments with an estimated average rupture speed of 1.7 km/s. Slip distribution is obtained from waveform inversion, and Rake angle for all segments is assumed to be 90°. Initial rupture time is varied for each segment. Fujii and Satake (2007) modeled the 2004 Sumatra-Andaman earthquake fault using the combined inversion of the recorded tsunami waveform at twelve tide gauge stations and three altimetry satellites. They divided the fault into twenty-two segments, with eight segments were divided into shallow and deep sections. The rupture speed was varied from 0.5 to 3.0 km/s with intervals of 0.5 km/s. The rise time for each segment is 1 - 2 minutes including the effect of rupture propagation in each segment. In addition, to improve bathymetry accuracy Fujii and Satake (2007) combined ETOPO2 data and digitized nautical charts from the United Kingdom Hydrographic Office (2005). Furthermore, Piatanesi and Lorito (2007) divided the fault into sixteen segments by following the geometry and mechanism of Banerjee *et al*. (2007). The rupture velocity ranges from 0.25 - 5.0 km/s or 2.0 - 2.25 km/s. The inversion was carried out in a fully nonlinear manner to obtain the distribution of slip and rupture velocity. Additionally, Grilli *et al*. (2007) estimated the source of the 2004 earthquake and tsunami. They defined five Okada sources for five segments, based on the standard half-plane solution for elastic dislocations assuming all segments have rake angle = 90° and dip angle = 12°. The tsunami simulation was carried out in the bay of Bengal area. Simulation results are compared with JASON-1 satellite measurements and tide gauge stations. In contrast to all of them, a recent study by Suppasri *et al*. (2011) developed a tsunami source model which is a modification of Koshimura *et al*. (2009) for the Thai terrestrial region. Vertical displacement was obtained from radar satellite imagery and field measurements for all displacements. Changes in sea level as the initial condition of the tsunami from each fault segment were estimated by Okada (1985) theory. Suppasri *et al*. (2011) conducted a tsunami simulation corrected by RMSE.

Methods

Tsunami simulation aims to estimate the height and arrival time of a tsunami in space and time. Tsunamis are assumed to be shallow water waves, because their wavelength is greater than the depth of the sea floor. The TUNAMI programme is based on the shallow water equation. In the wave theory, the vertical acceleration of the water particles is negligible compared to the gravitational acceleration, except for the propagation of the tsunami. The equations used (Imamura *et al*., 2006) are as follows:

The continuity equation,

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad \text{.....................................} (1)$$

momentum equations,

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} = 0 \ldots (2)$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} = 0 \ldots (3)$$

In addition to the earthquake scenario parameter data, the input data used for tsunami modeling are bathymetric data from GEBCO (The General Bathymetric Chart of The Oceans) and the Digital Elevation Model from BIG (Geospatial Information Agency). Determination of the resolution of the region is done with a nested grid scheme, shown in Figure 3.

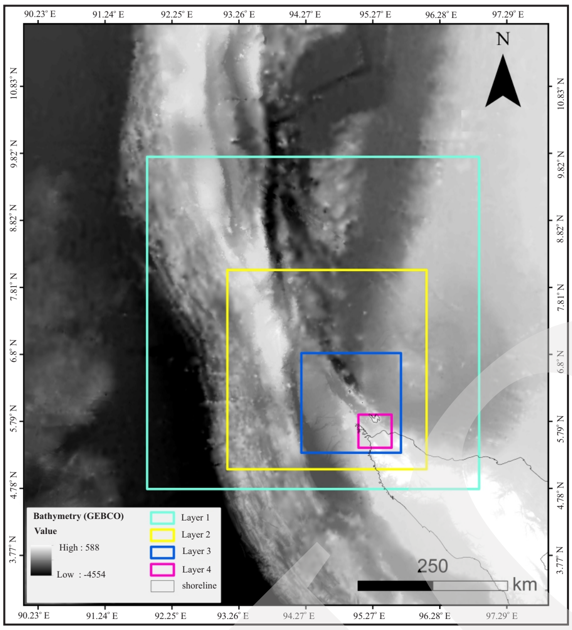

Figure 3. Determination of resolution of the region is done with a nested grid scheme.

The nested grid or commonly mentioned as layer, of the modeling area is shown in Figure 2. The location of the observation points is around Banda Aceh City and Aceh Besar District as shown in Figure 3. The roughness coefficient used are n = 0.025 which describes agricultural terrestrial cover, and n = 0.06 for residential terrestrial cover with moderate density (Kaiser *et al.*, 2011). Details of the grid size used in each layer are shown in Table 1.

A comparison between the height of the modeling results and the results of observations (NOAA) in Banda Aceh City and Aceh Besar District was analyzed based on the root mean square error (RMSE) and correlation coefficient. The RMSE value is calculated based on the equation bellow (Puspito and Gunawan, 2005).

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(elev^{cal} - elev^{obs})^2} \quad \text{......... (4)}$$

where:

N is the number of data,

$elev^{cal}$ is the height based on the model calculation, and

$elev^{obs}$ is the height of the observation result.

The correlation coefficient is calculated based on the equation:

$$r = \frac{\sum xy}{\sqrt{\sum xx \sum yy}} \quad \text{.. (5)}$$

with

$$\sum xy = \frac{\sum XY - \sum X \sum Y}{N}, \sum xx = \frac{\sum X^2 - (\sum X)^2}{N}, \sum yy = \frac{\sum Y^2 - (\sum Y)^2}{N} \quad \text{......... (6)}$$

where:

r is the correlation coefficient,

X is the height calculated by the model, and

Y is the height of the observation.

Correlation coefficient ranges from - 1 until 1 . A value of r = 1 indicates a perfect positive correlation, a value of r = -1 indicates a perfect negative correlation. Whilst r = 0 indicates there is no correlation between the value of the modeling results and the results of observations (Puspito and Gunawan, 2005).

In summary, the tsunami modeling parameters used in this study are shown in Table 2. The fault models compared in this study are symbolized as follows:

1. M1: fault model developed by Grilli *et al.* (2007)
2. M2: fault model developed by Tanioka *et al.* (2006)
3. M3: fault model developed by Fujii and Satake (2007)

Table 2. Parameters of Fault Model Used

Model	N (sub fault)	Slip (m)	Dip (°)	Rake (°)	Depth (km)	Magnitude M_w
M1	5	12 - 23	12	90	25	9.22
M2	12	0.0 - 24.4	3 - 17	90	5 - 27	9.2
M3	22	25 - 30	10	85 - 130	3 - 20	9.3
M4	16	0 - 30	11 - 35	90 - 139	30 - 50	9.1
M5	6	3 - 12	15	90	10	9.3

4. M4: fault model developed by Piatanesi and Lorito (2007)
5. M5: fault model developed by Koshimura *et al*. (2009).

Results and Analysis

The results of the tsunami modeling, that have been carried out, have obtained several information. Out of the five parameters of the tsunami model, the M2 fault model produces the maximum height, which is 34.66 m. Meanwhile, for the minimum tsunami modeling height generated by M3 is 8.14 m. The maximum and minimum values of the tsunami height of each model obtained from this study are presented in Table 3. Height values and location mentioned in this table are based on NOAA's observation points shown in Figure 4.

The value of the maximum correlation coefficient between the height observed by NOAA and the modeling results obtained by M5 is 0.90 and the minimum correlation coefficient obtained by M2 is 0.28. This indicates that the results of the tsunami modeling using the fault model M5 have a very strong relationship with the tsunami height observed by NOAA, while the modeling results using the fault model of M2 has a weak relationship with the height of the NOAA observations.

The maximum tsunami height on terrestrial generated by tsunami modeling based on the M2 fault model is 27.37 m in Peukan Bada. Meanwhile, at the same point, the observation is worth 11.9 m. While the minimum height on terrestrial generated by tsunami modeling based on the M5 fault model is 9.86 m with observation height of 8.8 m at the same point. In addition, the modeling results using M5 produce a maximum height of 17.73 m on terrestrial with an observation height at the same point of 20.3 m.

A comparison of the height of the NOAA tsunami observations and the results was analyzed based on the RMSE value, correlation coefficient (R), and coefficient of determination (R^2) to show the relationship between modeling and observations. The lowest RMSE value is 2.47 for the fault model of M5, while the highest RMSE value for the M4 is 4.12.

In addition, the tsunami heights modelled by using M2 source model weakly fit the observed height by NOAA which indicated by 7.69 % R^2 value. While using M5, the R^2 value is 81.59 %

Table 3. Maximum and Minimum Values of Tsunami Height Obtained from this Study

Model	Maximum tsunami height (m)	Minimum tsunami height (m)	Location of maximum tsunami height
M1	32.56	10.43	Leupung coastline
M2	34.66	15.87	Peukan Bada coastline
M3	27.74	8.14	Lhoknga coastline
M4	32.23	10.59	Lhoknga coastline
M5	29.28	9.49	100 m from Lhoknga coastline
NOAA Observation	34.7	6.58	Lhoknga coastline

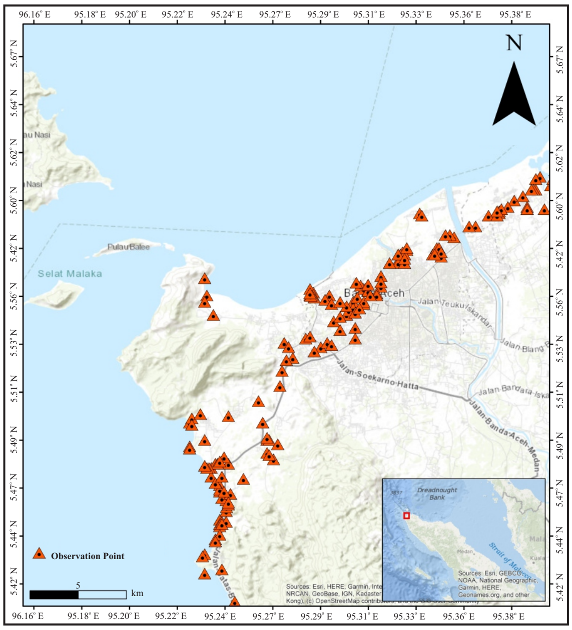

Figure 4. Observation points of NOAA.

which implies strong relation. The relationship between the observed height of NOAA and the height of the modeling results is described in detail in the determination graph (R^2) in Figure 5. Details of the validation results are listed down in Table 4. Meanwhile, the modeling results in the form of an inundation zone are shown in Figure 6.

Discussion

This study results showed that the fault model M5 of Koshimura *et al*. (2009) is a fault model that is suitable for mapping the Tsunami Prone Areas or "Kawasan Rawan Bencana (KRB)" for Banda Aceh City and Aceh Besar District. There are three out of the five models (M1, M4, M5) that generate tsunami heights with very strong relationship to the heights observed by NOAA. While modeling using fault model M2 by Tanioka *et al*. (2006) obtained a weak relationship between modeling height and NOAA observations.

The fault model which is inverted from the altimetry and tsunami waveform data produces a tsunami height that most closely matches the observed height as applied to M1, M3, and M4. However, the result of calculation of tsunami height that is the least in suitable with the observed results is generated by the fault model which is also inverted from the tsunami waveform, namely M2. While, the M1 fault model which is inverted from the seismic waveform produces a more suitable tsunami height.

The effect of variations in slip, dip, rake, and depth on the fault model (M1, M5) which is minimal gives tsunami height values that is

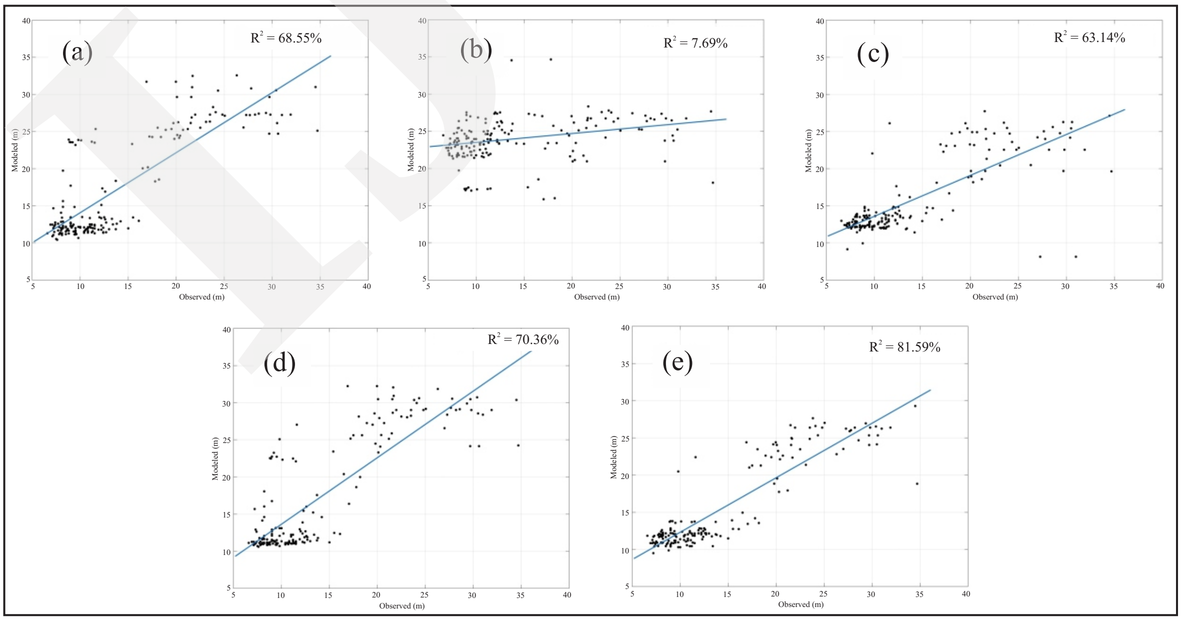

Figure 5. Linear regression graph comparison of modeling results with NOAA observations. (a) M1, (b) M2, (c) M3, (d) M4, (e) M5.

Table 4. Details of Validation Results of Tsunami Height Modeling Results Based on Applied Fault Models

Model	Data Source	RMSE (m)	R	R^2
M1	Seismic waveform	10.43	0.82793	68.55 %
M2	Tide gauge	15.87	0.27724	7.686 %
M3	Altimetry + tide gauge	8.14	0.79458	63.14 %
M4	Tide gauge	10.59	0.83881	70.36 %
M5	Altimetry + radar + field measurement	9.49	0.90325	81.59 %

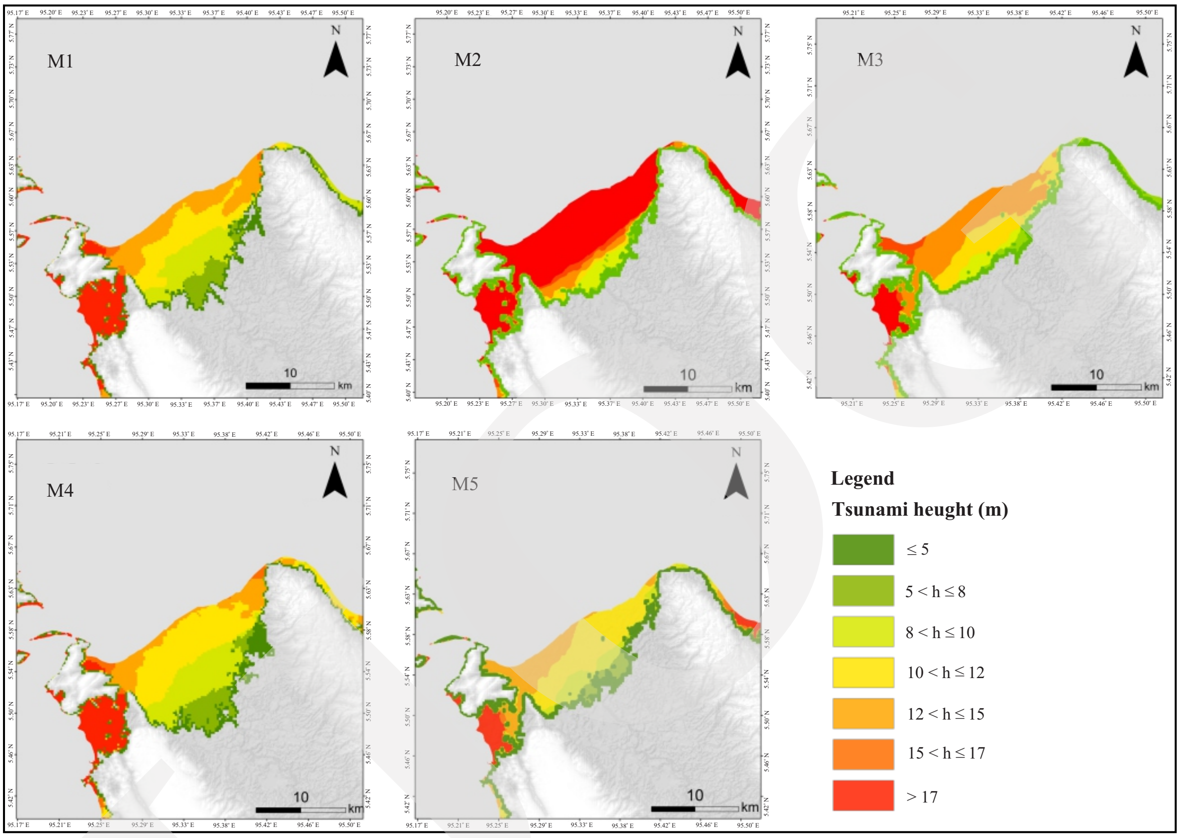

Figure 6. Modeled tsunami inundation layout based on the 2004 Sumatra-Andaman earthquake. Source of the tsunami generator is fault model (a) M1, (b) M2, (c) M3, (d) M4, and (e) M5.

more in line with observations height values. M5 produces a slightly higher tsunami height than the observed results, but the difference in height is not as significant as in M2, where the difference in height is massively significant.

Ultimately, the resulting model is a refinement of the previous modeling. The model proposed by Tanioka *et al*. (2006) is the first model to be estimated, in the form of blocks that are arranged in a quite straight line without following the actual path of the subduction zone. While the models developed in the following years such as M1 by Grilli *et al*. (2007), M3 by Fujii and Satake (2007), M4 by Piatanesi and Lorito (2007), and M5 Koshimura *et al*. (2009) show the arrangement of fault blocks that bend following the path of the subduction zone.

Research that examines the parameters of the 2004 tsunami fault model has previously been carried out for several areas affected by the 2004 tsunami. For example, Poisson *et al.* (2011) conducted tsunami modeling to study the effect of five fault models and the effect of rupture kinematics of the 2004 Indian Ocean tsunami generator. The result of the calculation of the tsunami height is compared with the recorded sea level height of

Jason-1. Patterns of maximum sea level elevation were analyzed around the Bay of Bengal and the coast of Sri Lanka. Another study was performed previously by Puspito and Gunawan (2005), the 2004 Indian Ocean Tsunami modeled using a fault model developed by Yagi (2005). The fault segment dislocations are assumed to be 11 m, and are homogeneous at all segments. Eyewitnesses reported that the tsunami arrived on the west coast of Sumatra about 15 - 20 minutes after the earthquake. Comparison of the calculation of tsunami height with tide gauge observations in Sibolga and Belawan areas was analyzed based on the root mean square error (RMSE) and correlation coefficient (R). The RMSE value in Sibolga is around 36% of the height observed at the first arrival, whereas in Belawan the RMSE value is around 60% of the observation height. The correlation coefficients in Sibolga and Belawan are 0.87 and 0.59, respectively, indicating a good relationship.

The difference of modeled tsunami with the observation results is due to several limitations. Bathymetry data used in this study has a large pixel size. The simulation is carried out based on the assumption that the southern segment of the rupture area is the only tsunami source without precisely considering the northern segments. This limitation causes the tsunami height model obtained to be different from the observation.

Based on the results of the study, all models state that Banda Aceh City is still a tsunami-prone area. It can be seen from the resulting inundation zone, that Banda Aceh City is classified as an area with a height of inundation of > 3 m. Referring to the Banda Aceh Regional Spatial Plan or "Rencana Tata Ruang Wilayah Banda Aceh (RTRW)" for 2009 - 2029, the inundation area includes strategic areas or parts of Banda Aceh City development area such as; Old City area as a development of socio-cultural centres, trade and services, offices, arrangement of heritage areas, provision of RTH, and sustainable management of marine fisheries. There are at least four parts of the development area in the "Rencana Tata Ruang Wilayah Banda Aceh (RTRW)" for 2009 - 2029, as shown in Figure 7, including Old City centre, New City centre, Ulee Kareng region, and Lamteumen region. Unfortunately, of the four areas only one is planned based on a disaster mitigation.

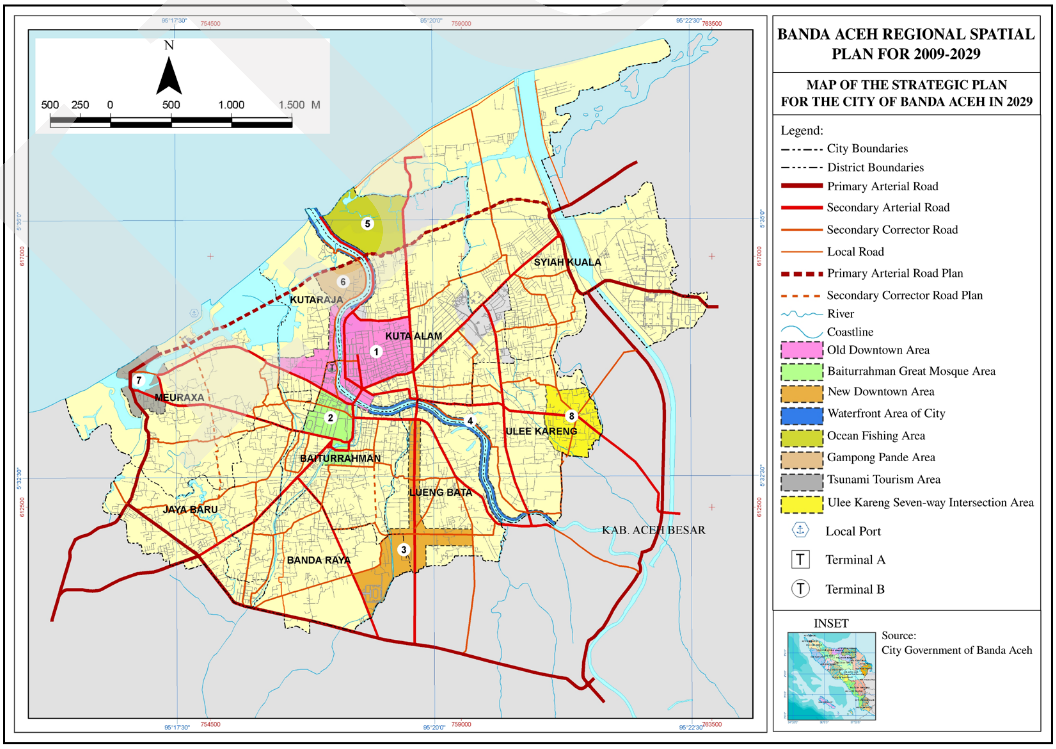

Figure 7. Banda Aceh Regional Spatial Plan for 2009–2029.

The 2004 Indian Ocean tsunami modeling using several models of earthquake sources resulted in variations of tsunami heights in this study. Each earthquake source model with variations in the distribution of slips has a significant influence on the pattern of tsunami propagation which has implications for variations in the time of arrival of the tsunami. The fault model with a slip variation of more than 23 m (in addition to the M1 and M5 models) gives a tsunami height that is not in accordance with the observed height. The fault model that produces the tsunami height that most closely matches the height observed in Banda Aceh-Aceh Besar is a fault model that is inverted from altimetry data, namely the M5 model. The M5 model divides the fault into six segments, with a maximum slip value of 12 m. The M5 model derived from ultimately altimetry data and radar + field measurement data in addition. Meanwhile, the fault model that produces the tsunami height that is at least in accordance with the observations is the result of the inversion of the tsunami waveform, namely the M2 model. The M2 model divides the fault into twelve segments with a maximum slip of 24.4 m.

However, the tsunami simulation performed in this study only used four layers with spatial grid size around 0.03 - 1° and single value of manning coefficient. The results of tsunami height modeling might be reasonably rough. Nevertheless, the results of this study are quite reliable upon to estimate which fault model may generate a tsunamiwith a height that best matches the 2004 tsunami height observations in Banda Aceh-Aceh Besar. The fault model is considered the best model for tsunami height modeling in order to map tsunami disaster-prone areas in Banda Aceh-Aceh Besar.

Conclusions

Based on statistical analysis, M5 is the best model for studying the tsunami hazard in Banda Aceh-Aceh Besar, because it is a fault model that generates tsunami heights that are closest to the observed heights in Banda Aceh-Aceh Besar. These results show that Lhoknga and Leupung are the areas most threatened by tsunami inundation. The M5 fault model is derived from the combined data. This model has a slip value of less than 15 m and a single dip and rake value. These properties are considered to be the most suitable for the method used in this research, so that the resulting tsunami height modeling results are most consistent with NOAA's observations in Banda Aceh-Aceh Besar. Meanwhile, the most suitable tsunami height modeling results are produced by reversed fault models from tide gauge data only. In general, the results of modeling tsunami heights tend to be higher than the observed heights.

The resulting inundation zone states that Banda Aceh City is classified as an area with an inundation height of >3 m. The inundation area is still a strategic area or part of the development area of Banda Aceh City such as The Old City centre area which is a planned area for the development of socio-cultural centres, trade and services, offices, arrangement of heritage areas, provision of green open space, and sustainable management of marine fisheries.

The validity of the fault model for the earthquake-tsunami source cannot be ascertained only by the magnitude of the slip or the number of segments. Therefore, further research related to the comparison of the earthquake-tsunami source fault model needs to consider other parameters to improve accuracy. The combination of data in tsunamigenic earthquake fault modeling produces a model of tsunami height that tends to be more reliable. It is highly recommended to apply the best fault model and maximize bathymetry accuracy and Manning coefficient for tsunami modeling. It is hoped that this will result in a more reliable map of tsunami-prone areas. Thus, the tsunami hazard in Banda Aceh-Aceh Besar can be studied more precisely, and the results are more reliable.

Acknowledgments

The authors would like to thank Meteorology, Climatology, and Geophysic Agency (BMKG), Aceh Geophysic Station for providing such data, Syiah Kuala University, and Tsunami and Disaster

Mitigation Research Centre (TDMRC-USK) for the research opportunity.

Reference

Ammon, C.J., Ji, C., Thio, H.K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., and Wald, D., 2005. Rupture process of the 2004 Sumatra-Andaman earthquake. *Science*, 308 (5725), p.1133-1139. DOI: 10.1126/science.1112260.

Banerjee, P., Pollitz, F., Nagarajan, B., and Bürgmann, R., 2007. Coseismic slip distributions of the 26 December 2004 Sumatra-Andaman and 28 March 2005 Nias earthquakes from GPS static offsets. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), p.86-102. DOI: 10.1785/0120050609.

Banyunegoro, V.H., Alatas, Z.A., Jihad, A., Eridawati, and Muksin, U., 2019. Probabilistic Seismic Hazard Analysis for Aceh Region. *IOP Conference Series: Earth and Environmental Science*, 273 (1). DOI: 10.1088/1755-1315/273/1/012015.

Berryman, K., 2006. Review of Tsunami Hazard and Risk in New Zealand. *Institute of Geological and Nuclear Sciences*, *September*, 139.

Chlieh, M., Avouac, J.P., Hjorleifsdottir, V., Song, T.R.A., Ji, C., Sieh, K., Sladen, A., Hebert, H., Prawirodirdjo, L., Bock, Y., and Galetzka, J., 2007. Coseismic slip and afterslip of the great Mw 9.15 Sumatra-Andaman earthquake of 2004. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), p.152-173. DOI: 10.1785/0120050631.

Fujii, Y. and Satake, K., 2007. Tsunami source of the 2004 Sumatra-Andaman earthquake inferred from tide gauge and satellite data. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), p.192-207. DOI: 10.1785/0120050613.

Grilli, S. T., Ioualalen, M., Asavanant, J., Shi, F., Kirby, J.T., and Watts, P., 2007. Source Constraints and Model Simulation of the December 26, 2004, Indian Ocean Tsunami. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 133 (6), p.414-428. DOI: 10.1061/(asce)0733-950x(2007)133:6(414).

Hall, R., 2009. *Indonesia, Geology. In:* Encyclopedia of Islands (p.454-460). University of California Press.

Hidajat, W.K., Anggoro, S., and Najib, 2021. Coastal Area Management Based on Disaster Mitigation: A Case Study in Purworejo Regency, Indonesia. *Indonesian Journal on Geoscience*, 8 (2), p.147-156. DOI: 10.17014/ijog.8.2.147-156

Hirata, K., Satake, K., Tanioka, Y., Kuragano, T., Hasegawa, Y., Hayashi, Y., and Hamada, N., 2006. The 2004 Indian Ocean tsunami:Tsunami source model from satellite altimetry. *Earth, Planets and Space*, 58 (2), p.195-201. DOI:10.1186/BF03353378.

Imamura, F., Yalçiner, A.C., and Ozyurt, G., 2006. Tsunami modelling manual. *Tsunami Modeling Manual*, *April*, 58.

Jihad, A. and Banyunegoro, V.H., 2017. Melihat potensi sumber gempa bumi dan tsunami Aceh. *Workshop II Tsunami Drill*.

Jihad, A., Muksin, U., Syamsidik, and Ramli, M., 2021. Earthquake relocation to understand the megathrust segments along the Sumatran subduction zone. *IOP Conference Series: Earth and Environmental Science*, 630, 012002. DOI: 10.1088/1755-1315/630/1/012002.

Kaiser, G., Scheele, L., Kortenhaus, A., Løvholt, F., Römer, H., and Leschka, S., 2011. The influence of land cover roughness on the results of high resolution tsunami inundation modeling. *Natural Hazards and Earth System Science*, 11 (9), p.2521-2540. DOI: 10.5194/nhess-11-2521-2011.

Koshimura, S., Oie, T., Yanagisawa, H., and Imamura, F., 2009. Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from banda aceh, Indonesia. *Coastal Engineering Journal*, 51 (3), p.243-273. DOI: 10.1142/S0578563409002004.

Latief, H., Puspito, N. T., and Imamura, F., 2000. Tsunami Catalog Indonesia.pdf. *Journal of Natural Disaster Science,* 22 (1), p.25-43. www.jstage.jst.go.jp/article/jnds/22/1/22_1_25/_pdf.

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 754, p.1135-1154.

Piatanesi, A. and Lorito, S., 2007. Rupture process of the 2004 Sumatra-Andaman earthquake from tsunami waveform inversion. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), p.223-231. DOI:10.1785/0120050627.

Poisson, B., Oliveros, C., and Pedreros, R., 2011. Is there a best source model of the Sumatra 2004 earthquake for simulating the consecutive tsunami? *Geophysical Journal International*, 185 (3), p.1365-1378. DOI:10.1111/j.1365-246X.2011.05009.x.

Pribadi, S., 2013. Characteristics of Earthquake Indonesia Based on Source Parameter. *Journal of Mathematics and Fundamental Science,* 45 (2), p.189-207. DOI: 10.5614/j.math.fund.sci.2013.45.2..8.

Puspito, N.T. and Gunawan, I., 2005. Tsunami sources in the sumatra region, Indonesia and Simulation of the 26 December 2004 Aceh tsunami. *ISET Journal of Earthquake Technology*, 42 (4), p.111-125.

Rhie, J., Dreger, D., Bürgmann, R., and Romanowicz, B., 2007. Slip of the 2004 Sumatra-Andaman earthquake from joint inversion of long-period global seismic waveforms and GPS static offsets. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), p.115-127. DOI: 10.1785/0120050620.

Sladen, A. and Hébert, H., 2008. On the use of satellite altimetry to infer the earthquake rupture characteristics: Application to the 2004 Sumatra event. *Geophysical Journal International*, 172 (2), p.707-714. DOI: 10.1111/j.1365-246X.2007.03669.x.

Song, Y.T., Ji, C., Fu, L.L., Zlotnicki, V., Shum, C.K., Yi, Y., and Hjorleifsdottir, V., 2005. The 26 December 2004 tsunami source estimated from satellite radar altimetry and seismic waves. *Geophysical Research Letters*, 32 (20), p.1-5. DOI: 10.1029/2005GL023683.

Stein, S. and Okal, E., 2005. Speed and size of the Sumatra earthquake. *Nature*, 434, p.581-582.

Subarya, C., Chlieh, M., Prawirodirdjo, L., Avouac, J.P., Bock, Y., Sieh, K., Meltzner, A.J., Natawidjaja, D.H., and McCaffrey, R., 2006. Plate-boundary deformation associated with the great Sumatra-Andaman earthquake. *Nature*, 440 (7080), p.46-51. DOI: 10.1038/nature04522.

Suppasri, A., Fumihiko, I., and Shunichi, K,. 2008. *Comparison Among the Proposed Models for the 2004 Indian Ocean Tsunami Comparison Among the Proposed Models for the 2004 Indian Ocean Tsunami*. *December 2014*, 2004-2006.

Suppasri, A., Koshimura, S., and Imamura, F., 2011. Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. *Natural Hazards and Earth System Science*, 11 (1), p.173-189. DOI:10.5194/nhess-11-173-2011.

Tanioka, Y., Yudhicara, Kususose, T., Kathiroli, S., Nishimura, Y., Iwasaki, S.I., and Satake, K., 2006. Rupture process of the 2004 great Sumatra-Andaman earthquake estimated from tsunami waveforms. *Earth, Planets and Space*, 58 (2), p.203-209. DOI: 10.1186/BF03353379.

Tsai, V.C., Nettles, M., Ekström, G., and Dziewonski, A.M., 2005. Multiple CMT source analysis of the 2004 Sumatra earthquake. *Geophysical Research Letters*, 32 (17), p.1-4. DOI: 10.1029/2005GL023813.

United Kingdom Hydrographic Office, 2005. *Catalogue of Admiralty Charts and Publications*. United Kingdom Hydrographic Office.

USGS, 2015. *M 9.1 - 2004 Sumatra-Andaman Islands Earthquake Intensity Map*. https://earthquake.usgs.gov/earthquakes/eventpage/official20041226005853450_30/dyfi/intensity.

USGS, 2020. *Earthquake Catalog*. https://earthquake.usgs.gov/earthquakes/search/.

Vallée, M., 2007. Rupture properties of the giant Sumatra earthquake imaged by empirical green's function analysis. *Bulletin of the Seismological Society of America*, 97 (1 A SUPPL.), 103–114. DOI: 10.1785/0120050616.

Vigny, C., Simons, W.J.F., Abu, S., Bamphenyu, R., Satirapod, C., Choosakul, N., Subarya, C., Socquet, A., Omar, K., Abidin, H. Z., and Ambrosius, B.A.C., 2005. Insight into the 2004 Sumatra-Andaman earthquake from GPS measurements in southeast Asia. *Nature*, 436 (7048), p.201-206. DOI: 10.1038/nature03937.

Yagi, Y. ,2005. Preliminary results of rupture process for 2004 off coast of northern Sumatra giant earthqauke (ver. 1). *http://Iisee.Kenken.Go.Jp/Staff/Yagi/Eq/Sumatra2004/Sumatra2004.Html*. http://ci.nii.ac.jp/naid/10024491121/en/.